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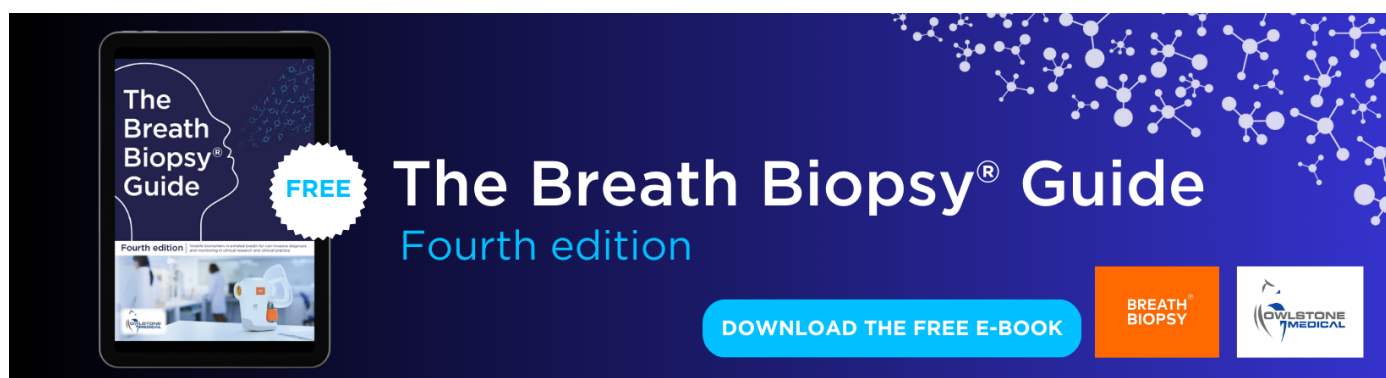
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Quantifying land use of oil sands production: a life cycle perspective

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Abstract

Methods for the inclusion of land use in life cycle assessment are not well established. Here, we describe an approach that compares land disturbance between spatially compact and diffuse activities that contribute to the life cycle of a single product, in this case synthetic crude from Alberta's oil sands. We compare production using surface mining and *in situ* extraction technologies. *In situ* technologies disturb less land per unit of production than surface mining, but the spatial footprint of *in situ* production is more dispersed—increasing landscape fragmentation—and *in situ* production requires more natural gas which increases land use due to gas production. We examine both direct and peripheral land use of oil sands development by quantifying land disturbance using a parameterized measure of fragmentation that relies on 'edge effects' with an adjustable buffer zone. Using a life cycle perspective, we show that the land area influenced by *in situ* technology is comparable to land disturbed by surface mining when fragmentation and upstream natural gas production are considered. The results suggest that land disturbance due to natural gas production can be relatively large per unit energy. This method could be applied to other energy developments, for example, a comparison between coal mining and natural gas production when both fuels are used to generate electricity.

Keywords: oil sands, natural gas, life cycle assessment, land use, landscape ecology, fragmentation, edge effects

 Supplementary data are available from stacks.iop.org/ERL/4/024004

Nomenclature

bbl	barrel
bpd	barrel per day
CEMA	Cumulative Environmental Management Association
CSS	cyclic steam stimulation
EIA	environmental impact assessment
ERCB	Energy Resources Conservation Board
ILM	Integrated Landscape Management

LCA	life cycle assessment
m	meter
m ²	square meter
m ³	cubic meter
PSAC	Petroleum Services Association Canada
SEWG	Sustainable Ecosystems Working Group
SAGD	steam assisted gravity drainage
SFS	Southern Foothills Study
SCO	synthetic crude oil

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tcf trillion cubic feet
 ZOI zone of influence

1. Introduction

Bitumen production from Alberta's oil sands is rising rapidly reaching 1.3 mbpd (million barrels per day) or 7.7×10^7 m³/year in 2007 (ERCB 2008), equivalent to approximately 1.5% of global crude production. Bitumen production is widely expected to increase to as much as 4 mbpd by 2030 (Energy Information Administration 2008). In one scenario, 8 mbpd was considered as an upper limit for 2050 (CEMA-SEWG 2008). Oil sands products come in the form of synthetic crude oil (SCO) and non-upgraded bitumen. In 2007, Alberta produced 0.7 mbpd of upgraded bitumen in the form of SCO and 0.5 mbpd of non-upgraded bitumen (ERCB 2008). The extraction of bitumen and its conversion to final hydrocarbon products requires substantially larger amounts of natural gas than is needed for conventional oil extraction and refining (Brandt and Farrell 2007). Bitumen is extracted either by surface mining or *in situ* production methods. Surface mining techniques remove shallow depth oil sand deposits by truck and shovel and extract the bitumen by mixing the oil sand with water warmed using natural gas (Alberta Chamber of Resources 2004). *In situ* technology is used for deeper deposits where natural gas is used to produce steam that is injected to reduce the viscosity of the bitumen which is then pumped to the surface using production wells. The ERCB (2008) reported that 40% of bitumen was produced with *in situ* recovery in 2007 while the other 60% was produced with surface mining. It is currently estimated that 82% of recoverable bitumen deposits will be extracted using *in situ* technologies (ERCB 2008).

The United Nations (2009) defines land use as human activities that produce, change or maintain a specific land cover type. The use of land to produce goods and services is considered by some to be the most significant human alteration of the Earth's ecosystem (Vitousek *et al* 1997). The impacts of this land use are often complex and value-laden, ranging from changes in the Earth's biogeochemical cycles (Watson *et al* 2000) to biodiversity impacts (Lindeijer 2000a). A societal dilemma arises from those land uses that provide economic and social gains while simultaneously altering ecosystem services that humans value and depend upon (Foley *et al* 2005). Energy development in Alberta exemplifies this issue. While the extraction, sale, and use of bitumen results in economic gains, social, environmental and cultural values are also impacted. As a result, oil sands have been the focus of debate by a wide range of environmental organizations (e.g. Schneider and Dyer 2006, UNEP 2008).

Surface mining and *in situ* recovery affect the landscape in different ways (Alberta Chamber of Resources 2004, CEMA-SEWG 2008). Land use of surface mining is comprised largely of polygonal features (mine sites, overburden storage, tailing ponds and end pit lakes); whereas *in situ* development is mostly defined by linear features that extend across the lease area (networks of seismic lines, access roads, pipelines and well sites). The latter technology is considered by some to be

more environmentally benign in terms of land use (Sherrington 2005, Alberta Chamber of Resources 2004); however, this does not include landscape fragmentation caused by *in situ* projects and upstream natural gas production. This is particularly significant as *in situ* technologies are expected to be used for developing approximately 137 000 km² of land (98% of the oil sands area) under current technological and economic conditions (CAPP 2009). In addition, the Alberta Chamber of Resources (2004) estimated that *in situ* production requires approximately four times the quantity of natural gas used for surface mining on a production volume basis. Natural gas production requires the creation of linear features, similar to *in situ* oil sands development. Although the area disturbed by surface mining is straightforward to quantify, the incremental fragmentation effects of linear features are more difficult to quantify per unit production. These effects have not previously been quantified on a production basis for oil sands projects.

As shown in figure 1, bitumen production results in land use impacts in the boreal eco-region. At the same time, natural gas is required for the extraction and processing of bitumen. This natural gas is purchased from Alberta's market and results in additional natural gas development across the province and additional land use impacts. It should be noted that the provincial natural gas market is part of a global market; however, we focus on Alberta for this study. We quantify the land use of oil sands technologies from a life cycle perspective to understand the scale of upstream land use of natural gas production relative to the on-site land use of oil sands operations when an additional barrel of SCO is produced.

The creation of both linear and polygonal features results in landscape fragmentation, which in turn affects both biodiversity value and other values society places on land. Simply using the area of land cleared is not a sufficient measure for the effects of development on a landscape. If a forest is fragmented, species are exposed to the conditions of different ecosystems (Saunders *et al* 1991). When two ecosystems are adjacent to each other, they interact to some degree through an edge. Different species composition and abundance occurs at the edge as opposed to within larger patches in the landscape. This phenomenon is known as the edge effect (Forman and Godron 1986). We propose an approach to including land disturbance and fragmentation in a life cycle assessment (LCA) inventory using the example of oil sands development (refer to section 2 for the definition of LCA). Our assessment goes beyond direct land impacts to assess landscape fragmentation through quantifying edge effects caused by key life cycle stages. Before detailing our approach and providing results, we develop the necessary background on landscape fragmentation specific to our research and then describe the relationship between oil sands development, natural gas markets and land use.

2. Landscape fragmentation

Life cycle assessment (LCA) is a decision making tool used to evaluate environmental burdens and consequences of developing a product or process over its life cycle from cradle to grave (Environmental Protection Agency 1993). Ongoing

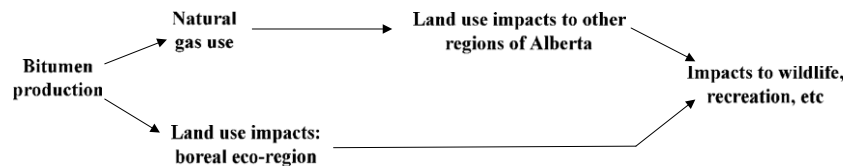


Figure 1. On-site and upstream land use of oil sands development. Each development results in a variety of activities on the landscape which result in a variety of impacts, such as wildlife, recreation and wilderness.

debate surrounds the inclusion of land use impacts into LCA, particularly around what indicators to consider and what methodology should be used (Antón *et al* 2005). Due to the number of values society places on land and the ecosystem services provided, there is a diverse selection of impacts that can be assessed. Landscape fragmentation has recently been identified as a new research area for assessing land use effects in LCA (Canals *et al* 2006).

Fragmentation is a process in which ‘a large expanse of habitat is transformed into a number of smaller patches of smaller total area, isolated from each other by a matrix of habitats unlike the original’ (Wilcove 1987). It can occur through natural disturbances, such as fire, or through human activities. Though fragmentation can either increase or decrease local biodiversity, some species are adversely affected at a large scale (Saunders *et al* 1991, Wilcove 1987). Fragmentation can result in diminished native biodiversity and homogenization of flora and fauna across landscapes (Noss 1983, 1990). Some species will use anthropogenic edges to their advantage; for example, some carnivores may use linear features to facilitate predation. Species most likely to be adversely affected by habitat fragmentation include specialist species that require niche habitats (Fahrig 2003) and large carnivores that require extensive tracts of undisturbed habitat (Yahner 1988). For example, grizzly bear (*Ursus arctos horribilis*) mortality has been found to increase near anthropogenic edges in the Central Rockies of Alberta (Nielsen *et al* 2004). Impacts of fragmentation can be reduced through decreasing the amount of linear features on the landscape or mitigating the effects of these features. For example, the effects of pipelines can be mitigated by elevating the pipeline to facilitate wildlife movement underneath or by constructing crossing structures to facilitate wildlife movement over the pipeline (Dunne and Quinn 2009).

Studies conducted in the boreal forest of Alberta confirm that fragmentation can significantly affect the occurrence and behavior of wildlife. Woodland caribou (*Rangifer tarandus caribou*) have been found to avoid anthropogenic edges at varying distances depending on disturbance type and time of year in Alberta’s north eastern boreal forest (Dyer *et al* 2001). These authors showed that caribou avoid habitat close to well sites at distances of up to 1 km and up to 250 m from roads and seismic lines. An ongoing study based on DNA and hormonal analysis of scat found by trained dogs has far greater statistical power to detect the impacts of anthropogenic land disturbance on wildlife in the oil sands region. Preliminary results from this study show that (a) caribou avoid high-use roads in areas being developed for bitumen production at distances to 4 km

if the foraging habitat is of relatively low value to the caribou; (b) in the case of high-value foraging habitat caribou show little evidence of avoiding roads but do show hormonal evidence of stress; (c) similarly, moose (*Alces alces*) were found to avoid roads and cutlines, whereas wolves (*Canis lupis*) were found to prefer them (Wasser 2009). Finally, Nielsen *et al* (2007) showed that the occurrence of 6 of 14 species surveyed in Alberta’s boreal forest was significantly related to road density. Occurrence of domestic dog (*Canis domesticus*), coyote (*Canis latrans*), deer (*Odocoileus* sp.) and snowshoe hare (*Lepus americanus*) increased with increasing road density, while the occurrence of lynx (*Lynx canadensis*), marten (*Martes americana*), wolf, and fisher (*Martes pennanti*) all decreased.

The effects of fragmentation vary across regions and are site and species specific. Nevertheless, these studies collectively demonstrate that land use disturbance due to oil sands operations can produce significant impacts on the behavior of keystone and profile species at distances that extend at least 0.1 km and in some cases several km from the disturbance. The detection of hormonal indicators of physiological stress suggests that disturbance may alter the welfare of affected species beyond the direct effects that stem from excluding land from active use.

Edge effects are defined not only by the length of human-created edge on the landscape, but also by the distance and magnitude of edge influence. Edge influence refers to the effect of edges on biotic and abiotic processes that result in a detectable difference in composition, structure and function on either side of the edge. The magnitude of edge influence refers to the extent to which given parameters differ at edges as opposed to reference conditions. The distance of edge influence (also called buffer width) refers to how far the effects will extend from the disturbance. Edge effects result in a larger zone of influence that extends beyond the area directly impacted (Knight 2000). For example, an edge may result in a higher abundance of a particular species that can increase forage intake by using the resources in both of the adjacent ecosystems. This zone can be created by a variety of effects, such as avoidance or preference by wildlife, changes in vegetation, human access (e.g. hunting and fishing access), noise, pollution from vehicles, and indirect changes in the landscape (e.g. from increased wind exposure). Development of linear features can result in ecological edge effects, but also can affect wilderness value that humans ascribe to landscapes. For example, many hikers may prefer wilderness areas that are free of infrastructure at distances on the order of kilometers rather than meters. Society also places value on the wildlife that is found on landscapes.

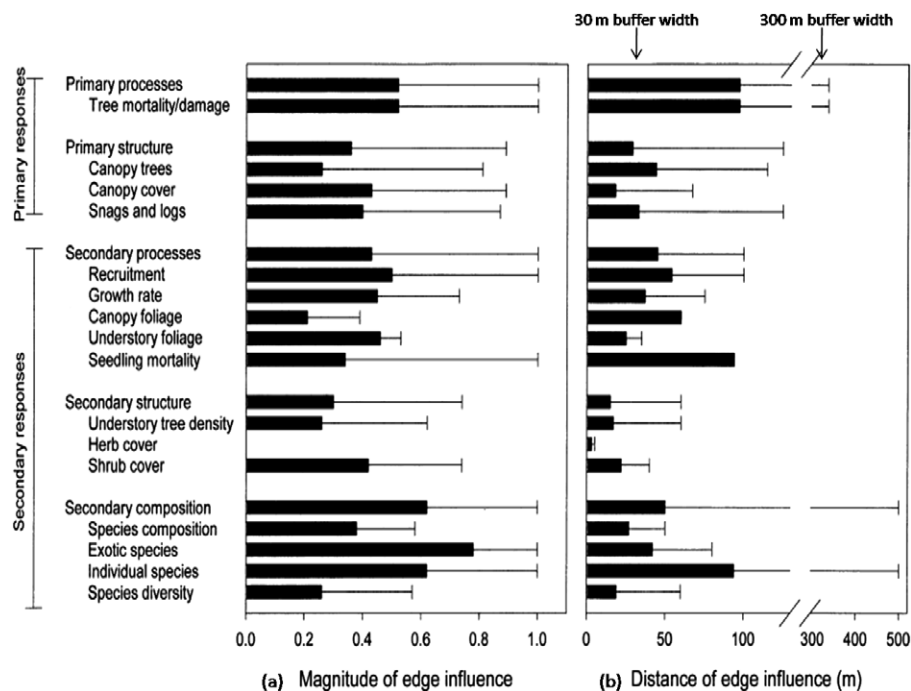


Figure 2. Magnitude (a) and distance (b) of edge influence for a range of response variables based on 44 individual studies. Reproduced from Harper *et al* (2005) with permission of Blackwell Publishing Ltd. The ranges provided are values derived from individual studies. Primary responses were classified as those resulting immediately and directly from edge creation, while secondary responses arise from the primary responses.

Yahner (1988) suggests edge widths should be defined through their functional use by wildlife. This poses some difficulty as response to edge will vary by species and region. Harper *et al* (2005) contribute to a ‘uniform theory of edge effects’ through (in part) compiling data from 44 studies in order to determine both the magnitude and distance of edge influence for different types of landscape disturbance with a focus on vegetation and forests. Figure 2 provides an example of how edge effects can vary by impact and region in studies undertaken across the world. Along with the regional studies presented, figure 2 provides a strong argument that edge effects can vary up to 500 m and beyond. We have selected a 30–300 m range for buffer width that we later use in the sensitivity analysis.

Quantifying the length of an edge is straightforward, but quantifying the distance of edge influence (i.e., the buffer width) is far more uncertain because it depends on species in question, the kind of disturbance considered and various local attributes. Nevertheless, if the buffer width associated with linear and polygonal features is known or can be estimated for a particular type of resource development, edge effects can be used as a proxy for fragmentation. A benefit of using this approach is that the effects can be quantified per unit output and that this same analytic method can be applied across various regions and extraction technologies. The drawback is that site-specific ecological impacts cannot be directly incorporated. Given the need for a systematic approach, the method is appropriate for life cycle assessment of land use impacts.

Our goal is a comparative assessment of the average land use impacts per unit bitumen or natural gas production. We

therefore adopt a systematically applicable parameterization of the impacts of land use disturbance that focuses on disturbance area from both direct land use and area associated with edge effects caused by the development of linear features. We first estimate the length, width and area of each component of resource development activity on the landscape, for example roads and seismic lines. We can then estimate the length of linear features, or ‘edge’ per unit production. Finally, we estimate the overall land use impact parametrically in terms of the area of a buffer adjacent to linear features.

To demonstrate how we quantify edge effects, we provide a simple example for both linear and polygonal features in figure 3. The direct land disturbance for figure 3(b) is the area of the pipeline (1 km × 10 m, or 1 hectare). The edge effect is equivalent to multiplying edge length (e.g. the pipeline length) for each side of the feature by the buffer width and then introducing a discount for the magnitude of edge influence. Edge effects are thus quantified by the edge length and the buffer width (1 km × 100 m for each side of the pipeline, or 20 hectares). The land disturbance including edge effects (or zone of influence) is 21 hectares, under the assumption that the edge influence is equivalent to 1. The same principles are applied for polygonal features where the edge is quantified by the perimeter of the feature (figure 3).

3. The relationship between oil sands development, natural gas markets and land use

In addition to the direct land use footprint of oil sands production, we also use similar methods (edge with a

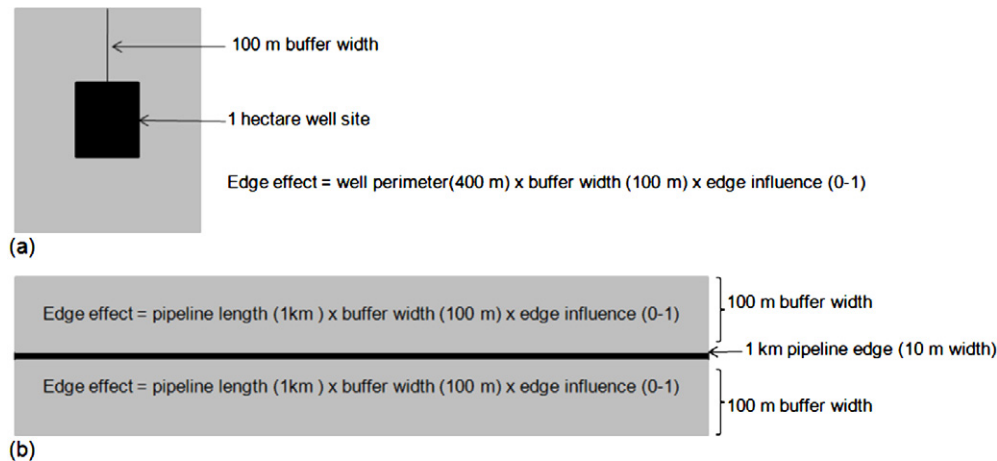


Figure 3. Edge and edge effects. The black square in (a) represents a well site and demonstrates how edge effects are calculated for polygonal features. The black line in (b) represents a pipeline and demonstrates how edge effects are calculated for linear features. The gray areas surrounding the black features represent edge effects.

parametric buffer width) to compute the indirect area that arises from natural gas used in the process. When considering natural gas inputs to oil sands developments, two issues are relevant. First, the two major production technologies use significantly different amounts of natural gas. Second, not all of this natural gas is purchased from the market. According to Alberta's Energy Resources Conservation Board (ERCB), 63% of the gaseous fuel used in oil sands development was purchased from the market in 2006 compared to 31% derived from the upgrading process, and 6% produced from bitumen wells. For this analysis, only natural gas purchased from the market was used for quantifying upstream land use. We assume $70 \text{ m}^3/\text{m}^3$ SCO of natural gas is purchased for extraction using surface mining, $220 \text{ m}^3/\text{m}^3$ SCO of natural gas is purchased for extraction using *in situ* recovery, and that in either case $50 \text{ m}^3/\text{m}^3$ SCO is used for upgrading the bitumen to SCO (Dunbar 2007). These values are converted to a barrel of SCO basis where necessary in order to compare on a consistent functional unit. For more details, see the supplementary information (available at stacks.iop.org/ERL/4/024004).

Alberta's conventional gas production is peaking and gas production in the basin is becoming 'mature'; as the high-quality gas fields are depleted gas producers are using smaller deposits with lower productivity wells (figure 4). The land use impacts per unit of gas production are consequently increasing as more drilling is required per unit production.

Our estimate of the upstream land use impacts due to natural gas consumed in oil sands operations depends on the assumption that (a) there is an efficient natural gas market so that an additional unit of demand is met by additional unit of production, and (b) that the specific land use data for natural gas extraction which we derive from the Southern Foothills of Alberta is representative of the average land use impacts of natural gas extraction (see section 4.1 for more details on these assumptions).

The oil sands industry accounted for 15% of natural gas demand in Alberta in 2007 (ERCB 2008). This has been forecast to grow to 32% by 2017. Oil sands operations are,

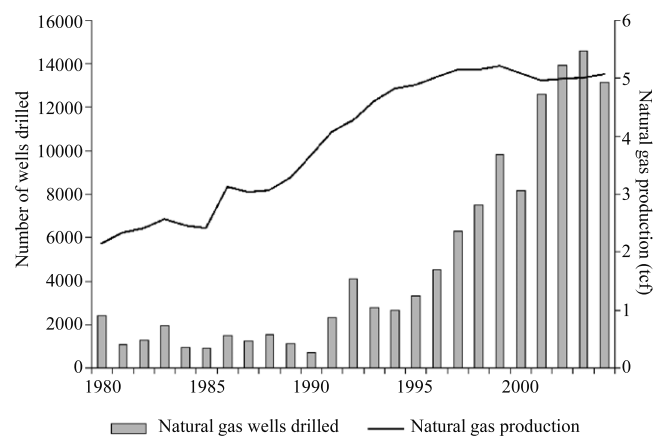


Figure 4. Alberta natural gas drilling and production trends for 1980–2006. Trends show a large increase in drilling over this time period while production stabilizes in the late 1990s and 2000s. These trends illustrate that the basin is becoming exhausted. Data are from Alberta's Energy Resources Conservation Board (ERCB 2007).

of course, only one of many consumers purchasing natural gas from the market. We assume that the land use impacts of gas purchased for oil sands operations are representative of the average impacts per unit gas produced in Alberta and are applicable to these other consumers as well.

4. Approach and analysis

We investigate the following question: what is the life cycle land use per unit of oil sands production and the associated landscape fragmentation? We use land disturbance (the area that is directly transformed from one state to another) to calculate direct land use and we use edge effect area (peripheral area impacted by the land disturbance) to account for the fragmentation caused by linear features. The analysis focuses primarily on oil sands operations and natural gas use in oil sands projects and upgrading, but we also investigate the relative magnitudes of upgrading and the transport to the

upgrader. The comparison includes transport to and upgrading of oil sands products at a hypothetical upgrader in the Industrial Heartland outside of Edmonton. In principle, a complete land use life cycle assessment should treat other inputs to production process such as electricity generation. Scoping calculations have shown that in the case of land use, natural gas is by far the most important upstream component of the life cycle (please see the supplementary information (available at stacks.iop.org/ERL/4/024004) for the comparison to electricity inputs). Boundaries are set to the province of Alberta for policy relevance and for data availability. We have assessed oil sands and natural gas development projects in two study areas in Alberta to characterize land disturbance and linear features created by these developments on the landscape.

4.1. Study areas

We characterize resource extraction projects in two different study areas based on two studies in Alberta; one characterized land use parameters of oil sands development and the other characterized land use parameters for natural gas production. The two study areas in question are (1) the Regional Municipality of Wood Buffalo (RMWB) which overlaps the Athabasca bitumen producing region and was used in CEMA-SEWG (2008) and (2) the study area defined in the Southern Foothills Study (SFS), which is one of Alberta's natural gas producing regions (for a map of these areas, refer to the supplementary information available at stacks.iop.org/ERL/4/024004).

A series of workshops were held in each study area with energy developers and stakeholders to estimate the land use parameters (e.g. road length and width) and resource production associated with the respective activity for land use simulations in 'a landscape cumulative effects simulator' (ALCES) (see ALCES (2009) for more information on this landscape and land use simulation model). Parameters estimated include the representative spatial dimensions for various specific activities (e.g. well pads) as well as their estimated life span until reclamation. These characterizations were used in our analysis as representative of typical developments in these areas.

The RMWB is found in Alberta's boreal forest and was used as the study area for recent work undertaken by the Cumulative Environmental Management Association (CEMA). CEMA is a multi-stakeholder group with 44 participating member organizations with the mandate of studying the cumulative environmental effects of industrial development in the RMWB and producing guidelines and management frameworks (CEMA 2009). One of its six working groups is the Sustainable Ecosystem Working Group (SEWG) which recently conducted an extensive study where development scenarios were developed to investigate the impacts of oil sands development on the landscape of the RMWB.

The RMWB overlaps the northeast portion of the oil sands area and encompasses 68 000 km² of boreal forest in northeast Alberta. By the year 2106, the gross cumulative land disturbance of both surface mining and *in situ* extraction of

oil sands in the RMWB has been simulated at approximately 8000 km² (CEMA-SEWG 2007). We use land disturbance parameters for typical surface mining and *in situ* recovery projects as defined by CEMA-SEWG (2008), which are further detailed in the supplementary information (available at stacks.iop.org/ERL/4/024004). CEMA-SEWG (2008) presented four generic SAGD land use characterizations: (1) development in thick pay, (2) development in thin pay, (3) development in thick pay using innovative approaches and (4) development in thin pay using innovative approaches. The pay zone describes the thickness of the bitumen deposit where the resource is recoverable under current economic and technological conditions. Pay thickness of less than 15 m was not considered economically recoverable by CEMA-SEWG. Bitumen deposits between 15 and 25 m were classified as thin pay while deposits greater than 25 m were classified as thick. As our base case, we consider the first generic characterization, *in situ* development in thick pay. Though we choose thick pay as our base case, it should be noted that some development is occurring in thin pay. These projects are assessed over the time frames reported by CEMA-SEWG (2008), 65 years for the *in situ* base case and 35 years for the surface mining base case. We assumed that surface mining will require the same level of exploration as *in situ* recovery, adding another 10 years to the 25 year life. These life spans represent the time from initial development until when the soil has been re-seeded or re-planted. The *in situ* development was assumed to be longer as the production wells will be operating in three sets for each case rather than a more intensive development case where all wells would exist on the landscape at the same time.

These characterizations are not representative of any particular project, but rather of a generic, typical oil sands project operating in the study area. 'Innovative approaches' are those management decisions which can reduce a project's land disturbance and the duration of this disturbance. CEMA-SEWG's (2008) innovative approaches included a suite of options to reduce land use impacts: increasing the number of production wells on a well site, aggressive reclamation targets, reducing widths of linear features, and increasing integrated landscape management by coordinating land disturbance of the energy sector with the forestry sector. Other methods to reduce and mitigate land use considered by CEMA-SEWG included developing a protected areas network within the RMWB and access management to reduce the use of linear features by humans and predators through time.

Natural gas production proceeds through two distinct mechanisms: intensification and extensification. Intensification, or infilling, involves increasing the density of drilling to increase production while extensification involves new production in (relatively) undeveloped areas. In Alberta intensification is concentrated in the southeast where over 50% of drilling occurred in 2007 (ERCB 2008). This region has the highest areal density of producing natural gas wells in Alberta (see the supplementary information available at stacks.iop.org/ERL/4/024004). We focus first on an example of extensification into natural areas, Alberta's southern foothills area, but later compare our results to infilling using sensitivity analysis.

Our data on the land use footprint of natural gas production is based on a study undertaken in the southern foothills of Alberta (Southern Foothills Study 2009). This region is 12 000 km² of land located in southwest Alberta covering Parkland, Mixedgrass and Rocky Mountain Natural Regions (Alberta Sustainable Resource Development 2005). As natural gas reserves in Alberta become exhausted, more environmentally sensitive areas, such as the southern foothills, are being explored and developed. This area was chosen because it is a natural gas producing region that was previously considered marginal for development due to costly drilling and environmental sensitivity. As of 2007, there were 160 producing conventional gas wells in the region (Gardner 2007). The SFS developed land use scenarios that showed potential for significant increases in drilling activity in this region. Though the infrastructure needs may be more significant than for infilling and there is more exploration risk, we use best management practices to characterize the development. More importantly, natural gas wells in the foothills have close to the highest well productivity in Alberta, an order of magnitude higher than infilling regions (section 4.3). Metrics for area, lifespan, and reclamation of natural gas infrastructure for the SFS region were developed through workshops involving regional gas producers.

4.2. Land use calculations

Each LCA stage was compared using a barrel of SCO as the functional unit. Data has been converted from bitumen to an SCO basis using ERCB's (2008) volumetric SCO to bitumen ratio of 0.85. We first calculate the land disturbance intensity in m²/m³ SCO for each oil sands technology over the life of the project, I_{SCO} , as follows:

$$I_{SCO} = \frac{A_{SCO}}{V_{SCO}} = \frac{1}{V_{SCO}} \sum_{i=1}^n A_i \quad (1)$$

where A_{SCO} is the area disturbed by the project, V_{SCO} is the total volume of SCO produced, A_i is the area of land disturbed for each component i of the development (e.g. roads or pipelines), and n is the number of features on the landscape for each respective development.

The land disturbance intensity of the natural gas development required for SCO production, I_{NG-OS} , is defined by:

$$I_{NG-OS} = \frac{A_{NG-OS}}{V_{SCO}} = \frac{V_{NG-OS}}{V_{SCO}} \frac{A_W}{V_{NG}} \\ = \frac{V_{NG-OS}}{V_{SCO}} \frac{1}{V_{NG}} \sum_{j=1}^m A_j \quad (2)$$

where A_{NG-OS} is the area disturbed by the natural gas purchased for the respective oil sands technology, V_{NG-OS} is the natural gas purchased for the oil sands technology in question, V_{NG} is the average conventional natural gas production over the lifetime of a well, A_W is the average area disturbed per well, A_j is the average area of land disturbed per well for each component j of the development (well pads,

seismic lines, pipelines and access roads⁵) and m is the number of components per well.

We then compare the land use of each surface mining and *in situ* recovery to the upstream land use from natural gas production in terms of land occupation (m² year/m³ SCO). Land occupation is a metric that represents not only the amount of land disturbed but is weighted according to the amount of time an activity remains on the landscape (Lindeijer 2000b). Land occupation for the oil sands technology in question, L_{SCO} , is defined by:

$$L_{SCO} = \frac{1}{V_{SCO}} \sum_{i=1}^n A_i t_i \quad (3)$$

where A_i is the area of land disturbed for each component i of the development (e.g. roads or pipelines), n is the number of features on the landscape for each respective development, and t_i is the amount of time the component will remain on the landscape in years.

The land occupation of the natural gas development required for SCO, L_{NG-OS} , is defined by:

$$L_{NG-OS} = \frac{V_{NG-OS}}{V_{SCO}} \frac{W}{V_{NG}} \sum_{j=1}^m \frac{A_j}{W} t_j \quad (4)$$

where A_j is the area associated with each feature j , m is the number of features on the landscape, and t_j is the amount of time the component will remain on the landscape in years. Though the production is variable (e.g. conventional natural gas wells generally produce more after being drilled then later in their production lives), we amortize the production of each development over the life of the project.

A parametric assessment of edge effects was undertaken for each technology by varying the buffer width associated with land use edges (pipelines, roads, seismic lines, etc). The area influenced by oil sands technologies including the edge, or the zone of influence ZOI_{SCO} , reported in m² year/m³ SCO, is defined by:

$$ZOI_{SCO} = \frac{1}{V_{SCO}} \sum_{i=1}^n (A_i + e_i b) t_i \quad (5)$$

where e_i is the length of the sides of the human-created, or anthropogenic edge created by each footprint component i in a typical oil sands project and b is the buffer width which represents the distance of edge influence.

Similarly, the zone of influence of the natural gas development required for SCO production, ZOI_{NG-OS} , is defined by:

$$ZOI_{NG-OS} = \frac{V_{NG-OS}}{V_{NG}} \frac{1}{V_{NG}} \sum_{j=1}^m (A_j + e_j b) t_j \quad (6)$$

where e_j is the average length of the sides of the human-created, or anthropogenic edge created by each component

⁵ Other land disturbance components of natural gas development that we have not considered include processing facilities, assumed to use relatively small amounts of land per unit output when one considers the lifetime of a plant, compression facilities and pipeline leakage.

Table 1. Ranges of land use intensities for oil sands and natural gas developments. For our analysis, we use the estimates noted in the fourth column. These estimates, with the exception of upgrading, were derived from the aforementioned studies.

Technology	Unit of measurement	Literature range	Estimate (study areas)
Mining	m ² /m ³ SCO	0.33 ^a –0.63 ^b	0.42
<i>In situ</i>	m ² /m ³ SCO	0.07–0.16 ^c	0.11
Upgrading	m ² /m ³ SCO	0.0075 ^d –0.023 ^e	0.011
Natural gas development	m ² /well	15 000–150 000	30 000
Productivity per well ^f	m ³ /well	5.1 × 10 ⁶ –5.8 × 10 ⁷	5 × 10 ⁷
Natural gas production	m ² /m ³ natural gas	0.000 26–0.030	0.000 95 ^g

^a The range of land use intensity from all operating surface mining projects in Alberta, derived from the project area divided by the initial established reserves from ERCB (2008). Initial established reserves are defined by the initial mineable area (using several criteria including a minimum saturation cut-off of 7 mass per cent bitumen and saturated zone thickness cut-off of 3.0 m) minus protected areas, isolate ore bodies, and surface facilities.

^b From ERCB (2008). See footnote a for more details.

^c These values are SAGD modeling assumptions from CEMA-SEWG (2008) ALCES workshops. Two cases were developed: base case and innovative approaches (using best land use practices). These parameters were used for each thin and thick bitumen pay. Five Environmental Impact Assessments (EIAs) were reviewed, giving a range of 0.04 m²/m³ for Canadian Natural (2006) and 0.15 m²/m³ for Suncor (2006). These were not used as features (roads, pipelines, etc) were reported inconsistently across EIAs; that is, some would report comprehensively on land use features, while others would only report a few.

^d From Shell Canada (2005); ^e from Synenco (2006).

^f These values were derived from the drilling to production ratios for different regions in Alberta based on ERCB (2007). Wells that are infilled have been found to produce as low as 2.8 × 10⁶ m³/well over the life of the well (Encana 2007); ^g including assumption of 50% well success.

j per well and b is the buffer width which represents the distance of edge influence. Estimates of edge lengths for mines were based on the perimeter of the development area, in this case 2331 hectares (23.31 km²) (CEMA-SEWG 2008). For *in situ* and natural gas extraction, edges induced by linear and polygonal features were estimated based on the two studies (see supplementary information available at stacks.iop.org/ERL/4/024004).

Each technology was assumed to be developed over a development area of 2331 hectare area as assumed by CEMA-SEWG (2008). The activities of oil sands operations and the associated fragmentation are assumed to be restricted to this area. As the zone of influence grows with an increasing buffer width, spatial overlap can occur with the zones of influence associated with different activities within the development boundary. As a result, we limit the size of the ZOI to the development boundary and the buffer width. Once the ZOI has surpassed the development boundary in terms of area, the size of the ZOI can only increase by an area equivalent to multiplying the buffer width by the development perimeter. In terms of land occupation, we apply a maximum limit for each technology based on this development area and the bitumen recovery (for more details, see the supplementary information available at stacks.iop.org/ERL/4/024004). Current conventional natural gas well density generally varies from 1 to 16 wells per section (2.6 km²) (Canadian Society for Unconventional Gas 2008). We assume here that wells are intensifying at a density of 1 well per section, meaning spatial overlap would occur at a buffer width of 800 m. As a result, we assume no overlap occurs as we vary the buffer width between 30 and 300 m.

Later we investigate an infilling scenario where natural gas development is intensifying.

4.3. Data and uncertainty

We present data that were collected from available literature in order to develop ranges of uncertainty for the basis of a sensitivity analysis (table 1) and compare these to the estimates from the study regions used in this analysis. These data are representative of the extensification of natural gas production in Alberta. Natural gas wells were assumed to have a 50% success rate in the analysis, as did the Southern Foothills Study. Disturbance associated with unsuccessful wells are assumed to be reclaimed as part of the landscape in 10 years. This assumption is later tested in the sensitivity analysis. For a more detailed breakdown of the parameters associated with each development as well as the life spans associated with each parameter, please see the supplementary information (available at stacks.iop.org/ERL/4/024004).

Estimates of land use metrics for the energy sector are inherently uncertain. For natural gas and oil sands development, land use intensity parameters vary by region. In the case of oil sands, the depth of the bitumen layer demonstrates both inter and intraregional variation, creating variability in the amount of energy that can be derived from a parcel of land. *In situ* technologies extract varying levels of the deposit, for example, cyclic steam stimulation (CSS) can extract in the range of 20–35% of the bitumen-in-place, where steam assisted gravity drainage (SAGD) extracts in the range of 40–70% (Alberta Chamber of Resources 2004). Surface mining technologies can generally recover 90% of the bitumen-in-place. For both oil sands projects and natural

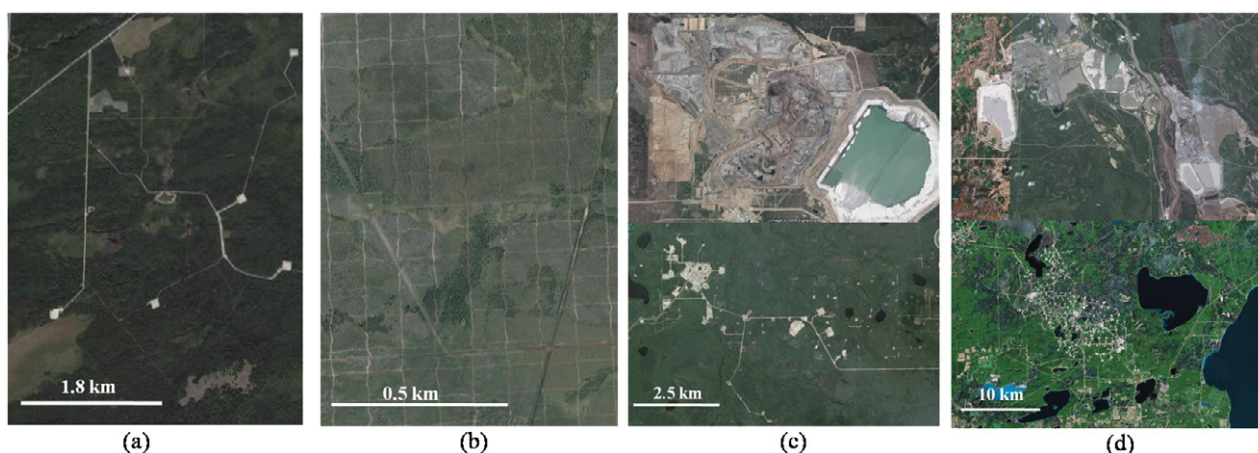


Figure 5. Satellite images of each of the developments (images extracted from Google Earth and attributed to Telemetrics, TeleAtlas and Digital Globe 2009). (a) shows conventional hydrocarbon development in Alberta, indicative of the disturbance caused by natural gas development. (b) shows exploration activities associated with oil sands development. (c) shows surface mining and *in situ* projects in earlier stages of development. (d) shows full scale surface mines and the longest running *in situ* projects located outside of the RMWB in the Cold Lake region. While these projects are currently among the longest running oil sands projects in Alberta, practices have changed with time so they are not representative of current practice.

gas, the levels of exploration will depend on how much geological information exists. In general, if the geologic properties of the reserve are well described, less exploration will be needed. Parameters will also vary depending on company practices. Individual companies have different practices and may be subject to more stringent regulations in environmentally sensitive areas. For example, natural gas development in the southern foothills of Alberta is subject to special regulations due to the environmental sensitivity of the area. In addition, industry practices generally improve with time—seismic line widths have been reduced from 6–8 m to as low as 1 m during the past 2 decades (CAPP 2003). Essentially, data obtained from spatial analysis such as through a GIS is unlikely to represent current practices but rather show a site-specific range of historic land activities that are generally more land intensive than current practices. Companies often reuse existing disturbance, so the magnitude of new disturbance will also depend on how much already exists. Best practices have also been adopted by some companies for reducing the lifespan of their land use. Our goal is to develop estimates for typical, current land disturbance. Figure 5 shows natural gas and oil sands developments in Alberta in different stages of their production lives.

As natural gas parameters are also subject to policy and management decisions that may reduce land disturbance and the creation of linear disturbances, we later test several scenarios that simulate such decisions. For more information on these scenarios, please see the supplementary information (available at stacks.iop.org/ERL/4/024004).

5. Results

Figure 6 shows the results of the analysis using estimates outlined in table 1. Natural gas purchased for oil sands development makes an important contribution to the life cycle land disturbance. For the case of *in situ* recovery, natural

gas disturbance without considering edge effects (figure 6(b), ‘Upstream (natural gas) area’) was found to be more significant than that of on-site SCO production (figure 6(b), ‘*in situ* area’) during the operational lifetime of the respective developments.

When considering the zone of influence (ZOI) with a 30 m buffer width, natural gas land disturbance is significant for both technologies, but much more so for *in situ* recovery. The increased land disturbance caused by unsuccessful wells is apparent in the case of natural gas development. These wells were assumed to be reclaimed and become part of the landscape in 10 years.

Results for land occupation of the life cycle phases defined within the boundaries are shown in figure 7. Our analysis of the land use intensity for surface mining indicates the most significant land use occurs on-site, rather than upstream. Under these assumptions, off-site land disturbance from natural gas production was found to be the most significant contributor to the land use intensity of *in situ* production indicating that impacts are displaced upstream, primarily to the natural gas production stage of the defined life cycle.

Land occupation depends not only on the area intensity, but also on the lifespan of the linear features on the landscape. Many linear features become access points for recreation and hunting (Weber and Adamowicz 2002). Many edge-related impacts results from human access. When seismic lines are being cut and wells are being drilled, human use will be high. Recreational use of linear features after their creation, such as hunting and off-road vehicle use, may propagate edge effects through time, much longer than some of the assumptions we have applied. Such impacts can be reduced by managing the access of hunting and recreation land uses to linear features.

6. Sensitivity analysis and scenarios

Land use parameters for natural gas development vary widely as shown in table 1. For natural gas, area intensity was most

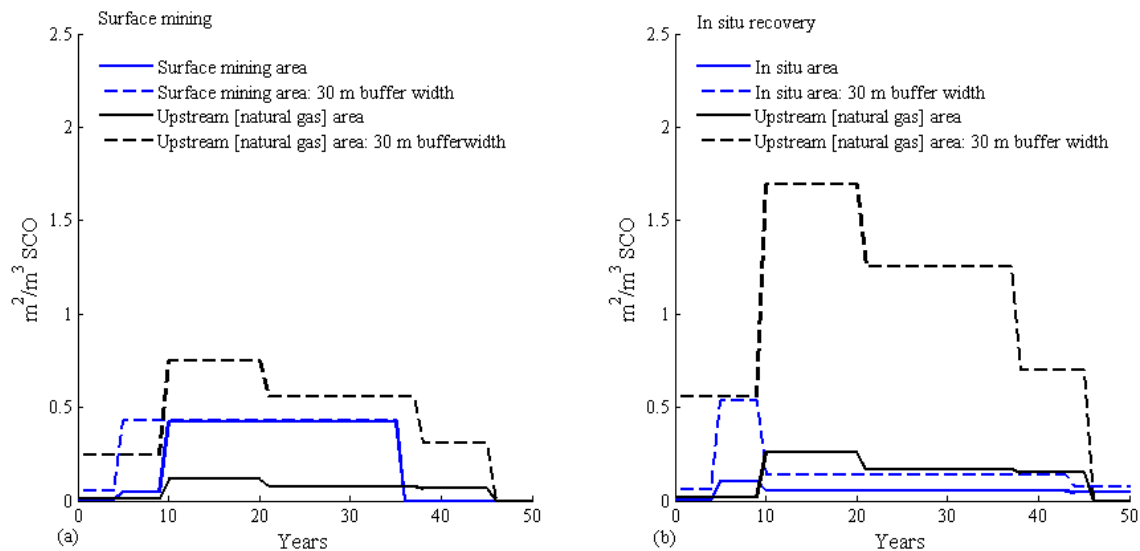


Figure 6. Time series for land disturbance intensity of (a) surface mining and the upstream natural gas purchased for extraction ($70 \text{ m}^3/\text{m}^3$ SCO) and upgrading ($50 \text{ m}^3/\text{m}^3$ SCO) and (b) *in situ* recovery and the upstream natural gas purchased for extraction ($220 \text{ m}^3/\text{m}^3$ SCO) and upgrading ($50 \text{ m}^3/\text{m}^3$ SCO). We assume here that surface mining and *in situ* recovery require the same levels of exploration before bitumen extraction occurs.

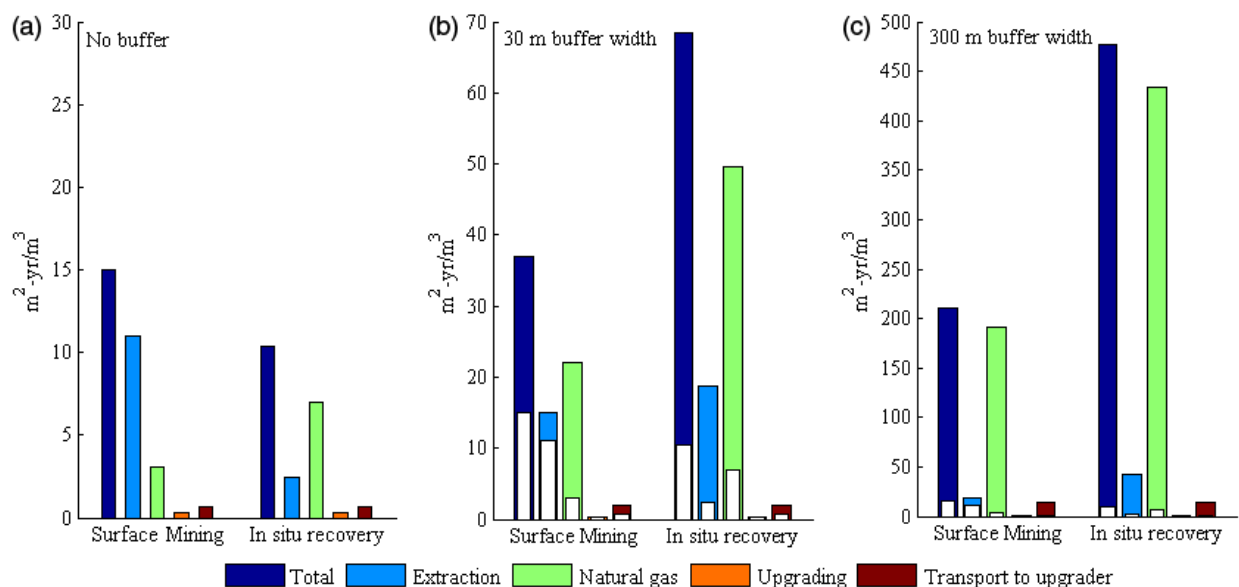


Figure 7. Relative magnitudes of land use from life cycle stages using parameters from the two study areas with and without edge effects. Natural gas assumptions here are the same as in figure 6. We include here the relative effects of the hypothetical upgrader and the transport to this upgrader. (a) shows the land occupation without accounting for edge effects while (b) shows the ZOI when applying a 30 m buffer width and (c) shows the ZOI when applying a 300 m buffer width. The ZOI includes both the direct area as well as the area influenced by edge effects. The white bars within (b) and (c) are the directly disturbed area as reported in (a).

sensitive to well success and productivity. We assumed in the analysis that only 50% of wells were successful. If we assume 100% success, the land use intensity is reduced to approximately 60% of the natural gas use of the base case. It is not reduced by 50% as pipelines were assumed not to be constructed for unsuccessful wells. Our base case has close to the highest well productivity in Alberta. Without considering the environmental sensitivity of the area, development in this region could be considered more efficient in terms of land use when compared to other natural gas developments with features of equivalent size. If the size of the well site is reduced

from $11\,500 \text{ m}^2$ to 30 m^2 and other parameters remain the same, the area intensity associated with natural gas reduced to 40% of the base case but remains 80% of the area intensity associated with *in situ* extraction. When compared with the ranges of data collected in table 1, the SFS natural gas parameters appear reasonably optimistic. The large ranges found in the literature do indicate a need to develop a system that monitors and reports such parameters.

Edge effects were explored by ranging distance of edge influence between 30 and 300 m. Figure 8 demonstrates at

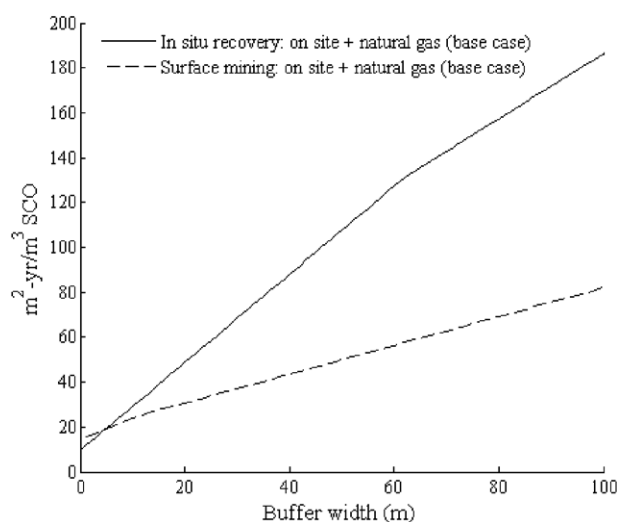


Figure 8. The sensitivity of the ZOI to the buffer width (m). The buffer width is left parametric here to show the range of the width that can result from the land disturbance.

what point the zone of influence of *in situ* recovery and the associated natural gas use becomes more significant than that of surface mining.

The total land disturbance alone for *in situ* technology is comparable to that of surface mining when including market driven natural gas production. When edge effects are considered, the influence of *in situ* recovery on the landscape becomes significantly larger than that of surface mining if the buffer width is larger than 5 m.

As previously discussed, four generic characterizations of *in situ* technologies were developed by CEMA-SEWG (2008). The ‘innovative approaches’ characterization reduced land disturbance by placing more wells on each well pad, reducing the number of delineation wells, reducing land disturbance by 25% through harmonization with the forestry sector, and reducing the life spans of various features. We compare each of these generic characterizations to investigate how much the ZOI can be reduced relative to surface mining.

Figure 9 shows that a significant reduction in land use and fragmentation occurs if thicker bitumen deposits are developed with ‘innovative approaches’ when compared with the base case developed over thinner bitumen layers. The key underlying differences in maximum land occupation of surface mining and *in situ* development here lie in CEMA-SEWG (2008) short lifespan for surface mining disturbance and the *in situ* recovery factor which we estimate may have been assumed to be as high as 73%, or even higher (see supplementary information available at stacks.iop.org/ERL/4/024004).

We have developed five scenarios for natural gas development to investigate model sensitivity of upstream land use for SAGD development (for more information, please see the supplementary information available at stacks.iop.org/ERL/4/024004). Of these, an infilling scenario based on Encana’s (2007) parameters for infilling in southeast Alberta was found to result in the smallest amount of upstream fragmentation. As a result, we focus on this scenario for our sensitivity analysis.

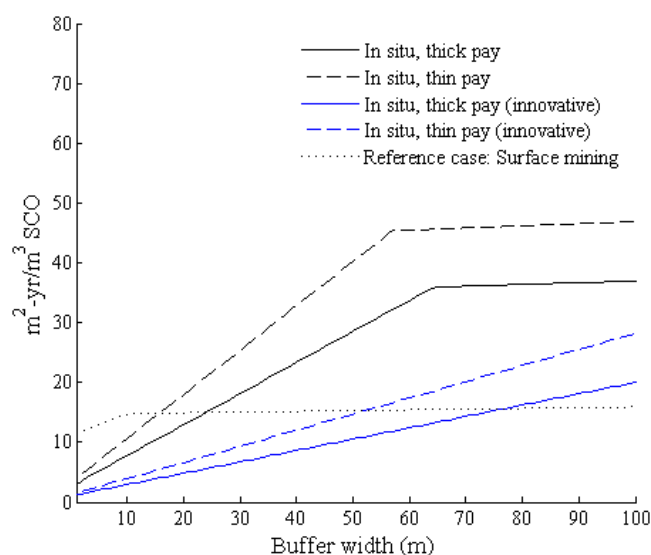


Figure 9. Land occupation for CEMA-SEWG (2008) characterizations for generic *in situ* recovery projects. Surface mining is included for reference. The four generic characterizations for *in situ* are: base case in thick pay, base case in thin pay, innovative approaches in thick pay, and innovative approaches in thin pay.

Non-forested regions that are infilled with low producing wells, such as in southeast Alberta, may have much smaller well sites and wells will require less new infrastructure. Our scenario for infilling would require 47–92% of the base case for natural gas in terms of land use intensity (this would be more if construction, all pipelines, compression stations and sumps were included). The land disturbance is 1–2 times the magnitude of the base case land disturbance of on-site *in situ* development on an intensity basis (table 1), still providing a significant contribution to the life cycle land disturbance. This is lower than one might expect as the wells are producing at a low level; however, the length of new access routes and pipelines needed for each new well were significantly decreased. The underlying reason is that existing roads and infrastructure can be used to access the new wells. The effects on land occupation will depend on the life span of the project. Encana (2007) estimated that the development could last between 20 and 40 years; here, the 20 year case is used to estimate the best case for land occupation. Figure 10 shows this infilling case for both surface mining and *in situ* development. To test the most optimistic case for *in situ*, ‘innovative approaches’ for thick pay is used and compared to the base case in thin pay.

Figure 10 demonstrates that there is a significant reduction in land occupation and the associated fragmentation that can be achieved by infilling natural gas wells rather than extending into new areas. Though infilling results in a lower magnitude of land disturbance and fragmentation, this measure alone cannot be used alone to determine the appropriate location to drill new natural gas wells. Society places higher values on some landscapes, as is the case with some infilling developments, such as that shown in figure 10. This particular project was controversial as the region where the drilling will occur is Canadian Forces Base (CFB) Suffield’s National Wildlife Area

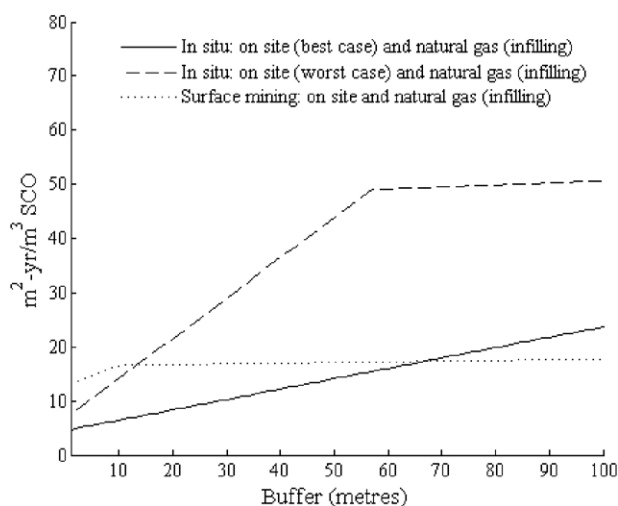


Figure 10. Parametric analysis of edge effects for natural gas infilling. Even using these parameters, *in situ* recovery results in a more significant ZOI. Though the infilling does not contribute significantly to edge effects, the land disturbance has increased significantly. The best case for *in situ* is the CEMA-SEWG characterization of an *in situ* project developed in thick pay with 'innovative approaches'. The worst case is the CEMA-SEWG characterization of an *in situ* project developed in thin pay.

in southeast Alberta. Current levels of drilling intensity will increase from 8 wells per section to 16 wells per section (Encana 2007). The incremental addition of land disturbed will be minimal when compared to the SFS case due to the use of existing infrastructure; however, the landscape is already fragmented with existing infrastructure. Though natural gas intensification can decrease the total land disturbance, the level to which it is acceptable to stakeholders will depend on where it is occurring and whether the company employs best practices. Intensifying natural gas development is one way to reduce life cycle land use impacts of oil sands development, but opportunity also exists to decrease the natural gas demand by improving recovery techniques and replacing the use of natural gas with alternative energy sources.

Coke, currently considered a by-product of oil sands development, or bitumen can be gasified to produce syngas for use in oil sands operations. Though this can replace some natural gas use in oil sands development, greenhouse gas emissions would be significantly increased. Carbon capture and storage is one method to reduce carbon emissions to the atmosphere; however, the land impacts of large scale carbon capture are yet unknown. The land use features would be similar to natural gas development and include: access roads, pipelines, and injection wells. Were carbon dioxide to be used for enhanced oil and gas recovery or if it were stored in depleted oil and gas reservoirs, land impacts could be reduced by using existing infrastructure. At the same time, natural gas is generally required for the compression of carbon dioxide into pipelines and injection. More research is needed to understand the land use implications of using substitutes for natural gas, such as coal gasification or nuclear energy.

Finally, the land use associated with bitumen transport can be reduced through industry coordination. The ERCB

(2008) reported nine existing pipelines that transport non-upgraded bitumen or SCO with five more proposed, excluding those associated with export to markets. Land use associated with pipelines used for bitumen transport can be reduced by companies using the same infrastructure rather than developing individual pipelines. This is also a significant opportunity for natural gas developers to construct roads and pipelines that are adjacent on the landscape to minimize edge effects.

7. Limitations and future research

There are several limitations to this analysis, presented below.

- (1) Ecological impacts of edge effects are not completely understood and vary greatly depending on region, type of structure (e.g. road or well site), and human use. The impacts associated with the edges will be different than that of the direct land disturbance, which is not taken into account in this model. We treat all edge effects as if they are the same; however, the magnitude of edge influence will vary by indicator, as shown by figure 2. ZOIs may result in varying magnitudes of edge influence; for example, they may result in either full avoidance by wildlife or may reduce use by only 10%. In essence, edge effects are not the same as direct habitat removal—they will likely result in reduced habitat effectiveness. Future research could focus on improving such analysis to investigate the effects of human use of linear features, type of linear feature, and impacts on particular species as well as biodiversity indices.
- (2) This study is subject to boundary issues—a frequent criticism of LCA. The entire life cycle of oil sands products has not been captured within the boundaries of this analysis; for example, we have not included a comprehensive assessment of the land disturbance caused by the consumption of electricity. Several methods have been defined to overcome boundary selection issues in LCA. For example, economic input–output analyses include all economic transactions associated with a product and use these to identify environmental burdens throughout the economy (Carnegie Mellon 2009). Similar land use databases and models do not yet exist in the public domain and we hope this analysis may highlight the need to further develop such databases.
- (3) Reclamation is an important aspect of human activities on the landscape. For example, natural gas development may have more reclamation success than oil sands mines; however, an increasing number of wells are being abandoned without reclamation certification in Alberta (Alberta Environment 2009a). Though the land disturbance associated with these activities can be reclaimed, the landscape may not be restored to its pre-disturbance state. This is particularly important for oil sands mining, where reclamation can be challenging. Alberta Environment (2009b) reports that there has been significant land reclamation for oil sands surface mining though little of it has been certified. In 2008, however, 104 hectares of an oil sands mine was certified as reclaimed by the Government of Alberta. We assumed

here that mines can be reclaimed in 25 years; however it is uncertain if reclaimed landscapes will be acceptable to stakeholders. For example, peatlands require on the order of thousands to tens of thousands of years to form naturally (Koellner and Scholz 2008). Surface mines developed on peatlands are currently reclaimed to a mixture of uplands and wetlands. The same challenge exists for *in situ* development. If *in situ* production occurs on peatlands, the areas are generally reclaimed to uplands (e.g. Petro-Canada Mackay River Expansion).

- (4) The natural gas market is not confined to Alberta, so the impacts of additional consumption will extend beyond Alberta altering the land use footprint per unit production. Moreover, a unit of additional consumption will produce less than one additional unit of production if demand were relatively elastic and supply less so.
- (5) *In situ* estimates presented here are based on SAGD technologies; however, SAGD only accounts for approximately one third of *in situ* production (ERCB 2008). Further research is needed to characterize the land use per unit output associated with CCS, primary production, and emerging technologies such as solvent-based extraction. Land use implications for substituting other energy sources, such as coal and nuclear energy, for natural gas are yet unknown. Also, the recovery factors for operating *in situ* projects should be further investigated as a key uncertainty in future analyses.

8. Discussion

This analysis suggests that the collective land use impacts of natural gas extraction may be more significant than previously recognized and are often under accounted. When an energy development results in a concentrated land disturbance, as is the case with the oil sands extraction, it appears of high magnitude. Diffuse energy developments, such as natural gas production, can result in less noticeable impacts due to their extensive nature. Yet, fragmentation affects societal values associated with landscapes and the species that occupy them. Despite the fact that less land is directly disturbed for *in situ* projects, we have shown that *in situ* developments can influence a magnitude of habitat that is larger than surface mining when edge effects and natural gas production are considered in the analysis. The reclamation timescales, bitumen recovery and land disturbance levels CEMA-SEWG has assumed provide direction for current *in situ* operators to reduce land disturbance. The way forward may be to hold companies accountable for maintaining such low levels of disturbance on an intensity basis. Upstream natural gas production was found to be a significant factor for *in situ* development in terms of land use. Similarly, management decisions of natural gas developers, such as increasing reclamation of abandoned wells and ensuring this reclamation is timely, drilling multiple wells from single well sites and developing sympatric linear features on the landscape can also reduce land disturbance. Pipeline crossing structures for wildlife remain an option for both *in situ* and natural gas developers to reduce their impacts on biodiversity—some *in*

situ developers are already implementing this technique. As Alberta's landscapes become more developed and fragmented, whether or not these mitigation options are implemented will depend on both industry and regulators.

Land use of *in situ* development may appear less significant than surface mining; however, much disturbance has been displaced upstream to Alberta's natural gas production system. As conventional natural gas reserves become exhausted, more environmentally sensitive locations are being developed and more land is being used per unit production. The effects of natural gas development occur across Alberta's landscape types and are more extensive than either type of oil sands technology. A major factor we have not considered is that land use impacts should be weighted by some measure related to the importance and scarcity of the land impacted. Oil sands development takes place in the boreal forest which is 58% of Alberta's land cover. Natural gas development is occurring across Alberta and in some natural regions much smaller than the boreal forest, such as the foothills region which is only 10% of Alberta's land cover. The foothills are considered by some to be under great environmental threat (Nature Conservancy 2004), perhaps greater than the boreal forest. By counting each phase of life cycle land use disturbance as equivalent we have (arguably) greatly underestimated the importance of natural gas in the life cycle of oil sands production as the natural gas development is occurring in places where the environmental impact per unit land disturbed is greater.

We present one approach of many that can incorporate land use in LCA. Our method provides a step towards the inclusion of landscape fragmentation into life cycle assessment, providing a method that can be used to systematically compare developments that are largely polygonal to those that are comprised largely of linear features. This approach can be applied to understand the relative impacts of similar products where the diffuse nature of a development may influence an analyst's perspective of land use impacts; for example, coal versus coalbed methane or wind farm versus natural gas production for electricity generation. This is particularly important for cases of scalability where diffuse developments appear to have a lesser impact on land.

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