Economic Incentives for Land Reclamation: Evidence from the Oilsands Industry in Alberta

by

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Abstract

This thesis explores the impact of a tax-refund scheme on early reclamation and improved boreal caribou habitat outcomes. The research examines the extent to which a tax-refund scheme addresses the externality arising from energy extraction and generates desirable social outcomes in the context of the oilsands industry in Alberta.

The data used in the study are based on in-situ oilsands projects (Hauer et al., 2018) and bitumen prices (Energy Information Administration, 2019). In addition, simulated data on output and cost are generated based on information from the Canadian Association of Petroleum Producers (2018) and energy project reports (Alberta Energy Regulator, 2018). A simulation model is constructed to assess firms' reclamation decisions, impacts on caribou populations, and economic welfare outcomes under three different cases: the base (no-tax) case, the damaged land tax case, and the tax-refund scheme. Because tax levels can result in some firms exiting the oilsands industry, several iterations are required for the simulation model to reach an equilibrium state.

We find that under a tax-refund scheme, oilsands projects would implement early reclamation of linear features in their licence area at certain tax levels, and this could generate a social outcome that is close to the socially optimal outcome associated with a damaged land tax. The tax-refund scheme also has other desirable properties such as improved political feasibility. In addition, this study's findings will also be of use for caribou recovery efforts and policy implementation.

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Glossary of Terms

s time period (s= 0, 1, 2, 3)

t the t th year (t=0, 1,…, 90)

i an in-situ oilsands project

q_i bitumen production (m3 per year) for i

φ_i production per well for i

w_i the number of wells for i

δ_i the ratio of bitumen output to the length of 4D seismic lines for i

q_i^{max} the reserves available per year over the 30 years of the project for i

β discount rate over the period s

$c(q_i)$ variable cost for i

ω the fixed non-energy operating cost per unit of q_i

A_i the total plant cost for i

σ capital maintenance rate

cw the cost of building a well

B_i the fixed cost of linear features for i

$c^{pipe}, c^r, c^{2D}, c^{3D}, c^{4D}$ the construction cost of building one kilometre of pipelines, roads, 2D seismic lines, 3D seismic lines, and 4D seismic lines

RC_i reclamation cost for in-situ project i

FC_i fixed cost for in-situ project i

$p^{pipe}, p^r, p^{2DL}, p^{2D}, p^{3D}, p^{4D}$ the reclamation cost for one kilometre of pipelines, roads, 2D legacy seismic lines, 2D seismic lines, 3D seismic lines, and 4D seismic lines

$f_{is}^{pipe}, f_{is}^{r}, f_{is}^{2DL}, f_{is}^{2D}, f_{is}^{3D}, f_{is}^{4D}$ reclaimed length of pipelines, roads, 2D legacy seismic lines, 2D seismic lines, 3D seismic lines, and 4D seismic lines for i at the end year of period s

L_{is} the effective linear features affecting caribou population for i in period s

$P_{is}, R_{is}, E_{is}^{2DL}, E_{is}^{2D}, E_{is}^{3D}, E_{is}^{4D}$ the length of pipelines, roads, 2D legacy seismic lines, 2D seismic lines, 3D seismic lines, and 4D seismic lines for i for period s

D^{T} the total damage from linear features of oilsands industry

φ the constant damage per kilometre of linear features

θ impacting factor for low impact seismic (2D, 3D, and 4D)

NCT the present value of net tax per unit of output plus the reclamation cost for i

$\rho_{i}^{pipe}, \rho_{i}^{r}, \rho_{i}^{2D}$ the ratio of the length of pipelines, roads, and 2D seimic lines to bitumen output for i

s_i output share for i

d refund share in a tax-refund scheme

τ tax rate

τ^{T} total tax pool

W social welfare

$\kappa_i = \frac{[\tilde{\boldsymbol{\beta}}^{\mathbf{30}}\boldsymbol{\rho}\mathrm{s}_i + \tilde{\beta}^{30}\mathcal{L}_i D'(\mathrm{s}_i)]}{(\tilde{\boldsymbol{\beta}}^{\mathbf{90}} - \boldsymbol{\beta})\boldsymbol{\rho}}$

$Area_{n\bar{t}}$ the geographical area (kilometre square) of herd n

$Den_{nt} = L_{nt}/Area_{nt}$ the density of linear features in kilometre per kilometre square for herd n at year t

A_{nt} the proportion of the area with young forest less than thirty years of age to the total area for herd n at year t

1 Introduction

The energy sector plays an important role in Canada's economy. Canada's energy sector directly and indirectly provided 900,000 jobs, and it contributed nearly 11% to Canada's nominal GDP in 2017 (Natural Resources Canada, 2019). Canada has an abundance of energy resources including crude oil, coal, nuclear energy, renewable energy, natural gas and so forth, and 29,331 petajoules[1] of primary energy were produced in Canada in 2016 with 31% from crude oil and 24% from natural gas (Natural Resources Canada, 2019). Alberta produced the most energy; the majority of which is crude oil and natural gas (Statistics Canada, 2019). Crude oil is mainly derived from oilsands that are about 142,200 square kilometres of land in northern Alberta, and around 97% of the oilsands area covers reserves are recoverable by in-situ *(Latin for: in place)* methods such as steam-assisted gravity drainage (SAGD) in which the bitumen reservoir is heated to reduce the viscosity of the bitumen, allowing it to flow to a vertical wellbore (Alberta Energy Regulator, 2018).

However, the energy sector, including the mining and in-situ oilsands industry, can generate negative externalities, which lead to substantial environmental damage. Theoretically, negative externalities are present if agent A's utility is adversely affected by another agent B, without an offer of compensation to the effect on A's well-being (Baumol et al., 1988). Empirically, energy activities may occupy and disturb agricultural land and habitats for endangered species, and some mining activities could generate mine drainage, tailing ponds containing toxic waste, rock dumps, contaminated dust, and

[1] Petajoule is a unit for calculating energy production and is defined as one quadrillion (10^{15}) joules.

greenhouse gases (White et al., 2012). Abandoned mine sites are also a severe problem that requires timely measures of reclamation (White et al., 2012). For those projects extracting bitumen using in-situ techniques that are widespread in the north of the province of Alberta, in-situ facilities generally generate more greenhouse gas emissions per barrel of bitumen than conventional oil producers. This is because in order to heat the bitumen in the ground, in-situ extraction requires a large volume of steam that requires natural gas to heat water (Oilsands Magazine, 2018). Additionally, the creation of linear features, which include roads, pipelines, seismic lines, not only affects the natural landscape but also impacts habitat for an endangered species, boreal caribou, which could lead to an increased possibility of extinction of these species (Schneider et al., 2010; Hauer et al., 2018).

As a response, the provincial government has planned to address the impacts of the energy sector on the environment. The Environmental Protection and Enhancement Act (Province of Alberta, 2000) has identified an energy project's reclamation duties and the standard for the issuance of a reclamation certificate. Direction for Conservation and Reclamation Submissions (2016) further specifies project-level conservation and reclamation requirements. For endangered species like woodland caribou that are declining in population size and range size, the federal government has identified that Alberta's woodland caribou herds are among the most at risk in Canada (Environment Canada, 2009). The provincial caribou recovery plan seeks to maintain the current caribou population of all herds in the province despite the rapid development of oilsands industry and other energy activities (Government of Alberta, 2017).

However, the externalities arising from energy activity appear to require a more powerful scheme to create incentives for energy firms to accelerate reclamation of their damaged land. Specifically, a single regulation may not work. Although energy firms are required to reclaim their damaged land at the end of their projects, operators may strategically seek to put off declaring closure as long as possible in order to push reclamation costs into the future (Yang & Davis, 2018). In addition, a single policy of environmental bonds may not generate sufficient reclamation incentive to address both reclamation and externalities arising from land use impacts. Environmental bonds, or financial assurance mechanisms, have been used in the US and Canada to ensure firms have sufficient funds for the reclamation of damaged lands on closure. However, firms may have an incentive to strategically declare bankruptcy to avoid the reclamation cost, and there is little incentive to reduce the impacts that arise while extraction is on-going. Therefore, White et al. (2012) have argued that a "damaged land tax" on lands affected by energy activities could be combined with a financial assurance or performance bond to optimize extractive industry land use externalities. Yang and Davis (2018) further show evidence that a Pigouvian tax on damaged land is socially optimal and provides mining operators with the correct incentives to remediate stock pollution such as the contaminated surrounding lands and waterways.

However, a simple tax scheme may not be appropriate in practice when there are asymmetries in information or in bargaining power; situations that are common in reality (Sterner & Isaksson, 2006). Specifically, polluting firms may be able to resist taxes through powerful lobby and authorities may fail to deal with their threats of relocating or going out of business (Sterner, 2003). Additionally, firms can also declare themselves bankrupt to avoid the tax and reclamation cost if the regulator just uses a Pigouvian tax to provide incentives for mine reclamation (White, 2015).

The tax policy implicitly assumes that society is the holder of ownership rights to the environment and firms must pay the tax to be able to operate (a "polluter pays" approach). There is another situation where firms are not expected to pay the tax and would have to be subsidized to engage in environmental improvement (sometimes referred to as a "victim pays" approach). However, subsidizing firms can generate fiscal problems for the government, therefore we try to find another approach to address the externality where the firms are required to address the externality, but the revenues are returned to the industry.

Therefore, an alternative approach, an output-based tax-refund scheme, is considered as a mechanism to address externalities. Sweden employed such a scheme for NOx emissions (Sterner & Isaksson, 2006). This approach requires the government to levy taxes on polluting firms based on their environmental damage and then refund the tax revenues to these firms in accordance with their effective energy output. In the Swedish case study, the tax-refund scheme not only significantly reduced political pressure from industry on the governing authority but also provided nearly the same incentives for polluters to abate as the pure tax case. While the tax refund approach seems appealing, the basis of refunding in the tax-refund scheme requires a common output, which is hard to define. In the Swedish case, the consistent net beneficiaries of the tax-refund scheme were firms that produced and sold energy, while the pulp and paper industry was always the main net "loser" (Sterner & Isaksson, 2006). In addition, previous research has revealed that this approach may not be socially optimal under perfect competition (Gersbach & Requate, 2004), or may reduce abatement incentives under oligopoly (Fischer, 2011).

This thesis explores the impact of a tax-refund scheme on early reclamation and improved boreal caribou habitat outcomes, and examines the extent to which the tax-refund scheme generates desirable social outcomes in the context of the oilsands industry in Alberta. The land damage that we examine is the adverse impact on the habitat for a threatened species – boreal caribou. We use data on in-situ oilsands projects (Hauer et al., 2018) and bitumen price data (Energy Information Administration, 2019) to construct measures of revenue and cost for the in situ sector. In addition, simulated data on output and cost are generated based on information from the Canadian Association of Petroleum Producers (2018) and several energy project reports (Alberta Energy Regulator, 2018). A simulation model is constructed to assess firms' reclamation decisions, impacts on caribou, and economic welfare outcomes under three different cases: the current (no-tax) case, the damaged land tax case, and the tax-refund scheme.

The main contribution of this thesis lies in the empirical assessment of the tax-refund scheme in a specific situation (the oilsands industry in Alberta) and the evaluation of the efficacy of the tax-refund scheme in terms of economic welfare.

We find that a tax-refund scheme could generate similar outcomes as a tax in terms of caribou population and economic welfare if all existing in-situ oilsands projects choose to reclaim their affected land early. With reclamation, the number of caribou and economic welfare increases under the tax-refund scheme compared with levels under the current case where we maintain current land use practice and take no other actions. In addition, the tax-refund scheme makes fewer oilsands projects go out of business compared with the tax case because the tax payment is repaid to all oilsands projects as taxpayers. This is also why the total profits of the in-situ oilsands industry under the tax-refund scheme are higher than those under the tax case.

This thesis is organized into six chapters: introduction, literature review, theoretical model, data and methods, simulation model results, discussion and conclusion. Chapter 2 presents a literature review about the advantages and disadvantages of a stock Pigouvian tax and the theory and application of the tax-refund scheme. Chapter 3 delves into the theoretical model that is designed to describe the behaviour of firms in terms of economic activity and damaged land reclamation in the oilsands industry in Alberta under a land tax, and tax refund scheme. Chapter 4 focuses on data description, analysis and the implementation of the simulation method. Chapter 5 provides the main results from the simulation model. Chapter 6 presents a discussion on these results and discusses the political economy of the tax refund environmental policy. This chapter also provides the conclusions of this thesis and outlines recommendations for future research.

2 Literature review

This chapter provides a review of the literature on externalities, the Pigouvian tax in the case of a stock externality and the tax-refund scheme. The evolution of economic theory and the application of these two tax schemes are discussed. This chapter concludes with an explanation of the main contribution of this empirical study with respect to the tax-refund scheme in the context of the oil sands industry in Alberta.

2.1 The Pigouvian stock tax (Damaged land tax) policy

Negative externality occurs when one agent's utility depends directly and negatively on another agent's behavior, without an offer of compensation to the effect of the affected agent's well-being (Baumol et al., 1988). Previous studies show that there are natural links between the use of natural resources and environmental externalities (Cropper & Oates, 1992; Farzin, 1996). Energy activities could cause flow externalities (air pollution attributable to hazardous substances, land pollution caused by waste dumping) and stock externalities (soil depletion, groundwater contamination, and global warming issues such as the accumulation of greenhouse gases in the atmosphere). An intrinsic feature of environmental stock externalities is that the damage becomes appreciable only after the stock pollution has risen to a certain level (Farzin, 1996). However, if a natural process and/or a typical technology could clean up the stock pollution, the damage resulting from stock externalities is not necessarily irreversible. Therefore, there are some environmental policy instruments designed to deal with stock externality issues related to resource usage.

Pigouvian taxes for stock externalities have been used to correct market inefficiencies caused by stock externalities (Baudry, 2000). The early literature mainly focuses on theoretical research in the context of global warming, and can be classified into two groups. The first group of studies focuses on the optimal pricing of a non-renewable resource with adverse stock externalities (Farzin, 1996; Farzin & Tahvonen, 1996; Ulph & Ulph, 1994; Hoel & Kverndokk, 1996). All of these studies unequivocally show that the static Pigouvian tax, which represents the conventional rule of reducing emission to the point where the marginal abatement cost is equal to the marginal flow damage, would provide insufficient incentives to reduce emissions and result in too little abatement. Under some model specifications, the time path of the optimal tax first increases and then decreases with time (Ulph & Ulph, 1994). Farzin (1996) further points out that even if the current stock of pollution is considerably below the threshold level where consequent damage becomes noticeable, it will still be optimal to begin reducing pollution immediately rather than adopting a “wait-and-see” policy. The literature has since expanded to cover broader topics, including the existence of the Green Paradox where many countries’ environment policies actually aggravate environment issues (Sinn, 2008), backstop technology and risk management (Strand, 2010), and carbon capture and storage (Moreaux & Withagen, 2015)

The second group of studies that are related to Pigovian taxes on stock externalities focuses on the impact of Pigouvian taxes on pollution control based on different behavior of polluting firms or entities. Wirl (1995) analyzed a dynamic game between cartelised producers and a consumers' government and explored the linear Markov perfect strategies that represent pre-emption of the tax at the wellhead. Rubio and Escriche (2001) then study the interaction between a resource-exporting cartel and a resource-importing coalition, and show that a stock Pigouvian tax could theoretically solve a stock externality problem if the cartel is a monopolist and the monopolistic equilibrium is identical to a socially optimal outcome.

However, although a great number of insights have been shown in the abovementioned literature, many of these studies also assume that there is substantial natural decay of the stock pollution (Forster, 1975; Hoel & Kverndokk, 1996). In the case of linear features, the analogue to natural decay is that the linear feature grows back into forest and become indistinguishable from the rest of the forest. Additionally, these studies largely concentrate on the carbon tax on global warming. Therefore, the properties of a Pigouvian stock tax associated with land use in the energy sector, such as the mining industry and oil sands industry, is a relatively unstudied area, and only a few recently published papers are available.

Specifically, Sullivan and Amacher (2009) explore mine land reclamation and find that the mine operator efforts may not match socially optimal levels and consequently result in relatively high social costs. Therefore, they lay emphasis on the application of a bond system. White et al. (2012) extend the bond system to a combination of a bond and a Damaged Land Tax (DLT, a modified Pigouvian tax policy) to solve the bankruptcy problem and reclamation incentive issue. They also allow for continuous reclamation by mining firms during operations. They find that a bond policy alone provides little incentive for progressive reclamation and a damaged land tax may be a better choice for providing incentives for firms to reclaim abandoned mine sites. Doole and White (2013) give additional evidence to show that a damaged land tax that is constant across time or space could provide sufficient incentive for firms to reclaim degraded land. More recently, Yang and Davis (2018) show that although financial incentives in mine regulatory reform in the United States, China, and Western Australia do not include a Pigouvian stock tax, such a stock tax may be socially optimal under certain assumptions and provides the mining operators with the correct incentives to remediate stock pollution such as the contaminated surrounding lands and waterways. Lappi and Ollikainen (2019) investigate the optimal tax on waste rock production for a mine. They find, after considering the additional externality of a stock pollutant, the land tax should increase with time within a fixed mining operation period.

However, a simple tax scheme may not be appropriate in practice when there are asymmetries in information or bargaining power, a situation that is common in reality (Sterner & Isaksson, 2006). Specifically, polluting firms may be able to resist taxes through lobbying and authorities may fail to deal with their threats of relocating or going out of business (Sterner, 2003). Additionally, firms can also declare themselves bankrupt to avoid the tax and reclamation cost if the regulator just uses a Pigouvian stock tax to provide incentives for mine reclamation (White, 2015).

In some cases, governments provide incentives for firms to make significant investments in the reduction of negative externalities, but Gersbach (2002) shows that the inability of the authority to stick to a tough policy, like taxes, for a long period of time would create insufficient incentives for firms to invest in abatement technology. This indicates that firms could hold up the regulator when they face tough environmental policies in practice. As a result, a pure Pigouvian tax may therefore be politically infeasible in the real world. On the other hand, the important and pioneering study of Weitzman (1974) on the policy choice of a decision-maker in a cost-benefit setting points out that when the policy-maker faces uncertain costs, price-type instruments, such as taxes and charges, are socially preferable to quantity-type instruments. This finding is reaffirmed by a series of subsequent studies, which extend to the analysis of uncertain costs and benefits (Stavins, 1996) and tradable quantities (Williams, 2002; Kornek & Marschinski, 2018). In these cases, price-type instruments of a complex version, such as tax-refund schemes or refunded emission payments (REP), that combine taxes and subsidies, might be useful for providing proper incentives for firms to make abatement effort because these schemes cost less for polluting firms and therefore generate a lower level of political opposition.

2.2 The tax-refund scheme

An early example of a tax-refund scheme can be found in Porter (1974) in which each polluting firm pays a tax in each period that is based on the quantity of emissions that it expects to emit without abatement, then later receives a refund or a subsidy based on the quantity of emissions that the firm actually abates during that period. Therefore, Porter’s combination of tax and subsidy requires a firm to report both anticipated and actual emissions, and this shifts the burden of abatement proof to polluters and therefore reduces information costs and administrative costs for regulators. Such a check on the firm’s compliance could largely avoid firm deception. This view is subsequently reinforced by Kohn (1990) who shows that the combination of a tax and refund would not attract new firms to a polluting industry. This method could also be extended and applied to the context of solid waste disposal (Fullerton & Kinnaman, 1994) where the mechanism consists of a tax on all garbage output plus a rebate on proper disposal by either garbage recycling or waste collection. However, such a combination of tax and refund mainly focuses on the information disclosure of firms' or polluters' abatement behavior, and may not provide sufficient corrective economic incentive for firms or polluters to abate.

In comparison, the theory of the tax-refund scheme (or REP, short for Refunded Emissions Payments), which is used for providing proper incentives for polluters' abatement and circumventing political resistance for policy-makers, is first recorded in Sterner and Isaksson (2000). Specifically, polluters pay a charge based on their pollution level, and then the tax revenues are returned to the same group of polluters. The refund that each firm gains is not proportional to its tax payment, but to another measure, such as output and green-technology investment. Sterner and Isaksson (2000) further show that the tax-refund scheme could provide essentially the same incentives for abatement as a tax policy, but the tax-refund scheme does not generate an output reduction effect which could be caused by the pure tax scheme. Furthermore, if there are no administrative costs, the net effect of the payment and refund is that the firms with above-average emissions make net payments to the cleaner-than-average firms (Sterner, 2003).

Typically, there are several advantages related to the tax-refund scheme (Sterner, 2003). First, it reduces political resistance of polluting firms compared with the Pigouvian tax because all firms will pay less and some firms even make money under such a scheme. Second, it could provide the same incentive for negative externality reduction and application of clean technology as the Pigouvian tax. Third, the tax-refund scheme has little impact on the change in output prices because it is self-financing, and industry, as a whole, pays no net fees to society. Fourth, the scheme is expected to work well if there are significant technical abatement possibilities. Fifth, the tax-refund scheme provides an alternative policy option for policy-makers, which indicates that even if polluters have lobbying power to resist pure Pigouvian taxes, the regulator does not automatically have to turn to a quantity-type instrument such as grand-parented permits. Sixth, if we do not consider administrative fees, the tax-refund scheme is cost neutral (or self-financing). This means that it could be used for a subgroup of polluters without having to compromise their productivity compared with those polluters who are not included in the scheme.

The most remarkable example of the tax-refund scheme is the Swedish NOx reduction policy (Sterner & Isaksson, 2006). The state government levies taxes on the NOx emissions of polluting firms, including power plants, pulp and paper mills, food plants, metal plants, and waste incineration plants. This heterogeneous group of industries gains refunds in accordance with "useful energy produced" where for power and heating plants, it is equal to the energy that they sold; for other industries, it is defined as steam, hot water or electricity produced in the boiler. The results illustrate the success of the policy: between 1992 and 2000, mean emission rates of NOx were reduced by 40% for all plants in the tax-refund scheme. Due to the refund, the median firm only paid 4% of the tax as a net charge, and only 7% of those firms in the tax-refund scheme paid 50% or more of what they would have paid without a refund. This kind of refund is useful for reducing political resistance by those firms, and lobbying against the charge will be weaker.

In recent years, a series of theoretical studies provide additional evidence and extend the analysis of the tax-refund scheme. Gersbach and Requate (2004) find that under Cournot competition, the tax-refund scheme could theoretically result in a first-best outcome if the refund can be allocated dependent on both output and technology investment shares. They find that when firms have market power, a tax-refund scheme could simultaneously correct two market failures: underproduction and externality. Based on the possible situation where an entrant firm steals the business of incumbent firms, Cato (2010) proposes that the tax-refund scheme should also include an entry-license tax. Hagem et al. (2012) further compare the output-based tax-refund scheme and the abatement expenditure-based tax-refund scheme in terms of cost-effectiveness and the fee level. They find that the fee level in the output-based design exceeds the standard Pigouvian tax rate, while the fee level in the expenditure-based design is lower. Bontem (2019) finds that when polluters are heterogeneous, the refunding policy should be personalized designed based on the property of negative environmental externalities.

However, most of the abovementioned literature related to the tax-refund scheme focuses on air pollution or global warming, yet few studies examine land reclamation issues in the energy sector. In addition, most of the tax-refund schemes concentrate on flow emissions like NOx, but the adverse stock externality is rarely mentioned. Furthermore, a great deal of research regarding the tax-refund scheme explores desirable properties of the scheme in theory, but few studies implement empirical studies with simulated data in a close-to-reality context.

This thesis explores the potential for the use of a tax-refund scheme to address the damaged land issue in the context of the oil sands industry in Alberta. In this thesis, we assume that firms operate in a competitive market and have no market power, and this assumption differentiates our analysis from Gersbach and Requate (2004). We use data on in-situ oil sands projects to evaluate the effect of a damaged land tax on industry profits and reclamation behavior, and compare this to a tax-refund scheme in terms of the reclamation outcome and social welfare. The main contribution of this paper lies in the empirical assessment of the tax-refund scheme to a specific situation related to oil sands industry in Alberta and the evaluation of the efficacy of the tax-refund scheme in terms of social welfare compared with the no-tax case.

3 Model Formulation

This chapter presents a description of the study area and the theoretical framework. The study area is presented here as it plays an integral role in the formulation of the model. For the theoretical framework, we start by defining the socially optimal case and then describe the oilsands firm's problem, and get the allocations (q^*, f^*), $(\hat{q}, \hat{f})$, respectively, where q^* and $\hat{q}$ are the socially optimal and firm's chosen output level respectively and f^* and $\hat{f}$ are the socially optimal and firm's chosen reclamation level respectively. We prove that given the externality the firm's output and reclamation choices $(\hat{q}, \hat{f})$ are not Pareto (socially) optimal. Then we move to tax cases including four separate cases that differ in terms of the firms' responsibility for legacy linear features. In case X1, firms are responsible for the adverse impact of legacy linear features, and their entry decision (whether they produce or not) is treated as a marginal decision (how much bitumen they produce) and the impact of the legacy linear features on their marginal decision. In this case, the marginal impact of taxes on legacy linear features shows up in the decision making of the firm (the first order conditions) and legacy linear features are regarded as a variable cost of entry. In Y1 firms are not responsible for legacy linear features and these lines are treated like a fixed cost of entry. In this case, the marginal impact of taxes on legacy linear features does not show up in the first order conditions, and negative taxes (or subsidies) are needed to guarantee Pareto optimality. In case X1, an up-front subsidy is required to achieve Pareto optimal results. However, negative taxes or up-front subsidies may be politically unacceptable, and we therefore move to tax-refund schemes with firms responsible for legacy lines (X2) and firms not responsible for legacy lines

(Y2). We find that under certain conditions X2 and Y2 can provide Pareto optimal results, but neither of them can guarantee optimality. Finally, we employ the theoretical model to explore whether or not X2 and Y2 can improve the allocation (e.g. approach social optimality) compared with the competitive case ($\hat{q}$, $\hat{f}$). The basic information of these cases is shown in Table 3.1.

Table 3.1 Summary of different cases in the theoretical framework of the thesis

	responsible for legacy lines	not responsible for legacy lines
Tax	X1	Y1
Tax-Refund	X2	Y2
No-Tax	The current (competitive) case	

In our theoretical analysis, we compare these cases with the socially optimal case in terms of bitumen output and reclamation efforts. In our empirical study, we focus on the competitive case, case X1, and case X2.

3.1 Study area

The study area is shown in Figure 3.1. The caribou herd areas depicted by the shaded areas are obtained from Alberta Sustainable Resource Development (2010). The area of oilsands projects considered mainly covers the Cold Lake, East Side Athabasca, West Side Athabasca River, Red Earth, Richardson caribou herds. Therefore, these five regions comprise the study area in this thesis when we assess the impact on caribou populations and economic welfare under the tax case and the tax-refund case.

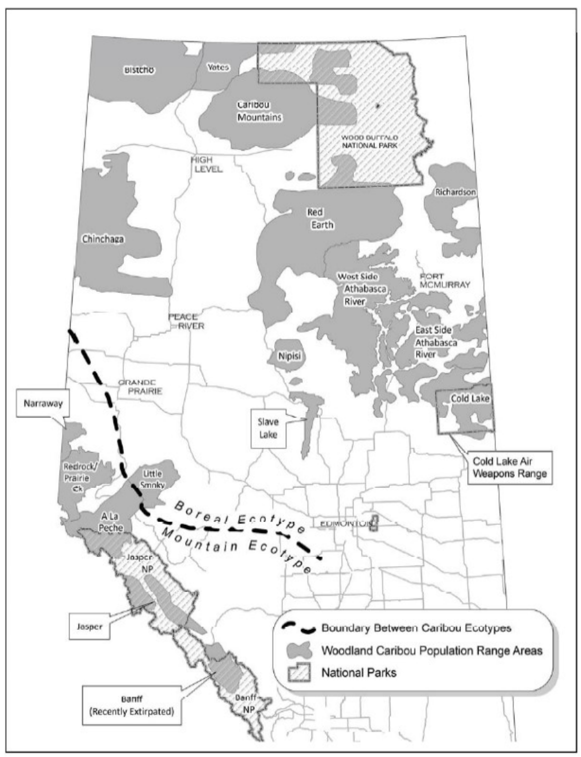

Figure 3.1 Study area showing the location of caribou herds in Alberta (Alberta Sustainable Resource Development and Alberta Conservation Association, 2010)

3.2 Theoretical model

3.2.1 Revenue function

We frame the firm's problem as a profit maximizing investment decision to invest or not under the assumption that project reclamation decisions are constrained by existing "end of project" reclamation regulations but with new tax and tax-refund schemes designed to create incentives to reclaim caribou habitat during the project's life. The year of production for a project is defined as t; typically, capital construction for initial development (including preliminary engineering, building seismic lines, drilling wells, building plants and infrastructure) is finished in $\mathrm{t} = 0$. We let $t = 1$ be the first year of production; we assume that each in-situ oilsands project has a production period of 30 years, so $\mathrm{t} = 30$ is the last year of production. We define s as the period indicator, and when t=0, s=0; t=1,…30, s=1; t=31,…,60, s=2; t=61,…,90, s=3. The relationship between t and s is shown in the figure below.

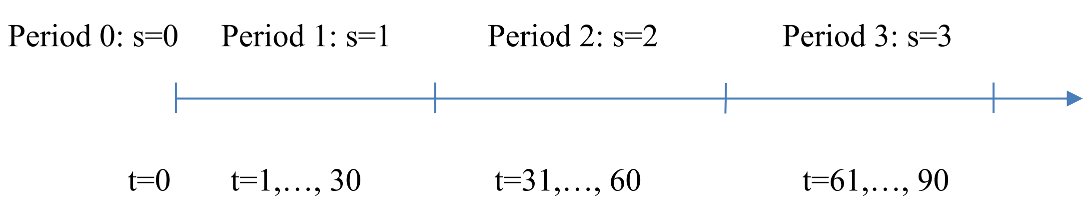

Figure 3.1 The relationship between years (t) and periods (s)

A variety factors affect caribou through land disturbance. Large fires and increased forest harvesting result in more young forest areas that are not suitable for caribou survival; developed areas such as parking lots and disturbed land for worker's residences and heating operations also contribute to the decline in caribou habitats; linear corridors, or what we call linear features, associated with roads, pipelines, and seismic lines, increase access by wolves, which increases the rate of wolf predation. Although all of these factors influence on the decrease in caribou habitats, this study mainly explores the impact of the reclamation of linear features on caribou habitat. In this thesis, we explore whether firms invest in early reclamation on reclaimable linear features at $t = 0$ under a tax or tax-refund scheme. Specifically, if they implement early reclamation under the tax schemes shown in the thesis, the damaged land will be completely reclaimed at $t = 30$, and reclamation benefits can be felt from $t = 30$ to $t = 90$. If firms do not implement early reclamation, they need to follow reclamation requirements where they have to reclaim at the end of their project at $t = 30$, and in this case reclamation benefits can be appreciated from $t = 60$ to $t = 90$.

At the project level, roads and pipelines are required to be reclaimed at the end of oilsands projects while there is no mandatory requirement for seismic lines (Direction for Conservation and Reclamation Submissions, 2016). Yet, the restorative impacts on caribou are not felt immediately because trees need time to grow and because early forest crown closure is used as the endpoint of reclamation activities. Therefore, we assume that 30 years of growth after a project's reclamation activities would be required to reach the endpoint of reclaimed forest (Hauer et al., 2018). Thus, T=90 indicates the end period of the entire scheme for each in-situ oilsands project. In addition, we define a typical in-situ oilsands project with a production period of thirty years, regardless of its related project extensions.

Bitumen production is denoted q_{is} for an in-situ project i in period s, and since we assume $q_{is} > 0$ for s=1 then we just define $q_i = q_{i1}$ for period 1. In other words, we assume production happens only in period 1 and is constant throughout period 1. We assume that firms make their production decisions based on profit maximization, and that there is little substitutability between bitumen production and the length of 4D seismic lines. Therefore, we assume fixed ratios between these variables and we have

$$q_i = \varphi_i w_i = \delta_i e_{i1}^{4D} \qquad (1)$$

where φ_i is production per well, and w_i is the number of wells required for a typical in-situ oilsands project i. We let e_{i1}^{4D} be the length of 4D seismic lines in the oilsands project i for period 1, and δ_i is the project-specific ratio of bitumen production to the length of 4D seismic lines. These components are project specific.

We note that

$$q_i \leq \frac{Reserves_i}{30} = q_i^{max} \qquad (1a)$$

, where $Reserves_i$ is the amount of extractable bitumen reserves available to project i and q_i^{max} is the reserves available per year over the 30 years of the project.

Additionally, the revenue for a project over period 1 can be expressed as

$$Rev_i = \sum_{t=1}^{30} \beta^t p q_i \qquad (2)$$

for the first thirty years, where the bitumen price at year t is denoted by p_t; we assume that p is constant for period 1. We also assume that oilsands projects are price-takers and that the bitumen market in Alberta is assumed to be competitive. The discount rate is assumed to be $\beta = 1/(1+0.04)$. The summation sign in equation 2 indicates that we calculate the total revenues of production for the period 1.

3.2.2 Production cost function

Variable cost is shown as $c(q_i)$, and we have:

$$c(q_i) = \omega q_i \tag{3}$$

where ω is the fixed non-energy operating cost per unit of q_i.

The derivation of fixed cost per in-situ oilsands project is obtained based on Hauer et al. (2018). The fixed cost equation can be computed as

$$FC_i = A_i + \sum_{t=1}^{30} \beta^t \sigma A_i + (\beta^0 + \beta^{10} + \beta^{20}) * w_i * cw + B_i(q_i) \tag{4}$$

where A_i is total plant cost for project i, and

$$A_i = \\ initial\ plant\ cost\ per\ peak\ barrel\ of\ production * \\ peak\ production\ of\ one\ well(thickness) * w_i \tag{5}$$

where σA_i is capital maintenance cost in the period 1, and cw is the cost of building a well. There are three cycles with ten years for each cycle, and a firm builds wells at t=0, 10, 20. That is why the cost is discounted at the 10 (β^{10}) and 20 years (β^{20}).

B_i is the fixed cost of linear features per in-situ oilsands project, and

$$B_i = c^{pipe} pipe_{i1} + c^r r_{i1} + c^{2D} e_{i1}^{2D} + c^{3D} e_{i1}^{3D} + c^{4D} e_{i1}^{4D} \tag{6}$$

where $c^{pipe}, c^{r}, c^{2D}, c^{3D}, c^{4D}$ are the construction cost of building a kilometre of pipelines, roads, 2D seismic lines, 3D seismic lines, and 4D seismic lines. In addition, $pipe_{i1}, r_{i1}, e_{i1}^{2D},\ e_{i1}^{3D}$ are the construction length of pipelines, roads, 2D seismic lines, 3D seismic lines for oilsands project i for the period 1.

We also assume that

$$e_{i1}^{4D} = e_{i1}^{3D}/3 \tag{7}$$

$\forall i$. Therefore, based on the equation (1) and equation (7), we have

$$e_{i1}^{4D} = \frac{1}{\delta_i} q_i \tag{8}$$

$$e_{i1}^{3D} = \frac{3}{\delta_i} q_i \tag{9}$$

We assume that the length of pipelines, roads, and 2D seismic lines are independent of bitumen production and we have

$$B_i(q_i) = c^{pipe} pipe_{i1} + c^{r} r_{i1} + c^{2D} e_{i1}^{2D} + c^{3D} e_{i1}^{3D} + c^{4D} e_{i1}^{4D}$$

$$= c^{pipe} pipe_{i1} + c^{r} r_{i1} + c^{2D} e_{i1}^{2D} + c^{3D} \frac{3}{\delta_i} q_i + c^{4D} \frac{1}{\delta_i} q_i \tag{10}$$

In addition, we have $e_{i1}^{4D} = \mu w_i$, where μ is the fixed ratio of 4D seismic lines to the number of wells (w_i). Therefore, $e_{i1}^{4D} = \mu w_i = \frac{1}{\delta_i} q_i$, and this implies $q_i = \delta_i \mu w_i$.

We note that the following components are project specific and therefore have an i subscript: $pipe_{i1},\ r_{i1}, e_{i1}^{2D}, e_{i1}^{3D}, e_{i1}^{4D}, q_i, B_i(q_i), FC_i, A_i, w_i$. This is because an in-situ oilsands project has different production technology, size of license area, production scale, thickness of bitumen deposit under the license area, production location, and so forth. For the purposes of modelling these components are drawn from distributions that reflect the actual variability in bitumen projects. Methods for selecting these distributions for policy simulation are discussed in chapter 4. In addition, only q_i and $B_i(q_i)$ are variables for oilsands projects, and other components are fixed for projects.

3.2.3 Reclamation cost function for Linear Features

Reclamation Cost

The reclamation cost is defined as RC, and we have

$$RC = RC(f_{is}) = p_f f_{is}$$

$$= p^{pipe} f_{is}^{pipe} + p^r f_{is}^r + p^{2DL} f_{is}^{2DL} + p^{2D} f_{is}^{2D} + p^{3D} f_{is}^{3D} + p^{4D} f_{is}^{4D} \qquad (11)$$

where $s = 0, 1, 2, 3$. For each component, the first term is reclamation cost and the second term is reclamation length. Specifically, p_f is a 6*1vector with components $p^{pipe}, p^r, p^{2DL}, p^{2D}, \ p^{3D}, p^{4D}$, representing the reclamation cost for one kilometre of pipelines, roads, 2D legacy seismic lines, 2D seismic lines, 3D seismic lines, and 4D seismic lines; f_{is} is a 6*1 vector with components $f_{is}^{pipe}, f_{is}^r, f_{is}^{2DL}, f_{is}^{2D}, f_{is}^{3D}, f_{is}^{4D}$, representing reclaimed length of pipelines, roads, 2D legacy seismic lines, 2D seismic lines, 3D seismic lines, and 4D seismic lines at the end year of period s.

Total Linear Features

We define L_{i1}, L_{i2}, L_{i3} as the effective linear features affecting caribou population for an in-situ project *i* for the first period (1-30 years) of the project, the second period (31-60) years, and the third period (61-90) years, respectively, and we have

$$L_{is} = P_{is} + R_{is} + E_{is}^{2DL} + \theta(E_{is}^{2D} + E_{is}^{3D} + E_{is}^{4D}) \quad (12)$$

where $s = 1, 2, 3$. P_{is} is the length of pipelines for an in-situ project i for period s, R_{is} is the length of roads for the in-situ project i for period s, E_{is}^{2DL} is the length of 2D legacy seismic lines for an in-situ project i for period s. These three types of lines are not low impact lines. E_{is}^{2D} is the length of 2D low impact seismic lines for an in-situ project i for period s,E_{is}^{3D} is the length of 3D low impact seismic lines for an in-situ project i for period s, E_{is}^{4D} is the length of 4D low impact seismic lines for an in-situ project i for period s. These three types of lines are Low Impact Seismic (LIS), and normally less than 4.5 m in width (MacFarlane, 2004). In addition, we define $\theta \in [0,1)$ as the portion of new seismic lines that affect caribou (a fairly small proportion), and this parameter is assumed to be 0.1 in Hauer et al. (2018). Considering the advancement in exploration technology, this study assumes θ to be 0.05. Dynamics of each component are described in the following sections.

Pipelines

We let $P_{i0}, P_{i1}, P_{i2}, P_{i3}$ represent the length of pipelines for an in-situ project i for period 0, 1, 2, 3, respectively. These notations apply to the case where firms are not responsible for legacy pipelines. Typically, P_{i0} is written as $P_{i0}\frac{q_i}{q_i^{max}}$ in the case where firms are responsible for legacy pipelines. If firm i fail to enter the energy sector, then $P_{i0}\frac{q_i}{q_i^{max}} =$

0, indicating that the old pipelines are irrelevant to the firm i if a reclamation firm is not allowed. Same interpretation is applied for old roads, old 2D legacy and 2D seismic lines, old 3D seismic lines, old 4D seismic lines. We assume $P_{i0}\frac{q_i}{q_i^{max}} \geq 0$. The length of pipelines built in an in-situ project i at period 0 is represented by p_{i0}; typically, $p_{i0} > 0$ and $p_{is} = 0$ for s>0 because this is the initial engineering work and pipelines are relevant to bitumen transmission. We let f_{i1}^{pipe} represent the length of pipelines reclaimed in an in-situ project i at the end year of period 1 (year 30). We define $\rho_i^{pipe} = \frac{p_{i0}}{q_i}$, indicates the ratio of the length of pipeline built by a project i to the bitumen output for the project, and it is a project specific parameter. The relationship between the lengths of pipelines among three time periods is shown as

$$P_{i1} = P_{i0}\frac{q_i}{q_i^{max}} + p_{i0} = P_{i0}\frac{q_i}{q_i^{max}} + \rho_i^{pipe}q_i$$

$$P_{i2} = P_{i1}$$

$$P_{i3} = P_{i2} - f_{i1}^{pipe} = P_{i1} - f_{i1}^{p} = P_{i0}\frac{q_i}{q_i^{max}} + \rho_i^{pipe}q_i - f_{i1}^{pipe} \geq 0 \tag{13}$$

$\forall i$. The first equation sets the length of pipeline in period 1 to be the sum of legacy pipelines (P_{i0}) and new pipelines (p_{i0}). The second equation sets the pipelines in period 2 (31-60 years) equal to the length of pipelines in period 1 (P_{i1}). The third equation sets the length of pipelines in period 3 to the length in period 2 minus the reclaimed length (f_{i1}^{p}) at the end of period 1 (at 30 years). We let 30 represent the number of years required before reclamation has protective impacts on caribou habitat. Therefore, the reclamation impact of f_{i1}^{p} at the end of period 1 is computed in period 3.

Roads

We let $R_{i0}, R_{i1}, R_{i2}, R_{i3}$ represent the length of roads for an in-situ project i for period 0, 1, 2, 3, respectively. These notations apply to the case where firms are not responsible for legacy roads. Typically, R_{i0} is written as $R_{i0}\frac{q_i}{q_i^{max}}$ in the case where firms are responsible for legacy roads. We assume $R_{i0}\frac{q_i}{q_i^{max}} \geq 0$. The length of roads built in an in-situ project i at period 0 is represented by r_{i0}; typically, $r_{i0} > 0$ and $r_{is} = 0$ for s>0 because this is the initial engineering work and roads are relevant to bitumen transmission. We let f_{i1}^r represent the length of roads reclaimed in an in-situ project i at the end year of period 1 (year 30). We define $\rho_i^r = \frac{r_{i0}}{q_i}$, indicates the ratio of the length of road built by a project i to the bitumen output for the project, and it is a project specific parameter. The relationship between the lengths of roads among three time periods is shown as

$$R_{i1} = R_{i0}\frac{q_i}{q_i^{max}} + r_{i0} = R_{i0}\frac{q_i}{q_i^{max}} + \rho_i^r q_i$$

$$R_{i2} = R_{i1}$$

$$R_{i3} = R_{i2} - f_{i1}^r = R_{i1} - f_{i1}^r = R_{i0}\frac{q_i}{q_i^{max}} + \rho_i^r q_i - f_{i1}^r \geq 0 \tag{14}$$

The equations for roads in each period are the same as those for pipelines, and the reclamation impact of f_{i1}^r at the end of period 1 is computed in period 3.

2D Legacy Seismic Lines

We let $E_{i0}^{2DL}, E_{i1}^{2DL}, E_{i2}^{2DL}, E_{i3}^{2DL}$ represent the length of 2D legacy seismic lines for an in-situ project i for period 0, 1, 2, 3, respectively. These notations apply to the case where firms are not responsible for 2D legacy seismic lines. Typically, E_{i0}^{2DL} is written as $E_{i0}^{2DL} \frac{q_i}{q_i^{max}}$ in the case where firms are responsible for 2D legacy seismic lines. We assume $E_{i0}^{2DL} \frac{q_i}{q_i^{max}} \geq 0$. We let $f_{i0}^{2DL},\ f_{i1}^{2DL}$ represent the length of 2D legacy seismic lines reclaimed in an in-situ project i at the period 0 and end year of period 1 (year 30), respectively, and we assumes no natural regeneration of forest along 2D legacy seismic lines. The relationship between the lengths of 2D legacy seismic lines among different time periods is shown as

$$E_{i1}^{2DL} = E_{i0}^{2DL} \frac{q_i}{q_i^{max}} \tag{15}$$

$$E_{i2}^{2DL} = E_{i1}^{2DL} - f_{i0}^{2DL}$$

$$E_{i3}^{2DL} = E_{i2}^{2DL} - f_{i1}^{2DL} = E_{i1}^{2DL} - f_{i0}^{2DL} - f_{i1}^{2DL} = E_{i0}^{2DL} \frac{q_i}{q_i^{max}} - f_{i0}^{2DL} - f_{i1}^{2DL} \geq 0$$

$\forall i.$ These equations differ from those related to roads (or pipelines) in two ways. First, there are no new 2D legacy seismic lines. There is a difference between new 2D and old 2D seismic lines in terms of width, and no new wide seismic lines will be built. Second, in the cases of roads and pipelines reclamation is not allowed in period 0 because these are used by the project for bitumen transmission. In comparison, 2D legacy seismic lines are reclaimed at either period 0 or the end year of period 1.

2D Seismic lines (Low Impact)

We let $E_{i0}^{2D}, E_{i1}^{2D}, E_{i2}^{2D}, E_{i3}^{2D}$ represent the length of 2D seismic lines for an in-situ project i for period 0, 1, 2, 3, respectively. These notations apply to the case where firms are not responsible for 2D seismic lines. Typically, E_{i0}^{2D} is written as $E_{i0}^{2D}\frac{q_i}{q_i^{max}}$ in the case where firms are responsible for 2D seismic lines. We assume $E_{i0}^{2D}\frac{q_i}{q_i^{max}} \geq 0$. We let $f_{i0}^{2D},\ f_{i1}^{2D}$ represent the length of 2D seismic lines reclaimed in an in-situ project i at the period 0 and end year of period 1 (year 30), respectively, and we assumes no natural regeneration of forest along 2D seismic lines. We define $\rho_i^{2D} = \frac{e_{i0}^{2D}}{q_i}$, indicates the ratio of the length of 2D seismic lines built by a project i to the bitumen output for the project, and it is a project specific parameter. The relationship between the lengths of 2D seismic lines among different time periods is shown as

$$E_{i1}^{2D} = E_{i0}^{2D}\frac{q_i}{q_i^{max}} + e_{i0}^{2D} = E_{i0}^{2D}\frac{q_i}{q_i^{max}} + \rho_i^{2D} q_i \tag{16}$$

$$E_{i2}^{2D} = E_{i1}^{2D} - f_{i0}^{2D}$$

$$E_{i3}^{2D} = E_{i2}^{2D} - f_{i1}^{2D} = E_{i1}^{2D} - f_{i0}^{2D} - f_{i1}^{2D} = E_{i0}^{2D}\frac{q_i}{q_i^{max}} + \rho_i^{2D} q_i - f_{i0}^{2D} - f_{i1}^{2D} \geq 0$$

$\forall i.$ These equations differ from 2D legacy seismic lines equations in period 0. Oilsands projects will build some 2D seismic lines before bitumen production and these lines generate land damage since they are built. In addition, 2D seismic lines are more recently built and thinner than 2D legacy seismic lines that are wide and built some time ago. In this thesis, we explore firms' early reclamation decisions on 2D seismic lines and 2D legacy seismic lines because both of these lines are of little use after firms have located their exact bitumen extraction location.

3D Seismic Lines (Low Impact)

We let $E_{i0}^{3D}, E_{i1}^{3D}, E_{i2}^{3D}, E_{i3}^{3D}$ represent the length of 3D seismic lines for an in-situ project i for period 0, 1, 2, 3, respectively. These notations apply to the case where firms are not responsible for 3D seismic lines. Typically, E_{i0}^{3D} is written as $E_{i0}^{3D}\frac{q_i}{q_i^{max}}$ in the case where firms are responsible for 3D seismic lines. We assume $E_{i0}^{3D}\frac{q_i}{q_i^{max}} \geq 0$. We let f_{i1}^{3D} represent the length of 3D seismic lines reclaimed in an in-situ project i at the end year of period 1 (year 30), and we assumes no natural regeneration of forest along 3D seismic lines. The relationship between the lengths of 3D seismic lines among different time periods is shown as

$$E_{i1}^{3D} = E_{i0}^{3D}\frac{q_i}{q_i^{max}} + e_{i0}^{3D} = E_{i0}^{3D}\frac{q_i}{q_i^{max}} + \frac{3}{\delta_i}q_i \tag{17}$$

$$E_{i2}^{3D} = E_{i1}^{3D} = E_{i0}^{3D}\frac{q_i}{q_i^{max}} + \frac{3}{\delta_i}q_i$$

$$E_{i3}^{3D} = E_{i2}^{3D} - f_{i1}^{3D} = E_{i1}^{3D} - f_{i1}^{3D} = E_{i0}^{3D}\frac{q_i}{q_i^{max}} + \frac{3}{\delta_i}q_i - f_{i1}^{3D} \geq 0$$

$\forall i$. These equations differ from those related to 2D seismic lines in terms of reclamation period. 3D seismic lines could only be reclaimed at the end year of period 1 because they are necessary for bitumen production. In addition, these equations also follow the relationship between e_{i0}^{3D} and q_i shown in equation (9). 2D seismic lines are mainly used for bitumen deposit exploration and 3D seismic lines are built for bitumen extraction and production. Normally, sensors are buried along 3D seismic lines and they emit and receive rays to detect the changing situation of under the ground (Niri, 2018). Therefore, 2D seismic lines and 2D legacy seismic lines are reclaimable and of little use for bitumen production once the process begins.

4D Seismic Lines (Low Impact)

We let $E_{i0}^{4D}, E_{i1}^{4D}, E_{i2}^{4D}, E_{i3}^{4D}$ represent the length of 4D seismic lines for an in-situ project i for period 0, 1, 2, 3, respectively. These notations apply to the case where firms are not responsible for 4D seismic lines. Typically, E_{i0}^{4D} is written as $E_{i0}^{4D} \frac{q_i}{q_i^{max}}$ in the case where firms are responsible for 4D seismic lines. We assume $E_{i0}^{4D} \frac{q_i}{q_i^{max}} \geq 0$. We let f_{i1}^{4D} represent the length of 4D seismic lines reclaimed in an in-situ project i at the end year of period 1 (year 30), and we assumes no natural regeneration of forest along 4D seismic lines. The relationship between the lengths of 4D seismic lines among different time periods is shown as

$$E_{i1}^{4D} = E_{i0}^{4D} \frac{q_i}{q_i^{max}} + e_{i0}^{4D} = E_{i0}^{4D} \frac{q_i}{q_i^{max}} + \frac{1}{\delta_i} q_i \tag{18}$$

$$E_{i2}^{4D} = E_{i1}^{4D} = E_{i0}^{4D} \frac{q_i}{q_i^{max}} + \frac{1}{\delta_i} q_i$$

$$E_{i3}^{4D} = E_{i2}^{4D} - f_{i1}^{2D} = E_{i1}^{4D} - f_{i1}^{2D} = E_{i0}^{4D} \frac{q_i}{q_i^{max}} + \frac{1}{\delta_i} q_i - f_{i1}^{2D} \geq 0$$

These equations for 4D seismic lines for each period are the same as 3D seismic lines. The relationship between e_{i0}^{4D} and q_i is based on equation (8). 4D seismic lines are used to monitor bitumen production with time. 3D and 4D seismic lines are indispensable for the bitumen production process and both of these lines are not reclaimable during period one. In addition, based on reclamation requirements, pipelines, roads, 3D and 4D seismic lines should be reclaimed at the end of period one.

Total Linear Features Revisited (expressed in terms of q_i and reclamation variables f_{is})

The total linear features equation (12), $L_{is}^{q} = P_{is} + R_{is} + E_{is}^{2DL} + \theta(E_{is}^{2D} + E_{is}^{3D} + E_{is}^{4D})$, can be expressed in terms of q_i and f_{is} substituting in equations 13-18 to obtain:

$$-\sum_{t=1}^{90} \beta^t \tau \left[\frac{P_{i0}}{q_i^{max}} + \rho_i^{pipe} + \frac{R_{i0}}{q_i^{max}} + \rho_i^r + \frac{E_{i0}^{2DL}}{q_i^{max}} + \theta\left(\frac{E_{i0}^{2D}}{q_i^{max}} + \rho_i^{2D} + \frac{E_{i0}^{3D}}{q_i^{max}} + \frac{3}{\delta_i} + \frac{E_{i0}^{4D}}{q_i^{max}} + \frac{1}{\delta_i}\right)\right]$$

$$L_{i1}^{q} = P_{i1} + R_{i1} + E_{i1}^{2DL} + \theta(E_{i1}^{2D} + E_{i1}^{3D} + E_{i1}^{4D})$$

$$= P_{i0}\frac{q_i}{q_i^{max}} + \rho_i^{pipe} q_i + R_{i0}\frac{q_i}{q_i^{max}} + \rho_i^r q_i + E_{i0}^{2DL}\frac{q_i}{q_i^{max}}$$

$$+\theta\left(E_{i0}^{2D}\frac{q_i}{q_i^{max}} + \rho_i^{2D} q_i + E_{i0}^{3D}\frac{q_i}{q_i^{max}} + \frac{3}{\delta_i} q_i + E_{i0}^{4D}\frac{q_i}{q_i^{max}} + \frac{1}{\delta_i} q_i\right) \qquad (19)$$

$$L_{i2}^{q} = P_{i2} + R_{i2} + E_{i2}^{2DL} + \theta(E_{i2}^{2D} + E_{i2}^{3D} + E_{i2}^{4D})$$

$$= P_{i0}\frac{q_i}{q_i^{max}} + \rho_i^{pipe} q_i + R_{i0}\frac{q_i}{q_i^{max}} + \rho_i^r q_i + E_{i0}^{2DL}\frac{q_i}{q_i^{max}} - f_{i0}^{2DL}$$

$$+\theta(E_{i0}^{2D}\frac{q_i}{q_i^{max}} + \rho_i^{2D} q_i - f_{i0}^{2D} + E_{i0}^{3D}\frac{q_i}{q_i^{max}} + \frac{3}{\delta_i} q_i + E_{i0}^{4D}\frac{q_i}{q_i^{max}} + \frac{1}{\delta_i} q_i \qquad (20)$$

$$L_{i3}^{q} = P_{i3} + R_{i3} + E_{i3}^{2DL} + \theta(E_{i3}^{2D} + E_{i3}^{3D} + E_{i3}^{4D})$$

$$= P_{i0}\frac{q_i}{q_i^{max}} + \rho_i^{pipe} q_i - f_{i1}^{p} + R_{i0}\frac{q_i}{q_i^{max}} + \rho_i^r q_i - f_{i1}^{r} + E_{i0}^{2DL}\frac{q_i}{q_i^{max}} - f_{i0}^{2DL} - f_{i1}^{2DL}$$

$$+\theta(E_{i0}^{2D}\frac{q_i}{q_i^{max}}+\rho_i^{2D}q_i-f_{i0}^{2D}-f_{i1}^{2D}+E_{i0}^{3D}\frac{q_i}{q_i^{max}}+\frac{3}{\delta_i}q_i$$

$$-f_{i1}^{3D}+E_{i0}^{4D}\frac{q_i}{q_i^{max}}+\frac{1}{\delta_i}q_i-f_{i1}^{4D} \tag{21}$$

$L_{is}^{q}\geq 0, s=1,2,3$. These equations are useful for deriving a firm's behavior in terms of production and reclamation decisions. We also have a situation where firms are not reclamation firms and not required to reclaim legacy linear features if they do not have bitumen production. We define a series of identical equations L_{i1}^{-q}(19'), L_{i2}^{-q}(20'), L_{i3}^{-q}(21') where $\frac{q_i}{q_i^{max}}$ do not appear in equation 19, 20, and 21. For equations L_{i1}^{-q}(19'), L_{i2}^{-q}(20'), L_{i3}^{-q}(21'), each variables $P_{i0}, R_{i0}, E_{i0}^{2DL}, E_{i0}^{2D}, E_{i0}^{3D}, E_{i0}^{4D}$ would exist with isolation as constants rather than as coefficients. For simplicity, L_1, L_2, L_3 could refer to either case of L_1^q, L_2^q, L_3^q or $L_1^{-q}, L_2^{-q}, L_3^{-q}$.

Reclamation Cost Revisited

The reclamation cost function (f_s) , s=0,1 is defined as

$$RC(f_0,f_1)=RC(\textstyle\sum_{i=1}^{n}f_{i0})+\sum_{t=1}^{30}\beta^t RC(\sum_{i=1}^{n}f_{i1}) \tag{22}$$

where $f_s=(f_{1s},\dots,f_{is},\dots,f_{ns})$ s=0,1 and f_{is} is a 6*n vector with components $f_{is}^{pipe}, f_{is}^{r}, f_{is}^{2DL}, f_{is}^{2D}, f_{is}^{3D}, f_{is}^{4D}$. In addition, the $RC(f_{is})$ could be expressed as

$$RC\left(f_{i0}^{2DL},f_{i0}^{2D},f_{i1}^{pipe},f_{i1}^{r},f_{i1}^{2DL},f_{i1}^{2D},f_{i1}^{3D},f_{i1}^{4D}\right)=p^{2DL}f_{i0}^{2DL}+p^{2D}f_{i0}^{2D}$$

$$+\beta^{30}\left(p^{pipe}f_{i1}^{pipe}+p^{r}f_{i1}^{r}+p^{2DL}f_{i1}^{2DL}+p^{2D}f_{i1}^{2D}+p^{3D}f_{i1}^{3D}+p^{4D}f_{i1}^{4D}\right) \tag{23}$$

This equation indicates that firms could choose to reclaim 2D legacy seismic lines and 2D seismic lines at period 0. In this case, they just reclaim pipelines, roads, 3D seismic lines, and 4D seismic lines within their license area at the end of period 1. If early reclamation of 2D legacy seismic lines and 2D seismic lines is postponed, firms would be required reclaim all linear features within their license area at the end of period 1.

Fixed Cost Revisited

Fixed cost can also be written as a function form of q_i by substituting equations (8 and 9) in equation (4) as follows:

$$FC_i(q_i) = A_i + \sum_{t=1}^{30} \beta^t \sigma A_i + (\beta^0 + \beta^{10} + \beta^{20}) * w_i * cw$$

$$+c^{pipe} pipe_{i1} + c^r r_{i1} + c^{2D} e_{i1}^{2D} + c^{3D} \frac{3}{\delta_i} q_i + c^{4D} \frac{1}{\delta_i} q_i \qquad (24)$$

Set I_i equal to the first 6 terms (all those without q_i) and linearize the investment cost with q_i / q_i^{max} and we have:

$$FC_i(q_i) = I_i \frac{q_i}{q_i^{max}} + c^{3D} \frac{3}{\delta_i} q_i + c^{4D} \frac{1}{\delta_i} q_i \qquad (q_i > 0) \qquad (24\text{-}1)$$

The linearization is appropriate here because $q_i = 0$, or q_i^{max} given the linearity of the overall model.

Summary

This section defines firms' revenue functions, production cost functions, and reclamation functions. In this section we understand that pipelines, roads, 3D and 4D seismic lines are essential for bitumen exploration, production, management, and these lines cannot be reclaimed at the beginning of period one. Therefore, the firms' profit maximizing problem framed in the next section mainly focuses on whether firms invest in reclamation of 2D seismic lines and 2D legacy seismic lines at the beginning of period one.

3.3 The social planner's problem and the in-situ oilsands firm's problem

In this section, we first develop the social planner's problem, and derive the first order conditions for the social welfare optimum. Then we move to the in-situ oilsands firm's problem under the current case and derive first order conditions for a firm's optimal behavior. We will show that solutions under the current case fail to implement the social planner's problem.

3.3.1 Social planner's problem

We define $\tilde{\beta}^{30} = \sum_{t=1}^{30} \beta^t = \frac{\beta(1-\beta^{30})}{1-\beta}$, $\tilde{\beta}^{60} = \sum_{t=31}^{60} \beta^t = \frac{\beta^{31}(1-\beta^{30})}{1-\beta}$, $\tilde{\beta}^{90} = \sum_{t=61}^{90} \beta^t = \frac{\beta^{61}(1-\beta^{30})}{1-\beta}$. The damage function is defined as:

$$D^T\left(L_{i1}^{-q}, L_{i2}^{-q}, L_{i3}^{-q}\right) = \sum_{t=1}^{30} \beta^t D\left(\sum_{i=1}^{n} L_{i1}^{-q}\right) + \sum_{t=31}^{60} \beta^t D\left(\sum_{i=1}^{n} L_{i2}^{-q}\right) + \sum_{t=61}^{90} \beta^t D\left(\sum_{i=1}^{n} L_{i3}^{-q}\right)$$

$$= D\left(\sum_{i=1}^{n} L_{i1}^{-q}\right)\tilde{\beta}^{30} + D\left(\sum_{i=1}^{n} L_{i2}^{-q}\right)\tilde{\beta}^{60} + D\left(\sum_{i=1}^{n} L_{i3}^{-q}\right)\tilde{\beta}^{90}$$

$$= \varphi\tilde{\beta}^{30} \sum_{i=1}^{n} L_{i1}^{-q} + \varphi\tilde{\beta}^{60} \sum_{i=1}^{n} L_{i2}^{-q} + \varphi\tilde{\beta}^{90} \sum_{i=1}^{n} L_{i3}^{-q}$$

where $D\left(\sum_{i=1}^{n} L_{is}^{-q}\right) = \sum_{i=1}^{n} \varphi L_{is}^{-q}$, $s = 1, 2, 3$, and φ is the constant damage per kilometre of linear features.

An optimal social allocation is $\{(q_i^*, f_{is}^*)_{\forall is} \in R_+^{2*n}\}$ solves the social planner's problem:

$$\mathbf{max}_{q_i, f_{is}} W = \sum_{i=1}^{n} \sum_{t=1}^{90} \beta^t [(p-\omega) q_i] - FC_i(q_i) - RC(f_0, f_1) - D^T\left(L_{i1}^{-q}, L_{i2}^{-q}, L_{i3}^{-q}\right) \tag{25}$$

$$\textbf{s.t.} \quad q_i \le q_i^{max}$$

$$P_{i0} + \rho_i^{pipe} q_i - f_{i1}^{pipe} \ge 0 \qquad R_{i0} + \rho_i^r q_i - f_{i1}^r \ge 0$$

$$E_{i0}^{2DL} - f_{i0}^{2DL} - f_{i1}^{2DL} \ge 0 \qquad E_{i0}^{2D} + \rho_i^{2D} q_i - f_{i0}^{2D} - f_{i1}^{2D} \ge 0$$

$$E_{i0}^{3D} + \frac{3}{\delta_i} q_i - f_{i1}^{3D} \ge 0 \qquad E_{i0}^{4D} + \frac{1}{\delta_i} q_i - f_{i1}^{4D} \ge 0$$

and equations 1 to 12, 22, 23

where $L_s^{-q} = (L_{1s}^{-q}, \dots, L_{is}^{-q}, \dots, L_{ns}^{-q})$ s=1,2,3 and for all i and s=1,2,3;

$f_s = (f_{1s}, \dots, f_{is}, \dots, f_{ns})$ s=0,1,2,3 and f_{is} is a 6*n vector with components

$f_{is}^{pipe}, f_{is}^r, f_{is}^{3D}, f_{is}^{4D}$ for all i and s=1, $f_{is}^{2DL}, f_{is}^{2D}$ for all i and s=0,1.

The socially optimal allocation is a situation where there are no uncompensated externalities or other market failures, and some people's welfare cannot increase without compromising other people's benefits. In addition, a society may contain more than one socially optimal allocation.

The Lagrange equation for the social planner's problem is:

$$La^W = \sum_{i=1}^{n}\sum_{t=1}^{90}\beta^t[(p-\omega)q_i] - FC_i(q_i) - RC(f_0, f_1)$$

$$-D^T\left(L_{i1}^{-q}, L_{i2}^{-q}, L_{i3}^{-q}\right) + \mu_i^q(q_i^{max} - q_i) + \mu_i^{pipe}(P_{i0} + \rho_i^{pipe}q_i - f_{i1}^{pipe})$$

$$+\mu_i^r(R_{i0} + \rho_i^r q_i - f_{i1}^r) + \mu_i^{2DL}(E_{i0}^{2DL} - f_{i0}^{2DL} - f_{i1}^{2DL})$$

$$+\mu_i^{2D}(E_{i0}^{2D} + \rho_i^{2D}q_i - f_{i0}^{2D} - f_{i1}^{2D}) + \mu_i^{3D}\left(E_{i0}^{3D} + \frac{3}{\delta_i}q_i - f_{i1}^{3D}\right)$$

$$+ \mu_i^{4D}\left(E_{i0}^{4D} + \frac{3}{\delta_i}q_i - f_{i1}^{4D}\right)$$

where μ_i^q is the marginal value (shadow price) of bitumen reserves for oilsands project i, $\mu_i^{pipe}, \mu_i^r, \mu_i^{2DL}, \mu_i^{2D}, \mu_i^{3D}, \mu_i^{4D}$ are the net benefit of reclaiming one kilometre of pipelines, roads, 2D legacy seismic lines, 2D seismic lines, 3D seismic lines, 4D seismic lines.

First Order Conditions

The first-order conditions with respect to q_i for the welfare optimum are:

$\frac{\partial La^W}{\partial q_i} = \sum_{t=1}^{30}\beta^t(p-\omega) - \left(\frac{3c^{3D}}{\delta_i} + \frac{c^{4D}}{\delta_i} + \frac{I_i}{q_i^{max}}\right) - \sum_{t=1}^{90}\beta^t\varphi\left[\rho_i^{pipe} + \rho_i^r + \theta\left(\rho_i^{2D} + \frac{3}{\delta_i} + \frac{1}{\delta_i}\right)\right] + \mu_i^{pipe}\rho_i^{pipe} + \mu_i^r\rho_i^r + \mu_i^{2D}\rho_i^{2D} + \mu_i^{3D}\frac{3}{\delta_i} + \mu_i^{4D}\frac{1}{\delta_i} - \mu_i^q \leq 0,$

$\frac{\partial La^W}{\partial q_i} = 0$ if $q_i > 0$ (26)

and we have

$$\mu_i^q \geq \sum_{t=1}^{90} \beta^t (p-\omega) - \left(\frac{3c^{3D}}{\delta_i} + \frac{c^{4D}}{\delta_i} + \frac{I_i}{q_i^{max}}\right) - \sum_{t=1}^{90} \beta^t \varphi \left[\rho_i^{pipe} + \rho_i^r + \theta\left(\rho_i^{2D} + \frac{3}{\delta_i} + \frac{1}{\delta_i}\right)\right] + \mu_i^{pipe}\rho_i^{pipe} + \mu_i^r \rho_i^r + \mu_i^{2D}\rho_i^{2D} + \mu_i^{3D}\frac{3}{\delta_i} + \mu_i^{4D}\frac{1}{\delta_i} \quad (26')$$

The first term on the right is the net operating value (price minus operating cost), the second term is the construction cost, the third term is the discounted caribou damages due to the initial construction of the linear features, and the final five terms are benefits (or reduced damages) arising from the reclamation of these linear features. The net discounted caribou damages of constructed linear features derive from the summation of the third term and the final five terms. We notice that μ_i^q could be interpreted as the maximum that a project i could pay for extracting all the bitumen resources. If the right side is negative then μ_i^q will be zero and the firms will not be willing to pay for the bitumen reserves.

The first-order condition with respect to μ_i for the welfare optimum is:

$$\frac{\partial La^W}{\partial \mu_i^q} = q_i^{max} - q_i \geq 0, \frac{\partial La^W}{\partial \mu_i^q} = 0 \; if \; \mu_i > 0 \quad (27)$$

This equation shows that the total bitumen output is less than or equal to the total bitumen reserves underground.

The first-order conditions with respect to f_{is} for the welfare optimum are:

$$\frac{\partial La^W}{\partial f_{i1}^{pipe}} \leq 0, -\beta^{30} p^{pipe} + \sum_{t=61}^{90} \beta^t \varphi \leq \mu_i^{pipe}\ , \ \frac{\partial La^W}{\partial f_{i1}^{pipe}} = 0 \text{ if } f_{i1}^{pipe} > 0 \quad (28\text{-}1)$$

$$\frac{\partial La^W}{\partial f_{i1}^{r}} \leq 0,\ -\beta^{30} p^{r} + \sum_{t=61}^{90} \beta^t \varphi \leq \mu_i^{r}\ , \ \frac{\partial La^W}{\partial f_{i1}^{r}} = 0 \text{ if } f_{i1}^{r} > 0 \quad (28\text{-}2)$$

$$\frac{\partial La^W}{\partial f_{i0}^{2DL}} \leq 0, \ -p^{2DL} + \sum_{t=31}^{90} \beta^t \varphi \leq \mu_i^{2DL} \ , \ \frac{\partial La^W}{\partial f_{i0}^{2DL}} = 0 \text{ if } f_{i0}^{2DL} > 0 \qquad (28\text{-}3)$$

$$\frac{\partial La^W}{\partial f_{i1}^{2DL}} \leq 0, \ -\beta^{30} p^{2DL} + \sum_{t=61}^{90} \beta^t \varphi \leq \mu_i^{2DL}{}_i \ , \ \frac{\partial La^W}{\partial f_{i1}^{2DL}} = 0 \text{ if } f_{i1}^{2DL} > 0 \qquad (28\text{-}4)$$

$$\frac{\partial La^W}{\partial f_{i0}^{2D}} \leq 0, \ -p^{2D} + \sum_{t=31}^{90} \beta^t \varphi\theta \leq \mu_i^{2D} \ , \ \frac{\partial La^W}{\partial f_{i0}^{2D}} = 0 \text{ if } f_{i0}^{2D} > 0 \qquad (28\text{-}5)$$

$$\frac{\partial La^W}{\partial f_{i1}^{2D}} \leq 0, \ -\beta^{30} p^{2D} + \sum_{t=61}^{90} \beta^t \varphi\theta \leq \mu_i^{2D} \ , \ \frac{\partial La^W}{\partial f_{i1}^{2D}} = 0 \text{ if } f_{i1}^{2D} > 0 \qquad (28\text{-}6)$$

$$\frac{\partial La^W}{\partial f_{i1}^{3D}} \leq 0, \ -\beta^{30} p^{3D} + \sum_{t=61}^{90} \beta^t \varphi\theta \leq \mu_i^{3D} \ , \ \frac{\partial La^W}{\partial f_{i1}^{3D}} = 0 \text{ if } f_{i1}^{3D} > 0 \qquad (28\text{-}7)$$

$$\frac{\partial La^W}{\partial f_{i1}^{4D}} \leq 0, \ -\beta^{30} p^{4D} + \sum_{t=61}^{90} \beta^t \varphi\theta \leq \mu_i^{4D}, \ \frac{\partial La^W}{\partial f_{i1}^{4D}} = 0 \text{ if } f_{i1}^{4D} > 0 \qquad (28\text{-}8)$$

When $\frac{\partial La^W}{\partial f_{is}} = 0$, firms compare the cost of reclaiming linear features with the benefit arising from the land damage to be reduced. We use 4D seismic lines as an example and all of them are similar in terms of specific costs and benefits. The first term ($\beta^{30} p^{4D}$) is the cost of reclamation and the second term ($\sum_{t=61}^{90} \beta^t \varphi\theta$) is the benefits of reclamation over the years that the reclamation has an effect. The Lagrange multiplier (u_i) represents the net benefit of reclamation and it will only be positive when the benefits exceed the costs (i.e. when the marginal benefits of reclamation φ in equations 28-1 to 28-4 and $\varphi\theta$ in equations 28-4 to 28-8 is sufficiently large). In addition, the costs of building pipelines is higher than that of building roads and 2DL seismic lines so we have $p^{pipe} > p^r > p^{2DL}$. This restricts the possible optimal outcomes for reclamation to the following cases:

1) If the marginal benefits of reclamation are low, firms do not reclaim 2D seismic lines, roads, or pipelines;

2) With a higher level of the marginal benefits of reclamation, firms reclaim 2D seismic lines, but do not reclaim roads or pipelines;

3) With a higher level of the marginal benefits of reclamation, firms reclaim 2D seismic lines and roads, but do not reclaim pipelines;

4) If we have highest marginal benefits of reclamation, firms will reclaim 2D seismic lines, roads, and pipelines.

In no case are pipelines reclaimed but not 2D seismic or roads.

Reclamation: The Regulator's Case

Alberta regulations require that firms reclaim all linear features at the end of the project. In terms of the notation presented here, that means that each project i reclaim its linear features at the end of period 1 so that we have the following constraints:

$$f_{i1}^{pipe} = P_{i0} + p_{i0} \tag{25-1}$$

$$f_{i1}^{r} = R_{i0} + r_{i0} \tag{25-2}$$

$$f_{i1}^{3D} = E_{i0}^{3D} + e_{i0}^{3D} \tag{25-3}$$

$$f_{i1}^{4D} = E_{i0}^{4D} + e_{i0}^{4D} \tag{25-4}$$

$$f_{i1}^{2DL} = E_{i0}^{2DL} \; if \; f_{i0}^{2DL} = 0 \tag{25-5}$$

$$f_{i1}^{2D} = E_{i0}^{2D} \; if \; f_{i0}^{2D} = 0 \tag{25-6}$$

These equations mean that it is possible that the regulations are inefficient if φ or $\varphi\theta$ are small and the net reclamation benefits (u_i) are negative. This is based on the assumption that φ represents all possible benefits. This means that regulator may focus on all benefits related to linear feature reclamation. In this study, we only focus on caribou benefits.

In this section, the objective function, constraints, and first order conditions are presented. In subsequent sections, we present only the objective function and constraints, and we place the first order conditions in the appendix.

3.3.2 Oilsands firm's problem

Under the no tax, or current, case, we assume that the in-situ oilsands industry operates in a market equilibrium. Also, we let π_i represent the total profits for an in-situ oilsands project i over three periods.

A competitive equilibrium is $\{(\hat{q}_i, \hat{f}_{is})_{\forall is} \in R_+^{2*n}\}$ such that for each firm i, $(\hat{q}_i, \hat{f}_{is})$ solves the individual firm's profit maximization problem:

$$\mathbf{max}_{\boldsymbol{q_i, f_{is}}}\ \pi_i = \sum_{t=1}^{90} \beta^t (p-\omega) q_i - FC_i(q_i) - RC(f_0, f_1) \qquad (29)$$

$$\textbf{s.t.}\ \ q_i \le q_i^{max}$$

$$P_{i0} \frac{q_i}{q_i^{max}} + \rho_i^{pipe} q_i - f_{i1}^{pipe} \ge 0 \qquad R_{i0} \frac{q_i}{q_i^{max}} + \rho_i^r q_i - f_{i1}^r \ge 0$$

$$E_{i0}^{2DL} \frac{q_i}{q_i^{max}} - f_{i0}^{2DL} - f_{i1}^{2DL} \ge 0 \qquad E_{i0}^{2D} \frac{q_i}{q_i^{max}} + \rho_i^{2D} q_i - f_{i0}^{2D} - f_{i1}^{2D} \ge 0$$

$$E_{i0}^{3D} \frac{q_i}{q_i^{max}} + \frac{3}{\delta_i} q_i - f_{i1}^{3D} \ge 0 \qquad E_{i0}^{4D} \frac{q_i}{q_i^{max}} + \frac{1}{\delta_i} q_i - f_{i1}^{4D} \ge 0$$

and equations (1) to (24), (25-1) to (25-6)

$\forall i$. Firms maximize total profits over three periods.

The Lagrange equation for firm's problem is:

$$La^{\pi}=\sum_{i=1}^{n}\sum_{t=1}^{90}\beta^{t}[(p-\omega)q_i]-FC_i(q_i)-RC(f_0,f_1)\mu_i^{q}(q_i^{max}-q_i)+\mu_i^{pipe}(P_{i0}\frac{q_i}{q_i^{max}}$$

$$+\rho_i^{pipe}q_i-f_{i1}^{pipe}+\mu_i^{r}\left(R_{i0}\frac{q_i}{q_i^{max}}+\rho_i^{r}q_i-f_{i1}^{r}\right)$$

$$+\mu_i^{2DL}\left(E_{i0}^{2DL}\frac{q_i}{q_i^{max}}-f_{i0}^{2DL}-f_{i1}^{2DL}\right)$$

$$+\mu_i^{2D}\left(E_{i0}^{2D}\frac{q_i}{q_i^{max}}+\rho_i^{2D}q_i-f_{i0}^{2D}-f_{i1}^{2D}\right)$$

$$+\mu_i^{3D}\left(E_{i0}^{3D}\frac{q_i}{q_i^{max}}+\frac{3}{\delta_i}q_i-f_{i1}^{3D}\right)+\mu_i^{4D}\left(E_{i0}^{4D}\frac{q_i}{q_i^{max}}+\frac{3}{\delta_i}q_i-f_{i1}^{4D}\right)$$

where μ_i^{q} is the marginal value (shadow price) of bitumen reserves for oilsands project i, $\mu_i^{pipe}, \mu_i^{r}, \mu_i^{2DL}, \mu_i^{2D}, \mu_i^{3D}, \mu_i^{4D}$ is the shadow price of one kilometre of pipelines, roads, and seismic lines.

The first order conditions in the appendix part 1 "Oilsands firm's problem" show the difference between the firm's decisions and the social planner's resource allocation: there is no reclamation benefits term in the firm's first order conditions and therefore the reclamation for each firm i will be zero.

Reclamation Regulations: Firm's Case with no Tax on Linear Features

Alberta regulations require each project to reclaim their linear features at the end of period 1 and we have the same constraints as in equation (from 25-1 to 25-6). The firm could still reclaim legacy 2D seismic lines (f_{i0}^{2DL}) and new 2D lines (f_{i0}^{2D}) at the end of the period 1. However, as shown in equation 32 both f_{i0}^{2DL} and f_{i0}^{2D} would be set to zero under the no-tax case with the end of project reclamation regulations.

Under the competitive equilibrium, firms produce more output than is socially optimal, and create more linear features and caribou damage than the socially optimal level. Proofs are shown in the appendix part 1 "Oilsands firm's problem". This departure from social optimality motivates the investigation of taxes, and the tax-refund scheme, to address the externality associated with caribou damage.

3.4 The tax case

We use τ as the tax rate per kilometre of linear features, and this variable is assumed to be fixed during the entire study period. We define the total tax payment for i as

$$\tau_i^T(L_{i1}, L_{i2}, L_{i3}) = \tau\tilde{\beta}^{30}L_{i1} + \tau\tilde{\beta}^{60}L_{i2} + \tau\tilde{\beta}^{90}L_{i3}$$

An equilibrium under the tax case is $\{(\tilde{q}_i, \tilde{f}_{is})_{\forall it} \in R_+^{2*n}\}$ such that for each firm i, $(\tilde{q}_i, \tilde{f}_{is})$ solves the individual firm's profit maximization problem:

$$\mathbf{max}_{q_i, f_{is}}\ \pi_i = \sum_{t=1}^{90} \beta^t\,(p-\omega)q_i - FC_i(q_i) - RC(f_{i0}, f_{i1}) - \tau_i^T(L_{i1}, L_{i2}, L_{i3}) \tag{33}$$

Case X1 constraints:

Responsible for legacy lines

s.t. $q_i \le q_i^{max}$

$P_{i0}\frac{q_i}{q_i^{max}} + \rho_i^{pipe}q_i - f_{i1}^{pipe} \ge 0$

$R_{i0}\frac{q_i}{q_i^{max}} + \rho_i^{r}q_i - f_{i1}^{r} \ge 0$

$E_{i0}^{2DL}\frac{q_i}{q_i^{max}} - f_{i0}^{2DL} - f_{i1}^{2DL} \ge 0$

$E_{i0}^{2D}\frac{q_i}{q_i^{max}} + \rho_i^{2D}q_i - f_{i0}^{2D} - f_{i1}^{2D} \ge 0$

$E_{i0}^{3D}\frac{q_i}{q_i^{max}} + \frac{3}{\delta_i}q_i - f_{i1}^{3D} \ge 0$

$E_{i0}^{4D}\frac{q_i}{q_i^{max}} + \frac{1}{\delta_i}q_i - f_{i1}^{4D} \ge 0$

Case Y1 constraints:

Not responsible for legacy lines

s.t. $q_i \le q_i^{max}$

$P_{i0} + \rho_i^{pipe}q_i - f_{i1}^{pipe} \ge 0$

$R_{i0} + \rho_i^{r}q_i - f_{i1}^{r} \ge 0$

$E_{i0}^{2DL} - f_{i0}^{2DL} - f_{i1}^{2DL} \ge 0$

$E_{i0}^{2D} + \rho_i^{2D}q_i - f_{i0}^{2D} - f_{i1}^{2D} \ge 0$

$E_{i0}^{3D} + \frac{3}{\delta_i}q_i - f_{i1}^{3D} \ge 0$

$E_{i0}^{4D} + \frac{1}{\delta_i}q_i - f_{i1}^{4D} \ge 0$

and equations (1) to (12), (19) to(24) and equations (1) to (12), (19) to(24)

Note: for $\tau_i^T(L_{i1}, L_{i2}, L_{i3})$, under the case X1, it is $\tau_i^T(L_{i1}^q, L_{i2}^q, L_{i3}^q)$; under the case Y1, it could be written as $\tau_i^T(L_{i1}^{-q}, L_{i2}^{-q}, L_{i3}^{-q})$, $\forall i$, where $L_{is} = P_{is} + R_{is} + E_{is}^{2DL} + \theta(E_{i1}^{2D} + E_{i1}^{3D} + E_{i1}^{4D})$ for all i and s=1,2,3. The differences between X1 and Y1 is that in X1 legacy linear features are treated as a variable cost on entry while in Y1 they are treated as a fixed cost. Therefore, the taxes for these legacy linear features show up as a marginal cost in the first order conditions for q_i in X1 but not Y1. This will affect the conditions for firms' entry into the industry.

The Lagrange equation for firm's problem in case X1 under the tax scheme is:

$$La^{tax} = \sum_{t=1}^{90} \beta^t[(p-\omega)q_i] - FC_i(qi) - RC(f_0, f_1)$$

$$-\tau_i^T\left(L_1^q, L_2^q, L_3^q\right) + \mu_i^q(q_i^{max} - q_i) + \mu_i^{pipe}(P_{i0}\frac{q_i}{q_i^{max}} + \rho_i^{pipe}q_i - f_{i1}^{pipe})$$

$$+\mu_i^r\left(R_{i0}\frac{q_i}{q_i^{max}} + \rho_i^r q_i - f_{i1}^r\right) + \mu_i^{2DL}\left(E_{i0}^{2DL}\frac{q_i}{q_i^{max}} - f_{i0}^{2DL} - f_{i1}^{2DL}\right)$$

$$+\mu_i^{2D}\left(E_{i0}^{2D}\frac{q_i}{q_i^{max}} + \rho_i^{2D}q_i - f_{i0}^{2D} - f_{i1}^{2D}\right) + \mu_i^{3D}\left(E_{i0}^{3D}\frac{q_i}{q_i^{max}} + \frac{3}{\delta_i}q_i - f_{i1}^{3D}\right)$$

$$+\mu_i^{4D}\left(E_{i0}^{4D}\frac{q_i}{q_i^{max}} + \frac{3}{\delta_i}q_i - f_{i1}^{4D}\right)$$

where μ_i^q is the marginal value (shadow price) of bitumen reserves for oilsands project i, $\mu_i^{pipe}, \mu_i^r, \mu_i^{2DL}, \mu_i^{2D}, \mu_i^{3D}, \mu_i^{4D}$ are the shadow price of one kilometre of pipelines, roads, 2D legacy seismic lines, 2D seismic lines, 3D seismic lines, 4D seismic lines. The lagrange equation for firm's problem in case Y1 under the tax scheme is identical to the case X with the exception of the existence of $\frac{q_i}{q_i^{max}}$ for linear feature terms ($P_{i0}, R_{i0}, E_{i0}^{2DL}, E_{i0}^{2D}, E_{i0}^{3D}, E_{i0}^{4D}$). We understand that Case X1 may exclude some firms that produce and reclaim relative to Case Y1.

First order conditions with respect to q_i, μ_i, and f_{is} are shown in the appendix part 2 "The tax case". Based on the empirical facts, we have $p^{pipe} > p^r > p^{2DL}$, and several socially optimal possibilities given the first order conditions with respect to f_{is} arise as follows:

1) If the τ is lower relative to the reclamation cost of 2D legacy seismic lines (p^{2DL}), $\frac{\tau}{p^{2DL}} < \frac{1}{\sum_{t=31}^{90} \beta^t}$, firms do not reclaim 2D seismic lines, roads, or pipelines;

2) With a higher level of tax $\frac{1}{\sum_{t=31}^{90} \beta^t} < \frac{\tau}{p^{2DL}}$, firms reclaim 2D seismic lines, but do not reclaim roads or pipelines;

3) With a higher level of tax $\frac{1}{\sum_{t=61}^{90} \beta^t} < \frac{\tau}{p^r}$, firms reclaim 2D seismic lines and roads, but do not reclaim pipelines;

4) If we have $\frac{1}{\sum_{t=61}^{90} \beta^t} < \frac{\tau}{p^{pipe}}$, firms will reclaim 2D seismic lines, roads, and pipelines

Allocation possibilities under a tax system with and without negative taxes (Case Y1)

Here we compare the $(\tilde{q}_i, \tilde{f}_{is})$ under a tax system with and without negative taxes under four possible cases for social optimality.

Case 1: in the socially optimal case, all firms produce $q_i^* > 0$, and no reclamation $f_i^* = 0$ arises. The marginal caribou benefits (φ) are too low to justify reclamation and all firms produce. In this situation, Y1 with and without negative taxes are optimal if governments levy $\tilde{\tau}$ equal to caribou damage (φ) per kilometre of linear features.

Case 2: in the socially optimal case, all firms produce $q_i^* > 0$ and reclaim $f_i^* > 0$ in the socially optimal case. Under Y1 with and without negative taxes, the marginal reclamation cost is lower than the marginal benefits of reclamation but the tax rates are low enough so that the tax payment never drives firms to exit (assuming no marginal firms). In this case, Y1 with and without negative taxes are optimal if governments levy $\tilde{\tau}$ equal to caribou damage per kilometre of linear features.

Case 3: in the socially optimal case, some firms produce $q_i^* > 0$ and reclaim $f_i^* > 0$, others do not produce $q_i^* = 0$ but reclaim $f_i^* > 0$ in the socially optimal case. For Y1 with negative taxes, the socially optimal outcome could be guaranteed: ①for firms ($q_i^* > 0, f_i^* > 0$), governments could set $\tilde{\tau}$ equal to per kilometre of linear features; ② for firms ($q_i^* = 0,\ f_i^* > 0$), governments could levy negative taxes (pay firms for reclaimed linear features) on these firms to allow them to reclaim the affected land. In comparison, for Y1 without negative taxes, the socially optimal outcome could only be guaranteed for firm with type ① ($q_i^* > 0, f_i^* > 0$). For firms ② ($q_i^* = 0,\ f_i^* > 0$), these firms have zero production and reclamation ($\hat{q}_i = 0\ ,\ \hat{f}_i = 0$), which is not socially optimal.

Case 4: in the socially optimal case, no firms produce $q_i^* = 0$ but all reclaim $f_i^* > 0$ in the socially optimal case. In this situation, the tax rates $\tilde{\tau}$ are relatively high so that all projects exit. Y1 with negative taxes could guarantee socially optimal outcomes by levying negative taxes on each firm, while Y1 without negative taxes will generate results that both production and reclamation would be zero ($\hat{q}_i = 0$, $\hat{f}_i = 0$).

Next, we provide detailed analysis these first order conditions (equation 34, 35) shown in the appendix.

Net Taxes are positive in each period

The last two terms in the first order condition in 34-X1 (in the appendix) define the present value of net tax per unit of output plus the reclamation cost for oilsands project i as

$$NCT_i^{X1} = \sum_{t=1}^{90} \beta^t \tau \left[\frac{P_{i0}}{q_i^{max}} + \rho_i^{pipe} + \frac{R_{i0}}{q_i^{max}} + \rho_i^r + \frac{E_{i0}^{2DL}}{q_i^{max}} + \theta\left(\frac{E_{i0}^{2D}}{q_i^{max}} + \rho_i^{2D} + \frac{E_{i0}^{3D}}{q_i^{max}} + \frac{3}{\delta_i} + \frac{E_{i0}^{4D}}{q_i^{max}} + \frac{1}{\delta_i}\right)\right] - \left[\mu_i^{pipe}\left(\frac{P_{i0}}{q_i^{max}} + \rho_i^{pipe}\right) + \mu_i^r\left(\frac{R_{i0}}{q_i^{max}} + \rho_i^r\right) + \mu_i^{2DL}\frac{E_{i0}^{2DL}}{q_i^{max}} + \mu_i^{2D}\left(\frac{E_{i0}^{2D}}{q_i^{max}} + \rho_i^{2D}\right) + \mu_i^{3D}\left(\frac{E_{i0}^{3D}}{q_i^{max}} + \frac{3}{\delta_i}\right) + \mu_i^{4D}\left(\frac{E_{i0}^{4D}}{q_i^{max}} + \frac{1}{\delta_i}\right)\right]$$

The present value of total net tax equals the present value of net tax per unit of output multiplying by q_i^{X1}. This means that projects have to pay a tax based on all linear features on their license area as long as they enter the industry and start to produce bitumen. The net taxes plus reclamation cost in the case X1 over 3 periods are greater than zero if firms produce $q_i > 0$.

To prove that net taxes are positive each period we consider two cases:

Case 1: $\mu_i = 0$. In this case, no reclamation occurs.

The first term (everything before the minus sign) in NCT_i^{X1} is greater than zero, the second term cancelled out; therefore, we have $NCT_i^{X1} > 0$.

Case 2: $\mu_i > 0$. Take pipelines as an example.

$$\sum_{t=1}^{90} \beta^t \tau \left[\frac{P_{i0}}{q_i^{max}} + \rho_i^{pipe}\right] - \left[\mu_i^{pipe}\left(\frac{P_{i0}}{q_i^{max}} + \rho_i^{pipe}\right)\right]$$

$$= \sum_{t=1}^{90} \beta^t \tau \left[\frac{P_{i0}}{q_i^{max}} + \rho_i^{pipe}\right] - \left[\left(\sum_{t=61}^{90} \beta^t \tau - \beta^{30} p^{pipe}\right)\left(\frac{P_{i0}}{q_i^{max}} + \rho_i^{pipe}\right)\right]$$

$$= \sum_{t=1}^{90} \beta^t \tau \left[\frac{P_{i0}}{q_i^{max}} + \rho_i^{pipe}\right] - \sum_{t=61}^{90} \beta^t \tau \left[\frac{P_{i0}}{q_i^{max}} + \rho_i^{pipe}\right] + \left(\beta^{30} p^{pipe}\right)\left(\frac{P_{i0}}{q_i^{max}} + \rho_i^{pipe}\right)$$

$$= \sum_{t=1}^{60} \beta^t \tau \left[\frac{P_{i0}}{q_i^{max}} + \rho_i^{pipe}\right] + \left(\beta^{30} p^{pipe}\right)\left(\frac{P_{i0}}{q_i^{max}} + \rho_i^{pipe}\right) > 0$$

The key step in the second line is to substitute the net benefit of pipeline reclamation for μ_i^{pipe}. Similar situations apply for roads, 2D legacy seismic lines, 3D seismic lines, 4D seismic lines, and we have $NCT_i^{X1} > 0$. Any tax reduction from reclamation occurs later than the initial reclamation. Following the same process, we also find that $NCT_i^{Y1} > 0$, indicating the net taxes of Y1 case is also larger than 0. However, $NCT_i^{X1} > NCT_i^{Y1}$ because we have $\frac{P_{i0}}{q_i^{max}}$ in X1, and it is positive.

Case X1 creates a higher cost of entry than Case Y1

Therefore, we understand that under the tax case X1, if oilsands projects enter the industry, the net cost of tax (tax cost and reclamation cost) is greater than zero. Furthermore, if the tax rate τ increases, the present value of net cost of tax per unit of output NCT_i^{X1}also increases. At some tax level, μ_i^{qX1} for some projects i that are positive will turn to zero, and this indicates in the case of X1, it is possible for the tax scheme to make some firms exit and stop them from producing bitumen and reclaiming linear features. Therefore, in the case of X1 where firms are responsible for all (both legacy and new) linear features on the landscape, it is not possible to have the situation where $q_i = 0$, and $f_{is} > 0$. However, under the socially optimal case, this is possible. Therefore, the tax case X1 may not bring about a socially optimal outcome. We prove this by first illustrating the net present value of resource for a firm i under case Y (μ_i^{qY1}) is greater than the net present value of resource for the same firm i under case X (μ_i^{qX1}). Therefore, it is possible that $\mu_i^{qY1} > 0 > \mu_i^{qX1}$, and we show it in figure 2.1 in the appendix.

Therefore, it is possible that $\mu_i^{qX1} < 0 < \mu_i^{qY1}$. In case Y1, we have $q_i^{Y1} > 0$, and at least for some project i, we have $f_{is}^{Y1} > 0, s = 1,2,3$, and we get socially optimal levels. In comparison, in case X1, we have $q_i^{X1} = 0$, and from the constraint $L_{is} \geq 0, s = 1,2,3$, we have $f_{is}^{X1} = 0, s = 1,2,3$. This indicates that we exclude some projects that should produce and reclaim linear features, leading to a departure from the socially optimal allocation outcome. To briefly summarize, case X1 creates a higher cost of entry to firms than case Y1, which leads to fewer than the optimal number of firms producing and reclaiming.

Case X1'

In case X1, legacy linear features are present in the first order conditions for production (q_i) as an additional marginal cost of production, and therefore, firms' entry decisions are affected (i.e. whether $q_i > 0$ or $q_i = 0$). In Y1 there might be separate reclamation firms that pay negative taxes to governments when reclamation benefits arise and exceed reclamation costs. In X1 we can still get the same outcome in terms of q_i and f_i only if we provide an up-front subsidy to have $q_i^* \geq 0, f_i^* \geq 0$. This is defined as case X1' with an up-front subsidy. Without the subsidy there is an assumption that reclamation needs to be paid by firms' profits in X1.

$$\mathbf{max}_{q_i,f_{is}}\ \pi_i = \sum_{t=1}^{90} \beta^t\,(p-\omega)q_i - FC_i(q_i) - RC(f_{i0}, f_{i1}) - \tau_i^T(L_{i1}, L_{i2}, L_{i3}) + \sigma_i q_i \tag{33'}$$

where σ_i is the subsidy per unit of output in the period of 0. This case is equivalent to case Y1 because we have τ, σ to have the optimal solutions that are the same to τ in case Y1.

Reclamation Regulations: The Firm's Case with a Tax on Linear Features

Alberta regulations require each project to reclaim their linear features at the end of period 1 and we have the same constrains in equation (from 25-1 to 25-6). The firm could reclaim legacy 2D seismic lines (f_{i0}^{2DL}) and new 2D lines (f_{i0}^{2D}) at the end of the period 1. However, as shown in equation 35 (in the appendix), there are several possibilities for firms to choose which kind of linear features to reclaim under the tax case with the end of project reclamation regulations. Here, we restrict reclamation inequalities (from 35-1 to 35-8) to be equalities for pipelines, roads, 2D legacy seismic lines, 2D seismic lines, 3D seismic lines, and 4D seismic lines. For pipelines, roads, 3D seismic lines, and 4D seismic lines, firms are required to do the reclamation only at the end of the period 1; for 2D legacy seismic lines, 2D seismic lines, firms could choose to reclaim at s=0 or conform to the requirement that the reclamation is implemented by the end of the period 1.

Summary

In this section we have shown that under the competitive equilibrium (the current situation), firms produce more output than is socially optimal, and create more linear features and caribou damage (the externality) than the socially optimal level. We have also shown that when taxes are used to address the externality, whether the firms are responsible for legacy linear features (case X1) or not responsible for legacy linear features (case Y1), socially optimal outcomes can arise. But the optimal outcomes cannot be guaranteed in case X1 or Y1 because high taxes may have impacts on entry and exit of firms.

In case Y1 firms are not responsible for legacy linear features and these lines are treated like a fixed cost of entry. Negative taxes are required to guarantee socially optimal outcomes. In case X1 firms are responsible for the adverse impact of legacy linear features, and these linear features are regarded as a variable cost of entry. An up-front subsidy is needed to achieve socially optimal outcomes.

In the next section, we examine the tax-refund approach (cases X2 and Y2) to assess whether they can produce socially optimal outcomes, and whether they can improve upon the no-tax (competitive) case.

3.5 The tax-refund scheme

We have shown that negative taxes or up-front subsidies are required to guarantee optimality under tax schemes (X1 and Y1). However, these may be politically unacceptable and the firms may not want to engage in a pure tax scheme. Perhaps a different mechanism could be publically acceptable where firms would also be willing to participate. This motivates the tax-refund scheme. Here, we examine whether or not the tax-refund scheme X2 is better than the competitive case in terms of allocations of production and reclamation.

Before we define a tax-refund equilibrium, we first define the total tax pool over 3 periods:

$$\tau^T(L_1, L_2, L_3) = \sum_i^n \tau_i^T(L_{i1}, L_{i2}, L_{i3})$$

and the tax used for refund over period 1 (the first thirty years):

$$\tau_1^T(L_1) = \sum_i^n \tau_{i1}^T(L_{i1}) = \tilde{\beta}^{30} \sum_i^n \tau L_{i1}$$

, for all i. $\tau_i^T(L_{i1}, L_{i2}, L_{i3})$ is defined above.

In addition, we define $\tau_{i1}^T(L_{i1} + \sum_{j \neq i}^n \bar{\bar{L}}_{j1})$ as above.

A tax-refund equilibrium is $\{(\bar{\bar{q}}_{it}, \bar{\bar{f}}_{it})_{\forall it} \in R_+^{2*n}\}$ such that for each firm i, $(\bar{\bar{q}}_{it}, \bar{\bar{f}}_{it})$ solves the individual firm's profit maximization problem. The individual firm's problem is described as

$$\max_{q_i, f_{is}} \pi_i = \sum_{t=1}^{90} \beta^t (p-\omega) q_i - FC_i(q_i) - RC(f_{i0}, f_{i1}) - \tau_i^T(L_{i1}, L_{i2}, L_{i3})$$

$$+ \sum_{t=1}^{30} \beta^t \tau_1^T \left(L_{i1} + \sum_{j\neq i}^{n} \bar{\bar{L}}_{j1} \right) d \frac{q_i}{q_i + \sum_{j\neq i}^{n} \bar{\bar{q}}_j}$$

(36)

Case X2 constraints:

Responsible for legacy lines

s.t. These equations are exactly the same in the tax case X1

Case Y2 constraints:

Not responsible for legacy lines

s.t. These equations are exactly the same in the tax case Y1

Note: for $\tau_i^T(L_1, L_2, L_3)$, under the case X2, it is $\tau_i^T(L_1^q, L_2^q, L_3^q)$; under the case Y2, it could be written as $\tau_i^T(L_1^{-q}, L_2^{-q}, L_3^{-q})\ \forall i$, where $L_s = (L_{1s}, \dots, L_{is}, \dots, L_{ns})$ s=1,2,3 and $L_{is} = P_{is} + R_{is} + E_{is}^{2DL} + \theta(E_{i1}^{2D} + E_{i1}^{3D} + E_{i1}^{4D})$ for all i and s=1,2,3; $f_s = (f_{1s}, \dots, f_{is}, \dots, f_{ns})$ s=1,2 and f_{is} is a 6*n vector with components $f_{is}^{pipe}, f_{is}^{r}, f_{is}^{2DL}, f_{is}^{2D}, f_{is}^{3D}, f_{is}^{4D}$ for all i and s=1,2. We notice that $\sum_i^n \frac{q_{is}}{q_{is} + \sum_{j\neq i}^n \bar{\bar{q}}_{js}} = \sum_i^n \frac{q_{is}}{Q_s}$, where $\bar{\bar{Q}}_s = q_{is} + \sum_{j\neq i}^n \bar{\bar{q}}_{js} = \sum_{i=1}^n \bar{\bar{q}}_{js}$, for all i. In addition, we have $\bar{\bar{L}}_s = L_{is} + \sum_{j\neq i}^n \bar{\bar{L}}_{js} = \sum_{i=1}^n \bar{\bar{L}}_{js}$, for all i. In this scheme, we let d be the proportion of tax revenue that is used as refunds, and $d \in [0,1]$. In this model, we do not consider administration fees related to the implementation of such a tax-refund scheme. The last term in the objective function shows that the amount of refund that an in-situ project gets is based on its share of bitumen production in the in-situ oilsands industry during period 1. The summation sign indicates the total refund that an in-situ oilsands project gains in the entire period. In addition, we know that there is no bitumen production during periods 2 and 3, so the in these two periods, the tax-refund scheme is the same as the tax scheme where the tax rate is τ^*.

The Lagrange equation for firm's problem under the tax refund in case X2 scheme is:

$$La^{tr} = \sum_{t=1}^{90} \beta^t[(p-\omega)q_i] - FC_i(q_i) - RC(f_{i0}, f_{i1}) - \tau_i^T(L_{i1}, L_{i2}, L_{i3})$$

$$+\sum_{t=1}^{30} \beta^t \tau_1^T\left(L_{i1} + \sum_{j\neq i}^{n} \bar{\bar{L}}_{j1}\right) d \frac{q_i}{q_i + \sum_{j\neq i}^{n} \bar{\bar{q}}_j} + \mu_i^q(q_i^{max} - q_i) +$$

$$\mu_i^{pipe}\left(P_{i0}\frac{q_i}{q_i^{max}} + \rho_i^{pipe} q_i - f_{i1}^{pipe}\right) + \mu_i^r\left(R_{i0}\frac{q_i}{q_i^{max}} + \rho_i^r q_i - f_{i1}^r\right) + \mu_i^{2DL}\left(E_{i0}^{2DL}\frac{q_i}{q_i^{max}} - \right.$$

$$\left. f_{i0}^{2DL} - f_{i1}^{2DL}\right) + \mu_i^{2D}\left(E_{i0}^{2D}\frac{q_i}{q_i^{max}} + \rho_i^{2D} q_i - f_{i0}^{2D} - f_{i1}^{2D}\right) + \mu_i^{3D}\left(E_{i0}^{3D}\frac{q_i}{q_i^{max}} + \frac{3}{\delta_i} q_i - \right.$$

$$\left. f_{i1}^{3D}\right) + \mu_i^{4D}\left(E_{i0}^{4D}\frac{q_i}{q_i^{max}} + \frac{3}{\delta_i} q_i - f_{i1}^{4D}\right) \quad (36')$$

where μ_i^q is the marginal value (shadow price) of bitumen reserves for oilsands project i, $\mu_i^{pipe}, \mu_i^r, \mu_i^{2DL}, \mu_i^{2D}, \mu_i^{3D}, \mu_i^{4D}$ are the shadow price of one kilometre of pipelines, roads, 2D legacy seismic lines, 2D seismic lines, 3D seismic lines, 4D seismic lines. The Lagrange equation for firm's problem in case Y2 under the tax-refund scheme is identical to the case X2 with the exception of the existence of $\frac{q_i}{q_i^{max}}$ for linear feature terms. This means that in case X2 we treat the legacy linear features as variable, while in case Y2, the problem is close to the social planners' problem where firms could just engage in reclamation activities (without bitumen production), and we allow for a subsidy or negative tax that is borrowed from taxpayers. In addition, an equilibrium occurs when all in-situ oilsands projects have maximized non-negative profits and each oilsands project takes other projects' bitumen output and reclamation decisions as given.

Under the current case, the set of operating firms will satisfy the non-negative profit condition. Under the tax case, the set of operating firms will satisfy the condition that profits less taxes is larger than or equal to zero. Under the tax-refund case, the set of operating firms will satisfy the condition that profits less taxes plus refunds is larger than or equal to zero.

First order conditions with respect to q_i, μ_i, and f_{is} are shown in the appendix part 3 “The tax-refund scheme”.

In order to know whether the tax-refund system (Y2) will generate the same outcome (Y1) in terms of output (q_i) and reclamation (f_i), we set $\mu_i^{qY1} = \mu_i^{qY2}$. If $q_i^* = \bar{\bar{q}}_i, f_i^* = \bar{\bar{f}}_i, \forall\, i$, we have a socially optimal outcome.

In order to simplify μ_i^{qY1} in the equation 34-Y1, we set A $= \sum_{t=1}^{30} \beta^t (p - \omega) - \left(\frac{3c^{3D}}{\delta_i} + \frac{c^{4D}}{\delta_i} + \frac{I_i}{q_i^{max}}\right)$, is the net benefit from operation, $\tilde{\beta}^{90}\boldsymbol{\rho_i} = \sum_{t=1}^{90} \beta^t \left[\rho_i^{pipe} + \rho_i^r + \theta\left(\rho_i^{2D} + \frac{3}{\delta_i} + \frac{1}{\delta_i}\right)\right]$, is the net present value of taxes (assuming no reclamation), $\boldsymbol{c}$ is a 5*n vector with elements $(\beta^{30}p^{pipe}, \beta^{30}p^r, p^{2D}, \beta^{30}p^{3D}, \beta^{30}\, p^{4D})$, indicating the reclamation cost, $\boldsymbol{\beta}$ is a 5*n vector with accumulative discount rates $(\sum_{t=61}^{90} \beta^t, \sum_{t=61}^{90} \beta^t, \sum_{t=31}^{90} \beta^t, \sum_{t=61}^{90} \beta^t, \sum_{t=61}^{90} \beta^t)$, indicating the length of time of tax reductions from reclamation, $\boldsymbol{\rho}$ is a 5*n vector with elements $(\rho_i^{pipe}, \rho_i^r, \theta\rho_i^{2D}, \frac{3\theta}{\delta_i}, \frac{\theta}{\delta_i})$, the length of linear features available for reclamation per unit of bitumen output, $\widetilde{\boldsymbol{\beta}}^{\mathbf{30}}\boldsymbol{\rho_i} = \sum_{t=1}^{30} \beta^t \left[\rho_i^{pipe} + \rho_i^r + \theta\left(\rho_i^{2D} + \frac{3}{\delta_i} + \frac{1}{\delta_i}\right)\right]$, $\mathrm{s}_i = \frac{q_i}{q_i + \sum_{j \neq i}^{n} \bar{\bar{q}}_j}$ (output share), $\mathcal{L}_i = L_{i1} +$

$\sum_{j\neq i}^{n} \bar{\bar{L}}_{j1}$, $D'(\mathrm{s}_i) = \frac{\sum_{j\neq i}^{n} \bar{\bar{q}}_j}{\left(q_i + \sum_{j\neq i}^{n} \bar{\bar{q}}_j\right)^2}$ (derivative of output share). With these substitutions, we obtain a condensed form of 34-Y1 and 37-Y2:

$$\mu_i^{qY1} = A - \tau^* \tilde{\beta}^{90} \boldsymbol{\rho_i} + (-\boldsymbol{c} + \boldsymbol{\beta}\tau^*)\boldsymbol{\rho_i} \geq \mathbf{0} \quad \text{if } q_i^* > 0 \tag{38-Y1}$$

Suppose $q_i^* = 0$, $A - \tau^* \tilde{\beta}^{90} \boldsymbol{\rho_i} + (-\boldsymbol{c} + \boldsymbol{\beta}\tau^*)\boldsymbol{\rho_i} < \mathbf{0}$.

$$\mu_i^{qY2} = A - \bar{\bar{\tau}} \tilde{\beta}^{90} \boldsymbol{\rho_i} + (-\boldsymbol{c} + \boldsymbol{\beta}\bar{\bar{\tau}})\boldsymbol{\rho_i} + \bar{\bar{\tau}}\bar{\bar{d}}[\boldsymbol{\tilde{\beta}^{30}\rho_i}\mathrm{s}_i + \tilde{\beta}^{30}\mathcal{L}_i D'(\mathrm{s}_i)] \geq 0 \tag{38-Y2}$$

Set $\mu_i^{qY1} = \mu_i^{qY2}$, we have

$$\tau^* \boldsymbol{\tilde{\beta}^{90}\rho_i} - \boldsymbol{\beta}\tau^* \boldsymbol{\rho_i} = \bar{\bar{\tau}} \boldsymbol{\tilde{\beta}^{90}\rho_i} - \boldsymbol{\beta}\bar{\bar{\tau}}\boldsymbol{\rho_i} - \bar{\bar{\tau}}\bar{\bar{d}}[\boldsymbol{\tilde{\beta}^{30}\rho_i}\mathrm{s}_i + \tilde{\beta}^{30}\mathcal{L}_i D'(\mathrm{s}_i)]$$

$$\tau^* = \bar{\bar{\tau}}\left(1 - \frac{\bar{\bar{d}}[\boldsymbol{\tilde{\beta}^{30}\rho_i}\mathrm{s}_i + \tilde{\beta}^{30}\mathcal{L}_i D'(\mathrm{s}_i)]}{(\boldsymbol{\tilde{\beta}^{90}} - \boldsymbol{\beta})\boldsymbol{\rho_i}}\right) \tag{39}$$

If we pick $\bar{\bar{d}}, \bar{\bar{\tau}}$ outside of the restrictions imposed by $0 < \bar{\bar{d}} \leq 1$, and $\tau^* = \bar{\bar{\tau}}\left(1 - \frac{\bar{\bar{d}}[\boldsymbol{\tilde{\beta}^{30}\rho_i}\mathrm{s}_i + \tilde{\beta}^{30}\mathcal{L}_i D'(\mathrm{s}_i)]}{(\boldsymbol{\tilde{\beta}^{90}} - \boldsymbol{\beta})\boldsymbol{\rho_i}}\right)$, we cannot guarantee that the solution is Pareto optimal. In other words, we want to know the possible range of $\bar{\bar{\tau}}, \bar{\bar{d}}$.

Characterising possible $\bar{\bar{\boldsymbol{\tau}}}, \bar{\bar{\mathbf{d}}}$(Proof of the optimality of Y2)

We want to implement a tax-refund scheme, and we want to pick $\bar{\bar{\tau}}, \bar{\bar{d}}$ such that $\mu_i^{qY1} = \mu_i^{qY2}$. This could be true if all projects have the same bitumen production. However, if projects are different in production, we need to have a less strict restriction.

If $q_i^* > 0$, instead of setting $\mu_i^{qY1} = \mu_i^{qY2}$, we want

$$\mu_i^{qY1}(\tau^*) > 0, \mu_i^{qY2}(\bar{\bar{\tau}}, \bar{\bar{d}}) > 0 \tag{40}$$

for all i. Therefore, the question is, could we find $\bar{\bar{\tau}}, \bar{\bar{d}}$ to make equation 40 true for all i.

We consider two cases:

Case 1: $0 < \mu_i^{qY1}(\tau^*) = \mu_i^{qY2}(\bar{\bar{\tau}}, \bar{\bar{d}})$

From the equation 39, we have $0 < 1 - \frac{\bar{\bar{d}}[\boldsymbol{\widetilde{\beta}^{30}\rho} s_i + \widetilde{\beta}^{30}\mathcal{L}_i D'(s_i)]}{(\boldsymbol{\widetilde{\beta}^{90} - \beta})\boldsymbol{\rho}} \leq 1$. Rewrite $1 - \frac{\bar{\bar{d}}[\boldsymbol{\widetilde{\beta}^{30}\rho} s_i + \widetilde{\beta}^{30}\mathcal{L}_i D'(s_i)]}{(\boldsymbol{\widetilde{\beta}^{90} - \beta})\boldsymbol{\rho}}$ as $1 - \bar{\bar{d}}\kappa_i$. So, $0 \leq \bar{\bar{d}} \leq \frac{1}{\kappa_i}$ or $0 \leq \bar{\bar{d}} \leq 1$ for a particular i. For all oilsands projects, we have $0 \leq \bar{\bar{d}} \leq \min_i \left(\frac{1}{\kappa_i}\right)$ or $0 \leq \bar{\bar{d}} \leq 1$. In addition, if $\kappa_i \leq 1$ for all projects i, then we could have a full refund scheme ($\bar{\bar{d}} = 1$) and guarantee socially optimal outcomes. On the other hand, if $\kappa_i > 1$ for any given i, then we cannot have a full refund system and we are unable to guarantee socially optimality. In this case, although it is possible to have the refund share $0 \leq \bar{\bar{d}} \leq \min_i \left(\frac{1}{\kappa_i}\right)$, the tax-refund scheme is indistinguishable from a pure tax case if $\min_i \left(\frac{1}{\kappa_i}\right)$ is close to or approaches zero.

Case 2: $0 < \mu_i^{qY1}(\tau^*) < \mu_i^{qY2}(\bar{\bar{\tau}}, \bar{\bar{d}})$

We have

$$\tau^* < \bar{\bar{\tau}}\left(1 - \frac{\bar{\bar{d}}[\boldsymbol{\widetilde{\beta}^{30}\rho_i} s_i + \widetilde{\beta}^{30}\mathcal{L}_i D'(s_i)]}{(\boldsymbol{\widetilde{\beta}^{90} - \beta})\boldsymbol{\rho_i}}\right)$$

$$0 \leq \bar{\bar{d}} < \frac{1}{\kappa_i} \qquad (41)$$

For both cases, we have to choose $0 \leq \bar{\bar{d}} < \min_i \left(\frac{1}{\kappa_i}\right)$, and $\bar{\bar{d}} \leq 1$. Once we have $\bar{\bar{d}}$, we could pick $\bar{\bar{\tau}} \geq \frac{\tau^*}{1 - \bar{\bar{d}}\kappa_i}$. In this case, Y2 could be optimal. However, we understand that in practice, if $\bar{\bar{d}}$ is close to 0, and $\bar{\bar{\tau}}$ is close to τ^*, this defeats the premise of the tax-refund scheme which is that firms are not willing to engage in the pure tax scheme so will likely not be willing to engage in a tax-refund scheme that is indistinguishable from the tax scheme. When we want the refund share $\bar{\bar{d}}$ to be significantly different from 0, Y2 is sometimes not optimal if there is firm i that has $\kappa_i > 1$. For example, the maximum κ_i in the empirical simulation for 317 oilsands projects is 2.33. This indicates that we are not able to find $0.43 < \bar{\bar{d}}_i \leq 1$ for this firm and guarantee that the scheme is optimal.

Case X2 and comparing X2 with Y2

Following the same process, we wish to know if X2 is more likely to generate optimal results or not. Equation (41) also applies but the difference lies in $\boldsymbol{\rho_i}$ and $\mathcal{L}_i$. In case X2, $\boldsymbol{\rho_i} = \frac{P_{i0}}{q_i^{max}} + \rho_i^{pipe} + \frac{R_{i0}}{q_i^{max}} + \rho_i^r + \frac{E_{i0}^{2DL}}{q_i^{max}} + \theta\left(\frac{E_{i0}^{2D}}{q_i^{max}} + \rho_i^{2D} + \frac{E_{i0}^{3D}}{q_i^{max}} + \frac{3}{\delta_i} + \frac{E_{i0}^{4D}}{q_i^{max}} + \frac{1}{\delta_i}\right)$, and $\mathcal{L}_i$ includes all of the legacy lines, including pipelines, roads, 2D legacy seismic lies. Empirical results for κ_i in X2 and Y2 are shown in the table 3-1.

Table 3-1 the statistical summaries of κ_i in the case Y2 and case X2

	min	max	average
κ_i (Y2)	0.16	2.33	0.88
κ_i (X2)	0.16	4.47	1.09

This table shows that most κ_i are larger in X2 than in Y2. This shows that although X2 could generate optimal results for some oilsands projects, Y2 has a higher possibility of achieving Pareto optimal results for more projects. In addition, although κ_i in X2 is larger than those in Y2, we assume that X2 will not collapse to the pure tax scheme.

Since we cannot guarantee that the tax-refund case produces optimal outcomes, it is possible to show that it produces better outcomes than the competitive case even if we deviate from the conditions on $\bar{\bar{d}}$ and $\bar{\bar{\tau}}$ imposed by equation 39. Suppose $\kappa_i > 1$ or $1/\kappa_i < 1$. We understand that a tax-refund system may be driven to a pure tax case. If we disallow this and propose a second best alternative that a full refund system with $\bar{\bar{d}} = 1$, we examine whether the allocation $(\bar{\bar{q}}_i, \bar{\bar{f}}_i)$ under the second best tax-refund scheme will be better than the competitive case.

Compare Y2 with the competitive case

Here we compare possible allocations under the competitive and tax refund cases to determine if the tax-refund case improves on the competitive case.

<u>Case 1</u>: Suppose all firms produce $q_i > 0$, and generate no reclamation $f_i = 0$ in both competitive and Y2 cases. The marginal damage is too low for the social planner to set reclamation greater than zero. In this case, the competitive case is optimal and Y2 is also optimal with taxes set to zero and refunds set to 1.

<u>Case 2</u>: Suppose all firms produce $q_i > 0$ and reclaim $f_i > 0$ in the socially optimal case, while all firms produce in the competitive case but do not reclaim $f_i = 0$ since there is no incentive to reclaim. Under the socially optimal case, the marginal reclamation cost is lower than the marginal benefits of reclamation but the marginal damages are low enough so that the social planner never sets $q_i = 0$ for any firm (assuming no marginal firms). In this case, Y2 without subsidy cannot be guaranteed to be optimal as shown above. However, it may be possible to find a tax-refund combination that keeps each firm in the industry and also gets at least some reclamation. The competitive case is not

optimal because reclamation is always zero. For the Y2 case, we set $\bar{\bar{d}} = 1$, and then we want to pick $\bar{\bar{\tau}}$ so that

$$\mu_i^{qY2} = A - \bar{\bar{\tau}}\tilde{\beta}^{90}\boldsymbol{\rho_i} + (-\boldsymbol{c} + \boldsymbol{\beta}\bar{\bar{\tau}})\boldsymbol{\rho_i} + \bar{\bar{\tau}}\left[\tilde{\boldsymbol{\beta}}^{\mathbf{30}}\boldsymbol{\rho_i}\mathrm{s}_i + \tilde{\beta}^{30}\mathcal{L}_i D'(\mathrm{s}_i)\right] \geq 0, \ \forall i,$$

and $(-\boldsymbol{c} + \boldsymbol{\beta}\bar{\bar{\tau}})\boldsymbol{\rho_i} >= 0$ for at least one oilsands project.

Case 3: Suppose some firms produce $q_i > 0$ and reclaim $f_i > 0$, others do not produce $q_i = 0$ but reclaim $f_i > 0$ in the socially optimal case, while all firms produce $q_i > 0$ but do not reclaim $f_i = 0$ in the competitive case. In this situation, the marginal damages are relatively high so that there are some firms that exit. The marginal reclamation cost is lower than the marginal benefits of reclamation. The competitive case is not optimal because reclamation is always zero. For the Y2 case, we set $\bar{\bar{d}} = 1$, and the refund could at least keep some firms in business ($q_i > 0$) and doing reclamation ($f_i > 0$). Although the number of firms staying in the industry in Y2 might be different from that in the optimal case, the remaining firms will reclaim, and this improves the social outcome compared with the competitive case.

Case 4: Suppose no firms produce $q_i = 0$ but all reclaim $f_i > 0$ in the socially optimal case, while all firms produce $q_i > 0$ in the competitive case but do not reclaim $f_i = 0$. In this case, the marginal damages are fairly high so that all projects exit. The competitive case is not optimal as firms produce and do not reclaim. For the Y2 case, we set $\bar{\bar{d}} = 1$, and the refund could at least keep some firms in business ($q_i > 0$) and doing reclamation ($f_i > 0$). The number of firms staying in business is greater than zero but less than that in the competitive case, and those remaining firms would reclaim their linear features. Fewer firms and more reclamation would provide improvement in social outcome compared with the competitive case.

To briefly summarize, in most cases, Y2 cannot guarantee Pareto optimal outcomes but it can provide improvement compared with the competitive case.

Compare X2 with the competitive case

The four cases are exactly the same as shown above when we compare Y2 and the competitive case with the exception that firms in X2 are responsible for legacy linear features. If damages from these legacy linear features are minimal, X2 will be close to Y2, and those four cases mentioned above also apply to X2. If these linear features play an important role in measuring all linear features for which firms are responsible, then although the improvement arising from X2 may be less significant than Y2, X2 could provide improvement in terms of an allocation $(\bar{\bar{q}}_i, \bar{\bar{f}}_i)$ compared with the competitive case under those four cases mentioned above.

Summary

In most cases, Y2, the case where firms are not responsible for legacy linear features and a tax-refund scheme is used to address the caribou externality, can generate socially optimal outcomes if Y2 is close to Y1; it can also provide improvement compared with the competitive case. Furthermore, X2 (tax-refund with firms responsible for legacy linear features) is less likely to generate socially optimal results compared with Y2, but it can improve on the no-tax (competitive) case. Earlier in this chapter it was shown that under the competitive equilibrium (the current situation), firms produce more output than is socially optimal, and create more linear features and caribou damage (the externality) than the socially optimal level. It was also shown that when taxes are used to address the externality (cases X1 and Y1), socially optimal outcomes can arise. However, this tax approach may require negative taxes or an up-front subsidy to generate socially optimal outcomes because of the possibility of firms exit. This summarizes the theoretical results of the four cases (X1, X2, Y1, and Y2), their potential to achieve socially optimal outcomes, and their comparison to the no-tax (competitive) case.

In the next chapter where we focus on the empirical simulation, we assume that governments will not borrow money from tax-payers (no lump sum subsidies), and that firms are responsible for their legacy linear features and the impact of legacy seismic lines affect their entry decisions (indicated by case X1 and X2). We take in-situ oilsands projects in the north Alberta as our sample, and examine whether or not X2 (tax-refund) could improve the allocation relative to the competitive case. We leave other cases (such as Y1 and Y2) for future research.

4 Data and Methods

This chapter focuses on the estimation of land damage using data on the economic benefits of caribou conservation. In addition, a detailed analysis of bitumen prices that are chosen for use in the simulations is presented. Data on existing and planned in-situ oilsands projects are also described in this chapter. Based on these components, the simulation framework is constructed and important assumptions are outlined.

This chapter mainly focuses on simulation framework. We intend to explore the impact of the tax and tax-refund cases on a series of in-situ oilsands projects with heterogeneity that may be built on the caribou ranges. The heterogeneity of in-situ projects in various ways will generate a range of costs and varying impacts on caribou. Therefore, in the simulation framework we generate a number of heterogeneous projects by simulating a number of important variables that affect caribou existence and the costs of projects. These variables include land damages, bitumen prices, bitumen production, and linear features per in-situ oilsands project.

4.1 Estimation of damage function

4.1.1 Caribou population model

Caribou, a low population density species, prefer and rely on an old type of forest habitat. However, factors including mountain fires, clearcuts, and linear features remove this type of habitat and alter it, making it possible for their predators to prey. A statistical model has been used to represent the influence on caribou habitat, including the impact of linear features, on caribou population growth rates over a herd range (Schneider et al., 2010;

Hauer et al., 2018). The model uses forest area less than 30 years age and linear features to predict caribou population growth rate. This section uses the caribou population model to derive the marginal impact of linear features on caribou population growth rates.

Although predator-prey relationships are not explicitly analyzed in the model, it is assumed that the relationships between the increase in caribou population and their predators, like wolves, are largely affected by habitat. The growth rate of the population of caribou (lambda) is described as a function of linear features and young forest area (Schneider et al., 2010; Hauer et al., 2018). Specifically, λ_{nt} is defined as the annual growth rate for caribou herd n at year t, and the caribou population of one herd at year $t+1$ is equal to the caribou population at year t multiplying by λ_{nt}. The value of λ_{nt} can change based on firms' energy activities and reclamation efforts, and this implies a change in the population of caribou at the stock level. L_{nt} is the length of effective linear features (roads, pipelines and seismic lines that generate land damage – or adverse effects on caribou) for the herd n at year t; $Area_{n\bar{t}}$ denotes the geographical area (kilometre square) of herd n, which is assumed to be constant over the years in this paper; $Den_{nt} = L_{nt}/Area_{nt}$ indicates the density of linear features in kilometre per kilometre square for herd n at year t; A_{nt} represents the proportion of the area with young forest less than thirty years of age to the total area for herd n at year. We understand that other factors, such as unexpected fires and clear-cuts, may have a significantly negative impact on the caribou population growth rate, but we exclusively focus on the linear features in the present study.

In the habitat lambda model, the linear function consists of two variables:

$$\lambda_{nt} = 1.0184 - 0.0234 * Den_{nt} - 0.0021 * A_{nt} \tag{42}$$

where Den_{nt}, showing the density of linear features in km per km2 of caribou range. The habitat lambda shows that the caribou growth rate decreases with the increase in energy resource development through linear feature development and forest harvesting, indicating that natural forest ageing and oil sands firms' reclamation of linear features could result in caribou population increasing annually and after thirty years (the age required to result in no negative effects on caribou), respectively. The estimated population size and the growth rate for woodland caribou in Alberta can be found in Table 4.1 based on equation (42) and the data in Schneider et al. (2010) and Hauer et al. (2018). As the table suggests, the estimated growth rates are currently less than 1 for all of these twelve herds.

Table 4.1 Estimated caribou population and λ (the growth rate) for caribou herds in Alberta (Harper, 2012)

Herds	Population	λ
Bistcho	195	0.89
Slave Lake	64	0.91
Caribou Mountains	350	0.92
Red Earth	190	0.92
Little Smoky	78	0.92
Cold Lake	150	0.93
East of A River	120	0.93
Chinchaga	250	0.94
Yates	350	0.95
Nipisi	56	0.95
Richardson	150	0.96
West of A River	240	0.99

The marginal impact of effective linear features on the growth rate can be derived through manipulation of the habitat lambda equation with respect to the length of effective linear features:

$$\frac{\partial \lambda_{nt}}{\partial D_{nt}} = -0.0234 \tag{43}$$

This means that one more kilometre per kilometre square of effective linear feature decreases the caribou population growth rate by the amount 0.0234. In practice this is reflected through the construction of new roads, pipelines, as well as intensive modern seismic lines that can cause damage to caribou habitat, thereby posing a threat to the number of caribou.

4.1.2 Economic benefits (Willingness To Pay) for marginal increases in the caribou growth rate

The economic benefits of caribou protection cannot be determined through observable market transactions because conventional markets for endangered species valuation do not exist (Hanemann, 1994; Grafton et al., 2008). Studies have shown that people may value these species even if they never expect to see them. These kinds of value are commonly referred to as existence values, or passive use values (Freeman et al., 2014). These values could be determined through nonmarket valuation using stated preference techniques where individuals are asked to reveal their willingness to pay (WTP) for alternative caribou conservation programs (Adamowicz et al., 1998; Harper, 2012).

In this thesis, we obtain the estimates of the economic value of improving caribou populations based on Harper (2012), and these estimates are used to understand what the cost of damaging caribou habitat is. These estimates could be regarded as economic benefits for caribou if firms do reclamation. Benefits are defined as the marginal willingness to pay for the reclamation of a caribou herd to a self-sustaining state ($\lambda \geq 1$). The valuation of caribou reclamation benefits is based on individual (household) responses to survey questions that are scaled up to the provincial level by multiplying the estimates of household marginal benefits by the total number households in Alberta in 2016 which was 1,527,675 (Statistics Canada, 2016).

A marginal increase in lambda is defined as an increase of 0.01 of the caribou population growth rate, which could be defined as one marginal unit. Marginal units for each caribou herd are shown in Table 4.2. The average willingness to pay for a marginal unit for all herds (MWTP, 5.41 million) can be derived by dividing the sum of Albertans' willingness to pay for reclamation by the total number of marginal units.

Table 4.2 The growth rate (**λ**), marginal units, size of range area, provincial willingness to pay for caribou herds in Alberta, and the marginal willingness to pay for one unit (0.01) increase in **λ** [2](Harper, 2012; Hauer et al., 2018)

Herds	λ	marginal units	WTP (Million)	Area(km2)
Bistcho	0.89	11	84.02	13267
Slave Lake	0.91	9	68.75	1497
Caribou Mountains	0.92	8	61.11	15328
Red Earth	0.92	8	53.47	19977
Little Smoky	0.92	8	51.94	2927
Cold Lake	0.93	7	45.83	5538
East of A River	0.93	7	39.72	14524
Chinchaga	0.94	6	36.66	17517
Yates	0.95	5	24.44	4489
Nipisi	0.95	5	0.00	1915
Richardson	0.96	4	-15.28	6546
West of A River	0.99	1	-22.92	15010
sum	-	79	427.75	-
WTP for 0.01 increase in λ	-	-	5.41	-

A quadratic specification of the provincial benefit for the herd variable is adopted to allow for decreasing marginal values, which is consistent with economic theory. The negative terms of the last two herds are generated as a result of the quadratic term and this term is used to capture decreasing marginal utility. However, it doesn't make sense theoretically for the term to become negative. If we impose a constraint on the estimation process that keeps the marginal willingness to pay non-negative, then these negative terms are replaced with zeros, and the average marginal willingness to pay for 0.01

[2] We also calculate the marginal willingness to pay for one unit (0.01) increase in λ based on the linearization assumption where people have approximately constant willingness to pay for per unit increase in λ, and on the assumption that the reclamation of linear features is one useful and effective method to increase caribou population.

increase in lambda increases from 5.41 million to 6.75 million. We use an average willingness to pay across all the herds as a measure for numerical simulation.

Therefore, the land damage per kilometre of effective linear features for each herd area can be derived by multiplying equation (43) by 6.75 million, as shown in equation (44).

$$\begin{aligned}
&Annual\ land\ damage_n \\
&= Willingness\ to\ pay\ for\ a\ marginal\ unit\ of\ \ \lambda \left(\frac{\frac{\$million}{year}}{0.01increment_{lamba}} \right) \\
&* \left(-marginal\ impact\ of\ linear\ features\ on\ \lambda \left(\frac{increment_{lambda}}{km\ linear\ features} \right) \right) \\
&= \$6.75\ * \frac{0.0234}{Area_{n\bar{t}}} \left(\frac{\frac{\$100million}{year}}{km\ linear\ features} \right) \qquad (44)
\end{aligned}$$

Table 4.3 Caribou herd area and land damage per kilometre of effective linear features for caribou herds per year

Herds	Area(km2)	Land damage($/year/km)
Bistcho	13267	1191
Slave Lake	1497	10551
Caribou Mountain	15328	1030
Red Earth	19977	791
Little Smoky	2927	5396
Cold Lake	5538	2852
East of A River	14524	1088
Chinchaga	17517	902
Yates	4489	3519
Nipisi	1915	8248
Richardson	6546	2413
West of A River	15010	1052
Average	12319	1639

As shown in table 4.3, the land damage that can be generated by an additional kilometre of effective linear feature lies in the range of $791 to $10551. The variation in damage across the herds is due to the form of the habitat lambda equation where the impacts of linear features are expressed as a density over the herd range (km/km2). This means that a kilometre of new linear features will have a lesser impact on caribou population growth in a herd occupying a large range than on the growth of a herd occupying a small range. Since most of the in-situ oil sands projects are located in five habitat ranges including East Athabasca River, West Athabasca River, Cold Lake, Richardson, and Red Earth, the average land damage of an additional kilometre of effective linear feature in these five caribou ranges is $1639, and the range of damage is [$791, $2852].

4.2 Data on bitumen price

Different bitumen prices are used to create several valuation cases. We first construct a data series on bitumen price, and then estimate a bitumen price distribution to find a number of critical price levels that can be used in the simulation model.

Data on bitumen prices produced in Alberta can be derived from the world crude oil price (Energy Information Administration, 2019) that is indicated by the price of West Texas Intermediate (WTI). For the analysis conducted here, quarterly data on historical and predicted WTI prices from 2001 to 2020 are adjusted by GDP deflators, and the year 2010 is assigned as the base year. The exchange rate between the U.S. dollar and the Canadian dollar is assumed to be fixed at 1.3 during the entire period.

Generally, WTI is priced as light oil with a low level of sulphur and other impurities, and its price serves as a benchmark in the world oil market. By comparison, bitumen and/or dilbit (short for diluted bitumen) extracted from oil sands deposits in Alberta belong to the heavy crude category and have a higher proportion of sulphur per barrel. While bitumen may be regarded as an intermediate product that can be upgraded to a synthetic light oil, this is a costly process, and is one reason that bitumen products are priced at a discount to lighter oils such as WTI. In addition, most bitumen in Alberta is delivered into the US and requires transportation via pipeline over a relatively long distance (Cortés et al., 2018). This increases the discounted price of bitumen at extraction sites in northern Alberta (Alberta Energy Regulator, 2019). In this paper, the bitumen netback is priced at a discount of 50% to WTI.

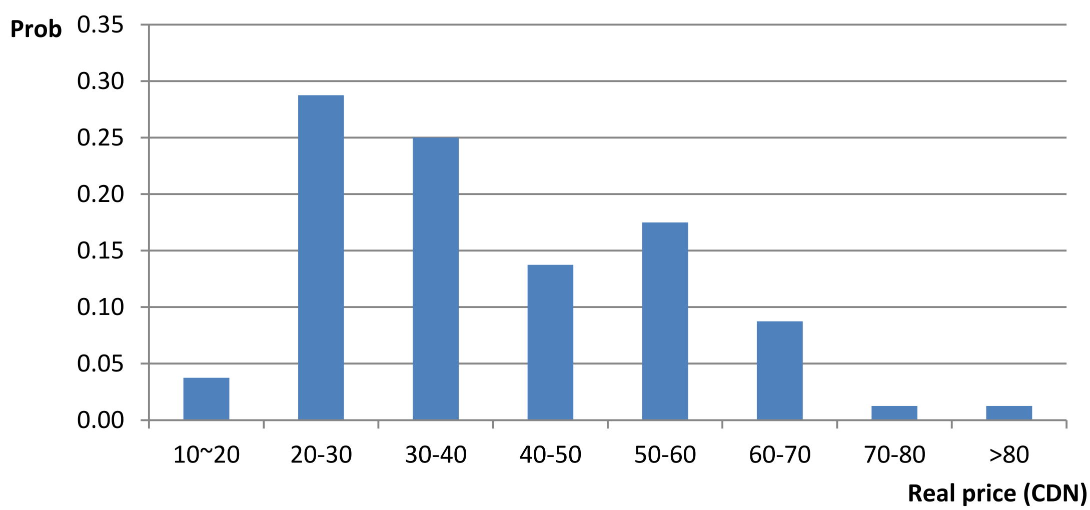

Figure 4.1 Probability distribution of quarterly bitumen prices from 2001 to 2020 (Alberta Energy, 2018; Energy Information Administration, 2019)

As figure 4.1 suggests, based on historical data, the real bitumen price mainly lies in a range between \$20 and \$70, and the prices for bitumen have been in the range of 20 and 40 about 50% of the time historically. We will use these data to estimate a bitumen price distribution through which we can draw a series of typical prices. These prices will be employed in the simulation model to examine the welfare change in accordance with these bitumen prices.

We fit the real price distributions to a variety of statistical distributions to determine the best fitting statistical distribution (Matlab, Version 2019a). Several distributions are selected, including a normal distribution, Weibull distribution, lognormal distribution, and gamma distribution. These distributions were fitted to the historical data through the distribution fitting tool in Matlab. The results in Table 4.4 show that the log-normal distribution gives the highest value of Log Likelihood, and therefore it is chosen to serve as the bitumen price distribution.

Table 4.4 Fitting results of a variety of distributions concerning historical bitumen prices

Distribution	Log Likelihood	Parameter	std. Err.	Parameter	std. Err.
Normal	-331.99	mu=40.30	1.73	sigma=15.44	1.23
Weibull	-329.87	A=45.36	1.89	B=2.84	0.24
Lognormal	-327.33	mu=3.63	0.04	sigma=0.39	0.03
Gamma	-327.54	A=6.98	1.08	B=5.77	0.92

Note: The log-likelihood values and estimates of critical parameters and their standard error are shown.

Fifty prices are drawn from the lognormal distribution with the price level of bitumen per barrel from \$13.81 to \$93.99. The mean price (\$41.32) is also drawn from the distribution. Sensitivity analysis is implemented in the next chapter.

4.3 In-situ project data

In addition to bitumen prices, data on existing and planned in-situ projects are also required, including bitumen thickness and the area of a bitumen project.

Specifically, project level data on in-situ oil sands activities are based on Hauer et al. (2018), where a reference in-situ project for bitumen extraction covers an area of a quarter township, approximately 2330 ha, over a 32 year period. The dataset consists of two types of projects: “old” projects that have already been built, and “new” projects that are predicted to be built (Hauer et al., 2018). Each project has the production period of 28 years with 3 cycles, and wells produce for 10 years with 1 year overlap between them. It takes five years before production begins due to engineering planning, infrastructure construction, and planting (Hauer et al., 2018).

Some potential projects are situated such that they intersect more than one caribou range. In the multi-herd case the damage estimate for an increment of linear features was constructed as a weighted average of the damage for each herd based on the fraction of the project area intersecting each herd. In addition, projects not intersecting caribou range boundaries were not considered and thus were not represented in the simulation model. Furthermore, There are 363 existing and planned in-situ projects in northern based on the data that we have, but considering the our main focus is the impact of linear features on caribou, we assume that the impact of linear features related to in-situ projects located outside of caribou ranges is zero. Based on these calculations, 317 projects are selected and defined as our sample with the information about their location in caribou habitat, areas that they cover, thickness of bitumen deposits, as well as the type of projects (whether they are existing or planned ones).

4.4 The simulation framework and key assumptions

Data on bitumen output (q_i), linear features (L_i), costs (c_i, FC_i, RC_i), and profits (π_i) are described in this section. A series of assumptions used are also listed in this section.

4.4.1 Bitumen output

Data from in-situ oilsands projects show that there are a variety of different sizes of projects with different numbers of wells on project areas with varying bitumen thicknesses. However, we do not have a full accounting of all the possible projects or the variability of those projects that could arise on the landscape. This is partly due to the fact that there are many possible future projects that have not been undertaken and we want to model those as well as existing projects. Yet, we expect to have variability of production per project in these potential projects.

To model the potential output variability we create some heterogeneous projects by choosing various project attributes from uniform distribution, roughly based limited data that we have on existing projects on observed ranges (Alberta Energy Regulator, 2018). The number of wells per project (w_i) is generated according to a uniform distribution between 20 and 40. The bitumen production per well (φ_i) is related to bitumen deposit thickness, and we assume a rough and consistent inventory of thicknesses by a quarter townships, although we understand that thickness may vary within 1/4 townships.

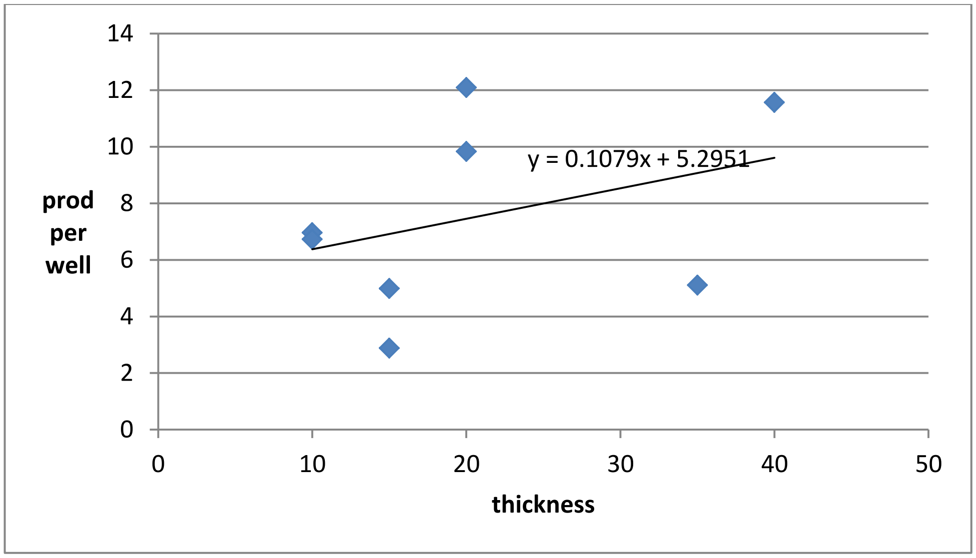

Figure 4.2 The relationship between bitumen thickness and production per well for several real bitumen extraction projects from project reports (Alberta Energy Regulator, 2018)

From Figure 4.2 we find that the production level per well (φ_i) generally has a positive relationship with the thickness of bitumen deposit since thicker deposits mean more resources available to extract. A typical project located in a 40 meter thickness area has an expected production of 9.6 thousand cubic meter per year, nearly 1.3 times a project in 20 meter thickness area with 7.5 thousand cubic meter per year. Therefore, the simulated data on production per well for each in-situ project is generated according to a summation of a normal distribution part and a bitumen thickness part. For bitumen thickness part we allow the simulated data on production per well to follow the same increasing trend in thickness shown above (the slope being around 0.1). We derive the average production per well (approximately 12,000m3/year) based on total bitumen production from in-situ projects (Canadian Association of Petroleum Producers, 2018).

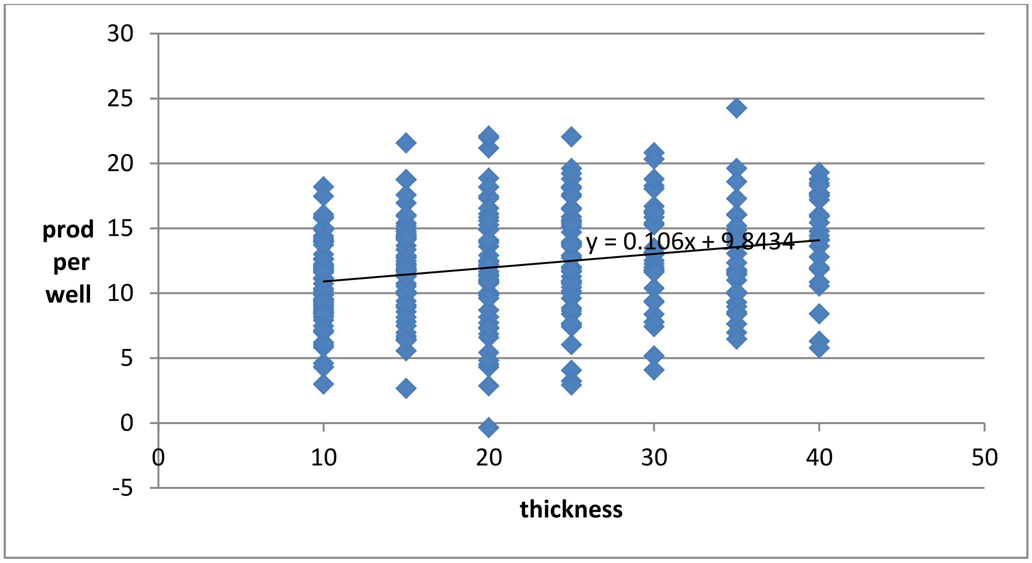

Figure 4.3 The relationship between bitumen deposit thickness and production per well from simulated projects

From the graph shown above, a typical project located in a 40 meter thickness area has an expected production of 13.9 thousand cubic meter per year, approximately 1.3 times a project in a 20 meter thickness area which yields 11.2 thousand cubic meter per year. Compared with the project reports, our simulation data show that the production per well increases. The increase in the production level per well may be attributable to drilling and extracting technology improvement with time.

Bitumen production per project (q_i) is derived from the product of the number of wells each project (w_i) and the production (1000m3) per well (φ_i) per year. The total production of bitumen from 363 in-situ projects is 2.31 billion cubic meters per year, which is relatively close to the forecasted estimate of 2.46 billion cubic meters per year in 2035, as forecasted by the Canadian Association of Petroleum Producers (2018).

4.4.2 Linear Features

Most projects in our sample are located in five caribou habitats: Richardson, Cold Lake, East Athabasca River, West Athabasca River, and Red Earth. The range size, linear feature disturbance density, and the percentage of young forest of each herd were obtained from Hauer et al. (2018), and Schneider et al. (2010).

Table 4.5 Range size, linear disturbance density, and percentage of young forest for five caribou herds (Hauer et al., 2018; Schneider et al., 2010)

Herd	Range Size (km2)	Seismic (km/km2)	Roads (km/km2)	Pipelines (km/km2)	Young Forest (%)
Cold Lake	5538	0.89	0.02	0.24	30.0
Richardson	6546	0.86	0.01	0.01	16.9
East Athabasca River	14524	1.49	0.05	0.24	24.6
West Athabasca River	15010	1.00	0.05	0.13	3.3
Red Earth	19977	1.98	0.05	0.07	27.1

Since the linear feature density data are updated to 2006, we assume that the seismic lines on the land for each herd include legacy 2D seismic lines (E_{i0}^{2DL}) and the lines built by old projects ($E_{i0}^{2D},\ E_{i0}^{3D},\ E_{i0}^{4D}$). The establishment of new projects will add to the density of seismic lines ($e_{i0}^{2D}, e_{i0}^{3D}, e_{i0}^{4D}$), roads ($r_{i0}$), and pipelines ($p_{i0}$). It is assumed that the proportion of young forest that is less than thirty years old is fixed over the 60-year study period.

Some of the projects are located within caribou habitat, while others are located on the edge. We assume that on average, the edge projects will have half the impact of projects fully inside the caribou range. Therefore, 1km of new linear feature for an edge project will add effectively only a 0.5 km new linear feature to the herd.

Simulated data on 2D legacy seismic (E_{is}^{2DL}), roads (R_{is}), and pipelines (P_{is}) are generated based on a uniform distribution with some heterogeneity for each in-situ bitumen project, and the summation of these data on linear features should be no greater than the overall data shown in Table 4.5, since the in-situ bitumen project area in one caribou herd may not cover all linear disturbances in that herd. The data on new 2D seismic lines (E_{is}^{2D}) are based on project reports like the Hangingstone project (2018) and on the assumed correlation between the number of wells eventually built and the length of new 2D seismic lines. The data on 3D seismic lines (E_{is}^{3D}) are based on distributions derived from project reports such as the Jackfish SAGD project (2018). The 3D seismic in these reports is counted by area (km2), which is then translated into length (km) based on Cooper, N. M. (1997). In addition, the length of 4D seismic lines (E_{is}^{4D}) is assumed to be one third of that of 3D seismic lines (E_{is}^{3D}) per project based on data from selected in-situ bitumen extraction projects (Alberta Energy Regulator, 2018). 4D seismic lines (E_{is}^{4D}) are considered to complement bitumen deposit surveillance techniques, and to reduce the uncertainty level of associated with monitoring process (Niri, 2018).

All linear features are assumed to be fully built in t=0, and early reclamation includes reclaiming all 2D legacy (E_{i0}^{2DL}) and all new 2D seismic lines (E_{i0}^{2D}). Seismic lines, often built in the period of project development in the search for oil resources, are the most common industrial linear features on the land and should be reclaimed because they are generally not needed after their initial use (Schneider et al., 2010). The new 2D, 3D, and 4D seismic lines (E_{is}^{2D}, E_{is}^{3D}, E_{is}^{4D}) are expected to have a significantly lower impact compared with the 2D legacy seismic (E_{is}^{2DL}) because they are much narrower and relatively invisible. Their existence may provide far less signal or clue for caribou predators, like wolves, to follow the escaping caribou (Harper, 2012). Here, we assume that 0.05 is the impact coefficient (θ) for new 2D, 3D, and 4D seismic lines. Due to the expected improvement in seismic technology in the future, this parameter is smaller than 0.1 that is used in Hauer et al. (2018).

4.4.3 Cost function

Total cost per project consists of variable costs (c_i) and fixed costs (FC_i). The variable cost component (c_{it}) reflects the cash costs of operation, while the fixed cost (FC_i) includes cost associated with production: plant establishment cost (A_i), well cost (cw), capital depreciating fees ($\sum_{t=1}^{30} \beta^t * \sigma * A_i$), the renewal of wells of two cycles ($(\beta^{10}+\beta^{20}) * w_i * cw$).

Based on the data on in-situ bitumen extraction projects (Hauer et al., 2018), the variable cost c_{it} of producing a barrel of bitumen for a reference project is \$13.39, which is consistent with estimates by Rahnama et al. (2008) and the estimates from Giacchetta et al. (2015). In this study, the variable cost of producing a barrel of bitumen is assumed to be fixed over 30 years of production. The total variable cost for each project is based on a function that defines the variable cost of producing a barrel of bitumen (ω) times the bitumen production per project per year (q_i). On average, the total variable cost for a project is \$28.89 million per productive year.

For the fixed cost (FC_i), the total plant cost can be derived by multiplying the initial plant cost per barrel of bitumen by the bitumen production for each in-situ project. The data on the initial plant cost per barrel of bitumen (\$22,056), the depreciating rate (σ, 0.0036), and the cost of building a well (cw, \$7.55 million) were obtained from the reference project based on Hauer et al. (2018). Therefore, the total fixed cost for a project (FC_i) is the summation of plant cost (A_i), capital sustaining cost ($\sum_{t=1}^{30} \beta^t * \sigma * A_i$), and the cost of changing wells (($\beta^0 + \beta^{10} + \beta^{20}) * w_i * cw$). On average, the fixed cost for a project is $484.71 million.

The reclamation cost of one kilometre of effective 2D legacy seismic lines (p^{2DL}) is around $10,000 per kilometre (Boutin, 2017). The reclamation cost of one kilometre of road (p^r) is about $20,000 (Rock to Road, 2016). The reclamation cost of one kilometre of pipeline (p^{pipe}) is about $150,000 (National Energy Board, 2018).

4.4.4 Profit function

The profit function is based on the cost of supply (c_i), revenue, tax (τL_{is}), and refund ($\tau L_i \frac{q_i}{Q_i}$) components.

The cost of supply includes fixed cost (equation 4), variable cost (equation 3), and reclamation cost (equation 6), all of which are discussed in chapter three. The revenue for each project is derived from the product of the amount of bitumen that it produces over 30 years period and the price of bitumen per unit. The mean bitumen price ($41.32) is chosen and we also select a series of prices in our simulation model.

For the land damage tax (τ), we equate the marginal land damage ($D'(L_{is})$) to the tax per kilometre of effective linear features. In principle, simulated tax levels per year should at least cover the range of land damage in these five herds [$791, $2852]. In the simulation model, we start from $1400 per kilometre of linear features because it is close to the average land damage ($1639). Then, as part of a sensitivity analysis, the tax level (τ)

varies with a successive decrease to \$0 as the minimum (the current case) and a successive increase to \$4000 as the maximum. In addition, we do not include royalties in the simulation model.

The refund parameter is set at 1 ($d = 1$), indicating that all the tax revenue collected by the provincial government will be rebated to in-situ projects. For simplification, administration fees are not included.

In the current case where there is no tax, the real profit for each project (π_i) is gained through the total revenue less the total supply cost for the entire production period ($c_i + FC_i$) and the compulsory reclamation cost (RC_i) in year 30 (objective function 13). In the pure tax case, after the gross profit is determined by total revenue minus total supply cost, a typical project would compare the tax reduction due to its reclamation on the 2D seismic at the initial period with the cost of implementing reclamation (objective function 17). In the no-tax and tax case, a profit maximizing decision would be made by each project with the assumption that other projects' reclamation behavior does not affect a typical project's reclamation decision.

In the tax-refund case, the calculation of the tax payment for each project is calculated in the same way that has been presented in the pure tax case, and the refund is computed based on the proportion of each project's bitumen production to the total amount of bitumen production (objective function 18). In this process, some marginal projects or low-productivity projects may have negative profits and exit the sector because of high tax payments or low bitumen prices (the non-negative profit condition is not satisfied). This could give rise to the emergence of an endogenous production outcome and endogenous effective linear features for each project. Specifically, if a project exits under the tax-refund scheme, it would not build linear features on land, nor would it do reclamation. In this way, endogenous bitumen production for this project is zero, and the endogenous effective linear feature for such a project is the length of 2D legacy seismic lines. This would affect the total tax pool and the amount of refund that other existing projects receive. Accordingly, these remaining projects' reclamation decisions might change. This so called "exit effect" of the tax-refund scheme on projects results in a situation where the simulation model has to be iterated based on those remaining projects in the tax-refund scheme, until an equilibrium is reached. Consequently, when no remaining projects exit, the equilibrium state (shown in chapter 3.4) has been reached and each project does not have any incentive to change its production level and reclamation decision.

Some projects will reclaim at a certain tax level (τ), and accordingly, the area suitable for caribou survival will increase, which will increase the number of caribou in the future. Therefore, the number of caribou will also be calculated based on the behavior of the energy sector under the different tax regimes.

Furthermore, the amount of social welfare (W) under all three cases can be computed. In the current case, the social welfare (W_1) is derived by subtracting the land damage costs (persisting for 60 years) from the total profit of existing projects. In the pure tax case, after the subtraction of the land damage from total profits, the resulting benefits of early reclamation from projects and/or the government will be added and we obtain W_2. In the tax-refund case, after the subtraction of the land damage from total profits, the benefits of projects' early reclamation will be accounted for in the calculation of social welfare and we obtain W_3.

To briefly summarize, three types of data concerning the land damage for each herd, historical bitumen prices, and in-situ projects are presented in this chapter, and these data are used in the simulation framework. In addition, a number of important assumptions employed in the analysis are also provided.

5 Simulation model results

Simulation results for welfare levels, firm profits, the number of existing projects, and caribou populations in 60 years are presented in this chapter for the mean bitumen price ($41.3 per barrel). In addition, these results are shown for a variety of tax levels under three different cases: the current case, the tax case, and the tax-refund case. An equilibrium state, where firms are no longer exiting the industry, is first established for all simulations. We assume that the land damage is equal to the tax rate, and simulate different levels of land damage through tax levels. We also understand from the theory chapter that the tax rate does not have to be equal to the land damage rate under the tax-refund scheme. However, for simplicity we maintain the equality of these two rates in the empirical analysis presented here.

5.1 Results at the mean bitumen price ($41.3)

Table 5.1 contains the profit levels and number of profitable projects as a function of tax schemes and rates. The total profit of in-situ bitumen projects under the tax case decreases with the tax rate because an increase in tax indicates a higher level of land damage that needs to be addressed either through tax payment or reclamation. In comparison, the total profit under the tax-refund scheme remains stable when the tax rate is below $1400 per kilometre of linear features. This is because the tax rate is relatively low and has not provided sufficient incentives for projects to reclaim their legacy and new 2D seismic lines early. In the tax-refund scheme, the total profit of these in-situ projects decreases from $202,326 million to a lower level of $201,931 million at $1400 per kilometre of linear features, after which it stays relatively stable. This means that all in-situ projects are expected to spend money on reclamation with a $1400 per kilometre of linear feature damage amount in order to save tax payments.

In addition, the number of existing firms is the same under the three different cases with a variety of tax rates, suggesting that there are no impacts of the tax-refund scheme on the number of existing projects at a bitumen price of $41.3 per barrel.

Table 5.1 Total profit and the number of existing firms with bitumen price being $41.3 per barrel

	total profit($,mi)			the number of existing projects		
tax rate	current	tax	tax-refund	current	tax	tax-refund
0	202326	202326	202326	314	314	314
200	-	202002	202326	-	314	314
400	-	201677	202326	-	314	314
600	-	201353	202326	-	314	314
800	-	201028	202326	-	314	314
1000	-	200704	202326	-	314	314
1200	-	200380	202326	-	314	314
1400	-	200086	201931	-	314	314
1600	-	199823	201931	-	314	314
1800	-	199559	201931	-	314	314
2000	-	199295	201931	-	314	314
2200	-	199031	201931	-	314	314
2400	-	198767	201930	-	314	314
2600	-	198504	201930	-	314	314
2800	-	198240	201930	-	314	314
3000	-	197976	201930	-	314	314
3200	-	197712	201930	-	314	314
3400	-	197448	201930	-	314	314
3600	-	197185	201929	-	314	314
3800	-	196921	201929	-	314	314
4000	-	196657	201929	-	314	314

As figure 5.1 shows, the total caribou population will be around 120 in sixty years without early reclamation. In comparison, the number is expected to increase to about

250 after the tax rate of $1400 per kilometre of linear features under the tax and tax-refund scheme because early reclamation is expected to be implemented by existing in-situ projects. This shows that the tax-refund scheme plays an important role in conserving caribou and restoring damaged land compared with the tax case. However, even if these projects reclaim damaged land early, the number of caribou is considerably lower than the present population (around 850) in the study area.

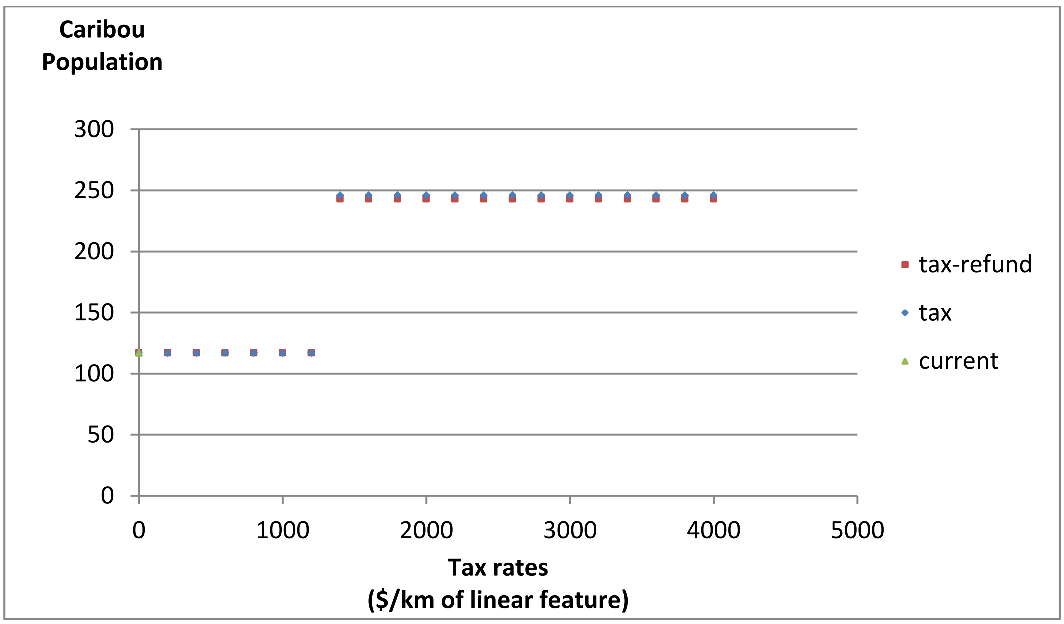

Figure 5.1 Caribou population under three cases (the current case, the tax case, and the tax-refund case) in 60 years with the bitumen price of $41.3 per barrel

In figure 5.2, W1, W2, and W3 represent economic welfare for the current case, the tax case, and the tax-refund scheme, respectively. There are two axes in this figure. The left axis presents economic welfare in millions, while the right axis indicates the differences between the tax case and the tax-refund case in terms of economic welfare. The downward trend of economic welfare with the increase in tax rate is attributable to the assumption that the land damage is equal to tax rates. There is a welfare jump at the tax rate of $1400 per kilometre of linear features. This is because all existing projects start to reclaim 2D seismic lines early and the resulting beneficial effects on caribou exceed the reclamation cost for projects. In addition, the economic welfare under the tax-refund scheme is close to the pure tax case with the welfare difference less than 1 percent of total welfare under different tax rates, showing that the tax-refund scheme is nearly economically efficient (or socially optimal) when the bitumen price is $41.3 per barrel.

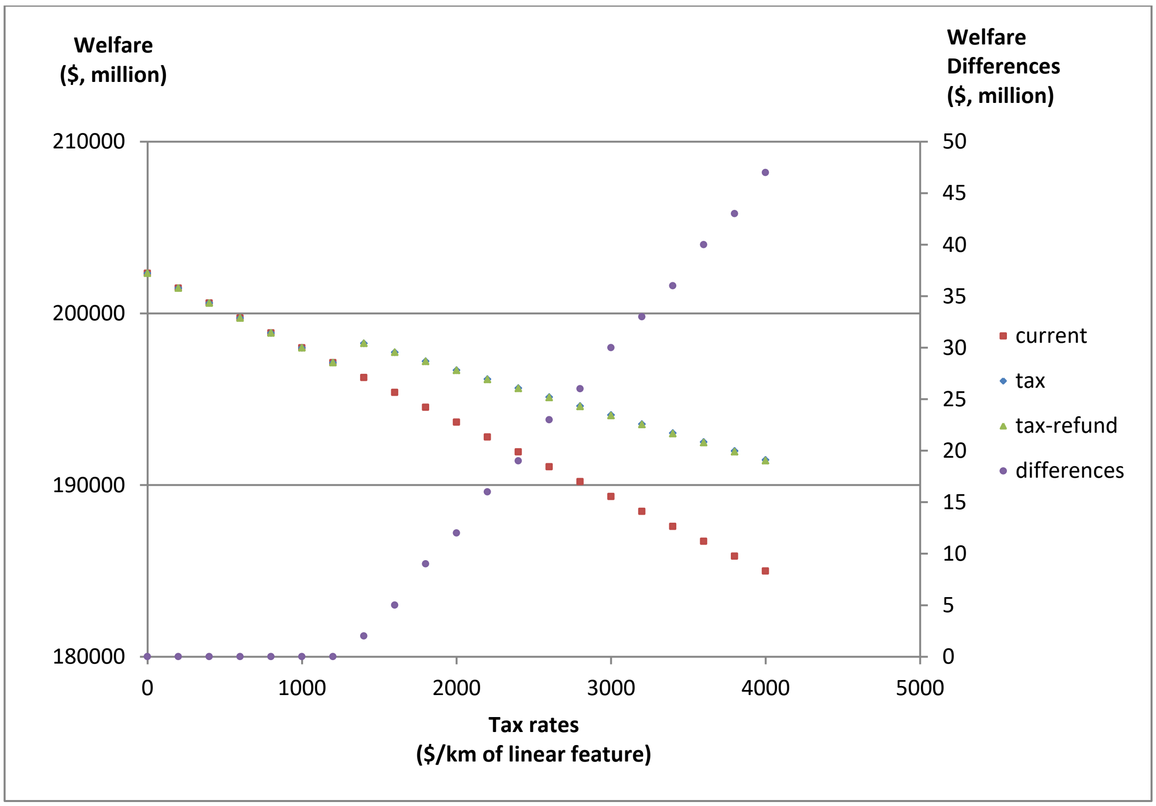

Figure 5.2 Economic welfare for three cases (the left axis) under three cases (the current case, the tax case, and the tax-refund case) for the entire 60-year period with the bitumen price of $41.3 per barrel (the difference between the tax and tax-refund scheme is on the right axis)

5.2 Simulation Results based on bitumen price distribution

The simulation results in this section are based on 50 draws from the bitumen price distribution shown in chapter 4. Given two tax levels ($1400 and $800 per kilometre of linear feature), the relationships between bitumen prices and several important indicators for three cases are presented in this section, including total profits, the number of existing firms, caribou populations in 60 years, and economic welfare.

5.2.1 Results for a tax rate of $1400 per kilometre of linear features

As shown in chapter 4, the marginal land damage per kilometre of linear features for five caribou herds is estimated to be $1639 per year. Therefore, $1400 is chosen to explore the relationship between bitumen prices and other indicators.

There are two axes in the figure 5.3. The left axis presents the total profit of the oilsands industry in millions, while the right axis indicates the differences between the tax case and the tax-refund case in terms of total profit in millions. Overall, the total profit of in-situ bitumen projects grows with the increase in bitumen prices, showing that higher prices result in more profit. In addition, the total profit of these projects under the tax-refund case is fairly close to that under the tax case with less than 1 percent of profit difference, indicating that the tax-refund scheme does not markedly affect the overall profitability for the in-situ oilsands industry in Alberta.

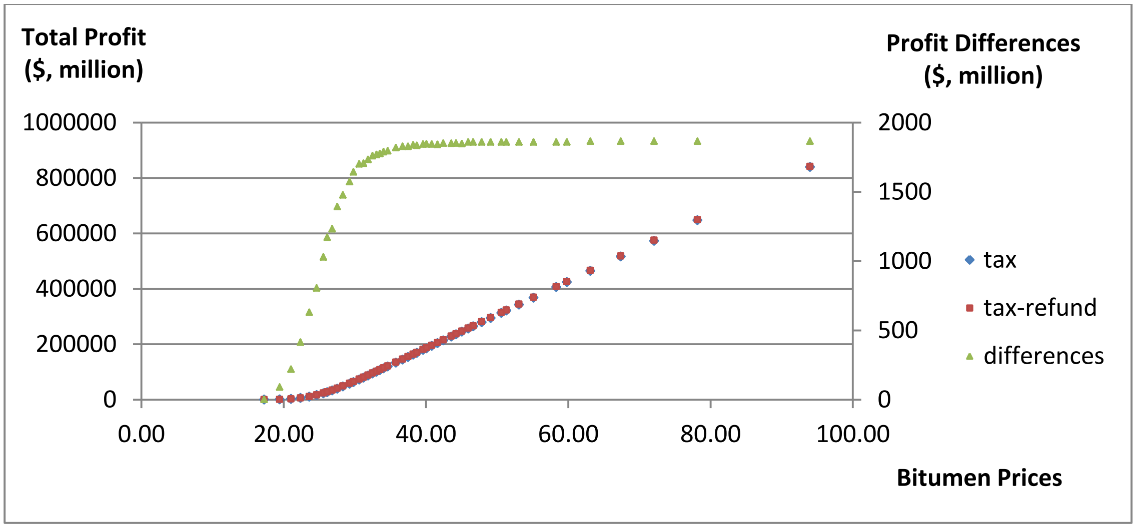

Figure 5.3 The relationship between the total profit of in-situ bitumen projects (the left axis) and bitumen prices for the tax case and the tax-refund case with the tax rate of $1400 per kilometre of linear features (the difference between the tax and tax-refund scheme is on the right axis)

There are two axes in the figure 5.4. The left axis presents the number of existing projects, while the right axis indicates the differences between the tax case and the tax-refund case in terms of the number of existing projects. Overall, the number of existing projects increases with the growth in bitumen prices because higher prices make more projects profitable. When the bitumen price is as low as $20 per barrel, few projects survive; when the price rises to $30 per barrel, over 90 percent of projects are able to profitably produce bitumen. The number of existing projects is similar under the tax case and the tax-refund case with the difference less than 6 firms, which demonstrates that the impact of the tax-refund scheme on firm exit is relatively low.

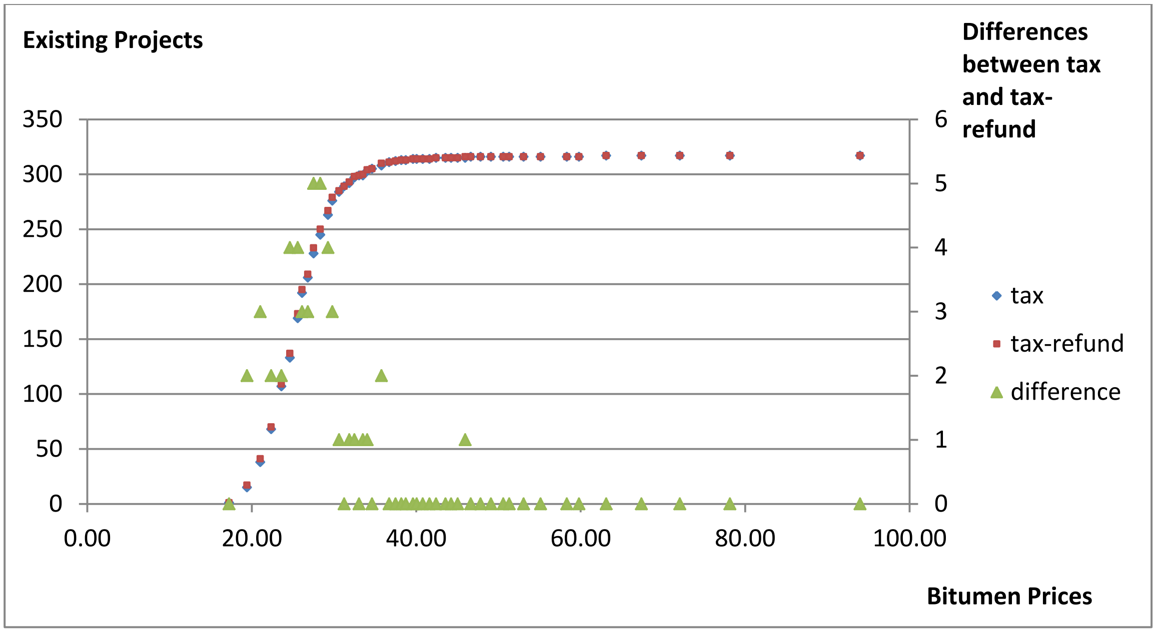

Figure 5.4 The relationship between the number of existing in-situ bitumen projects (the left axis) and bitumen prices for the tax case and the tax-refund case with the tax rate of $1400 per kilometre of linear features (the difference between the tax and tax-refund scheme is on the right axis)

The relationship between bitumen prices and caribou populations in 60 years shows different trends under different scenarios. Under the tax-refund scheme, the number of caribou in 60 years in Alberta increases steadily as the price of bitumen per barrel increases from $20 to $30. When the price is higher than $30 per barrel, the number remains relatively stable at around 240. In comparison, although the number of caribou in the tax case is similar to that in the tax-refund scheme when the bitumen price is below $25, such a figure increases markedly to around 260 above $25. This is because we assume that the government will reclaim the remaining legacy linear features if oilsands projects exit under the tax case. The caribou number declines slightly with the increase in bitumen prices and converges to around 240.

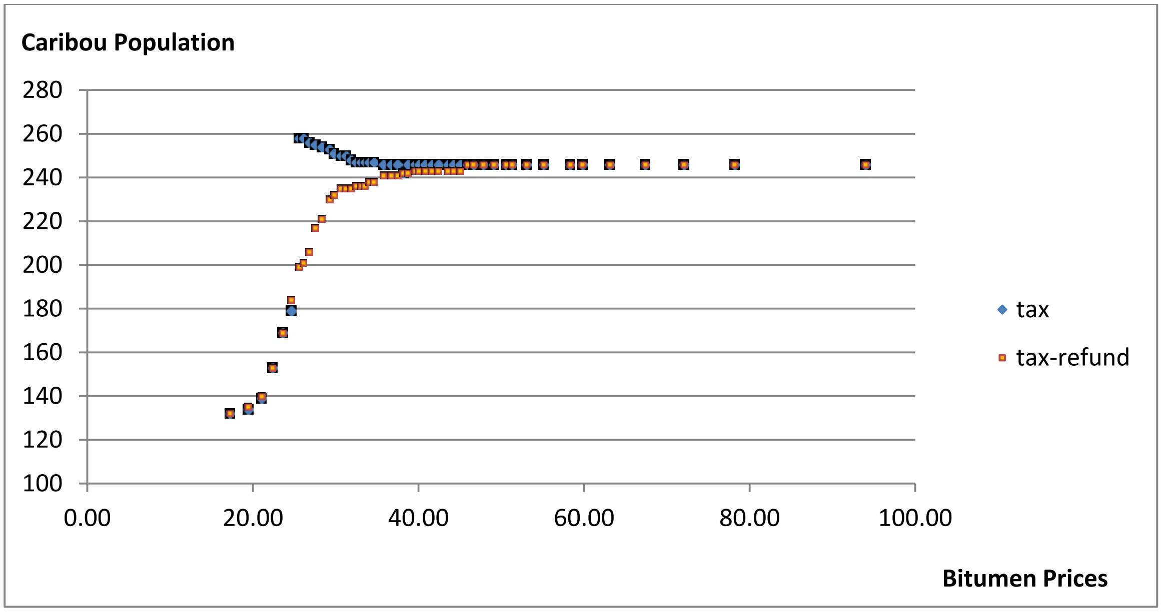

Figure 5.5 The relationship between caribou populations and bitumen prices for two cases (the tax case and the tax-refund case) with the tax rate of $1400 per kilometre of linear features

The figure 5.6 has two axes: the left axis presents the economic welfare, while the right axis indicates the welfare improvement from the current case to the tax-refund scheme. Overall, the economic welfare increases with bitumen prices for the three cases (the current case, the tax case, and the tax-refund case). The economic welfare under the tax-refund scheme improves compared with the current case with bitumen prices in the range from $17 to $93. This shows that in principle, the tax-refund scheme could bring about a relatively satisfactory economic outcome with little adverse economic impact.

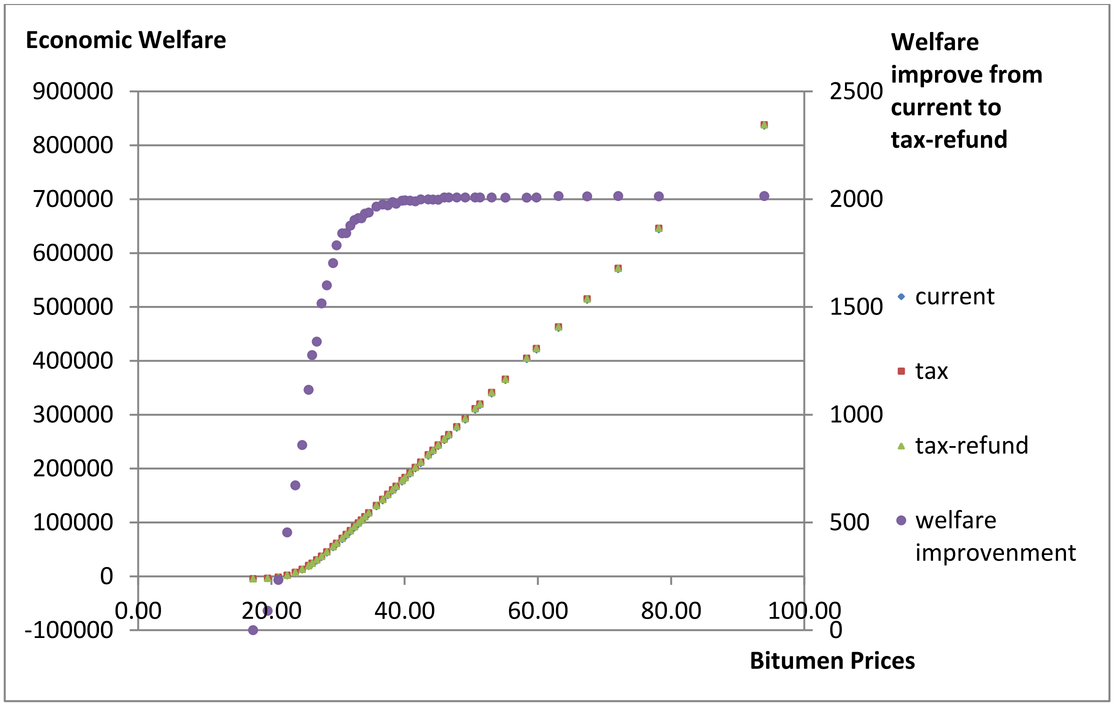

Figure 5.6 The relationship between economic welfare (the left axis) and bitumen prices for three cases (the current case, the tax case, and the tax-refund case) with the tax rate of \$1400 per kilometre of linear features (the difference between the tax-refund scheme and the current case is on the right axis)

Therefore, \$1400 per kilometre of linear features is sufficient to provide incentives for in-situ oilsands projects to implement reclamation of 2D seismic lines in order to conserve an improved (relative to the current situation) number of boreal caribou in these regions of Alberta. In addition, there are similar results for welfare levels, firm profits, number of existing projects, and caribou populations in 60 years with higher tax rates, like \$3000 per kilometre of linear features.

5.2.2 Results of a tax rate of $800 per kilometre of linear features

In comparison, when the tax rate is $800 per kilometre of linear features, no oilsands projects will choose to reclaim 2D seismic lines. This is because the discounted tax payment is far less than the 2D seismic line reclamation cost (around $10,000 per kilometre). In this case, the relationships between total profits, the number of existing projects, and bitumen prices are similar to the case with the tax rate of $1400 per kilometre of linear features, but the levels of caribou in 60 years, economic welfare, and bitumen prices show different patterns.

If no new oilsands projects are built at present, the number of caribou in the five herd areas in 60 years will be 132. This number decreases steadily with the increase in bitumen prices because higher prices make it possible for more projects to be profitable. When the price is higher than $35 per barrel of bitumen, the caribou population becomes 117. These numbers are applicable to both the tax case and the tax-refund case. Although we assume that governments will reclaim 2D seismic lines if in-situ projects do not reclaim these linear features under the tax case, the authority fails to collect sufficient funds to implement reclamation due to high reclamation costs.

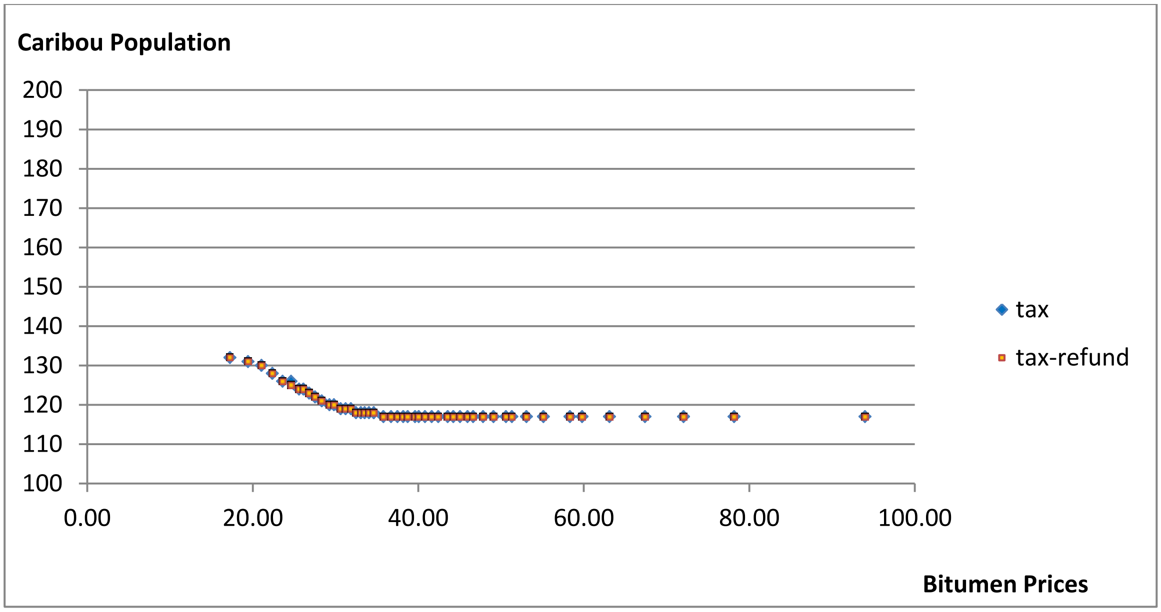

Figure 5.7 The relationship between caribou population and bitumen prices for two cases (the tax case and the tax-refund case) with the tax rate of $800 per kilometre of linear features

The economic welfare for three different cases (the current case, the tax case, and the tax-refund case) remains the same under the same bitumen price because the tax payment and refunding process are "income transfers" from different entities, which fail to bring about caribou habitat reclamation and economic welfare improvement.

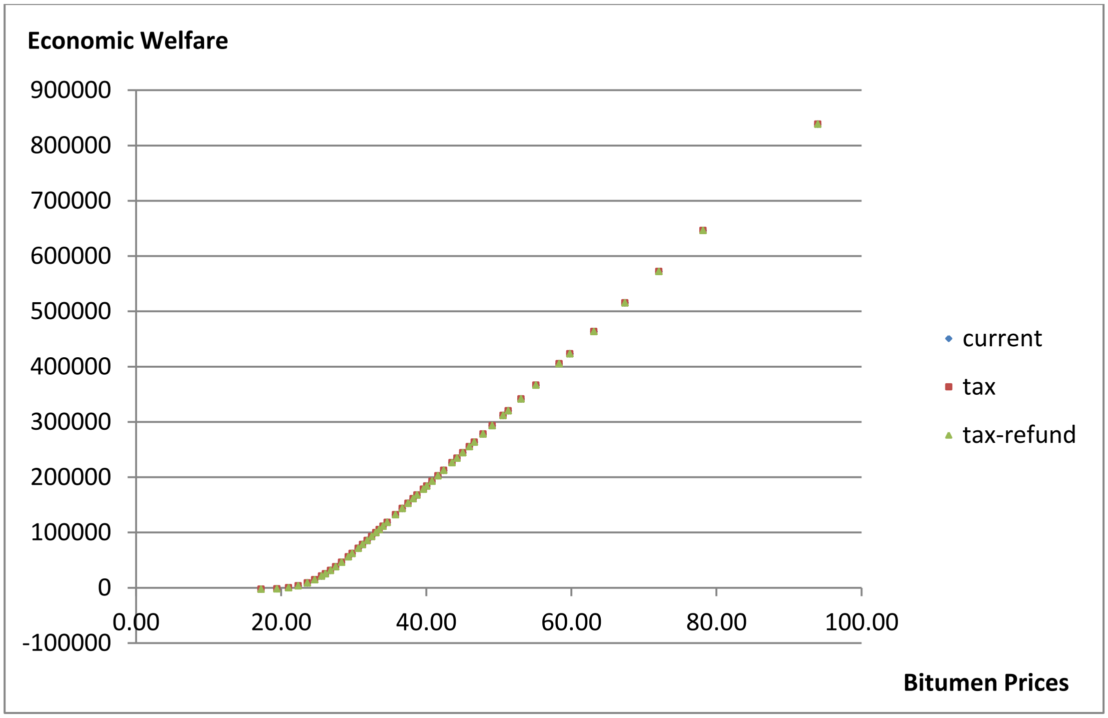

Figure 5.8 The relationship between economic welfare and bitumen prices for three cases (the current case, the tax case, and the tax-refund case) with the tax rate of $800 per kilometre of linear features

In conclusion, the tax-refund scheme could generate satisfactory economic welfare results that are fairly close to economic optimality (the tax case), and the scheme may lead to little adverse economic impact if the market structure is close to perfect competition. $1400 per kilometre of linear features provides sufficient incentives for in-situ projects to reclaim 2D seismic lines early, which leads to more caribou in sixty years. In comparison, lower levels of taxes, such as $800 per kilometre of linear features, are little more than "income transfers" among different organizations, which fail to provide economic welfare improvement.

6 Discussion and Conclusion

6.1 Conclusion

The purpose of the study is to explore the effectiveness of the application of a tax-refund scheme to the in-situ oilsands industry in Alberta to address a land-based externality. First we developed theoretical models of the social planner and the firms under various conditions (responsibility for legacy linear features or not, taxes, and tax-refund schemes). These theoretical models show that in some cases taxes and tax-refund schemes can generate social optimal outcomes, but complications can arise and neither a tax policy nor a tax-refund scheme can guarantee social optimality because of the potential impact of taxes on firm exit, and the stock nature of the externality associated with reclamation and oilsands mining. These theoretical results differ substantially from those often found in the assessment of externalities such as pollution taxes or carbon taxes. Based on the structure of the theoretical models we explore two cases empirically – a tax and a tax-refund case - and empirically compare social welfare levels with the current case, the tax case, and the tax-refund case.

In the empirical analysis we find that under a tax-refund scheme, at certain tax levels, oilsands projects would implement early reclamation of linear features at the beginning of production period, and this could generate a social outcome that is close to the socially optimal outcome associated with a Pigouvian tax. In addition, the tax-refund policy deals with, at least in part, firms' resistance to taxation, and this makes the policy more practical.

This study has several implications. It provides insights into caribou recovery. The Species at Risk Act requires governments to make recovery plans, but there might be few practical plans for implementation. This thesis shows that a tax-refund scheme offers insights into a caribou recovery plan. However, even if a tax-refund scheme is implemented at present, nearly all caribou herds are not sustainable (nearly all of lambda are less than one). This drives us to think about what other available methods, such as wolf control, should also be taken into consideration to preserve caribou.

Furthermore, the tax-refund scheme designed in this study could also provide important information for dealing with abandoned wellsites in the province. Abandoned wellsites generate stock negative externalities on land, and a lack of economic incentives drives firms to put off remediation as long as possible (Muehlenbachs, 2015). The application of a tax-refund scheme that applied to abandoned wellsites may be of use for remediating land damage left by previous energy extraction activities and may provide an incentive to speed up reclamation of existing sites.

In addition, this thesis takes the oilsands firms' reclamation of linear features as an example of a method to preserve caribou and deal with land damage, and this provides insights about similar methods that could be adopted by forestry firms and other related industries.

Finally, this study also provides insights for those renewable and non-renewable projects that have negative stock externalities. The tax-refund scheme could also be used in the context of coping with issues related to stock pollution such as climate change, soil erosion, and deforestation.

6.2 Limitations

6.2.1 No strategic pre-investment behavior

In chapter 3, we assume that in-situ oilsands projects in a tax-refund scheme will not engage in strategic behavior such as the implementation of pre-investment in production wells and associated facilities. However, projects may strategically overinvest in their production in order to obtain both a high market share and a higher proportion of refunds. In this case, the tax-refund scheme where the refund part is solely dependent on output share is theoretically not sufficient to provide results that are close to the first-best outcome, even though the projects are price takers on market (Gersbach & Requate, 2004).

Some previous studies have examined this issue in different cases. Sterner and Isaksson (2006) believe that such behavior could result in output effects, a situation that leads to a supply curve of output being lower than the corresponding curve for the tax case. In their study on the application of the tax-refund scheme in Swedish NOx abatement, the output effect is small. Mannix (2009) also points out that when the tax-refund scheme is used in the mining industry in Alberta, mining firms may have the propensity to produce higher-than-optimal levels of output, yet we have no idea about the specific impact in terms of output. Therefore, the impact of a tax scheme on firms' strategic behavior in the oilsands industry in Alberta is left for future research.

6.2.2 Political feasibility

The results shown in this thesis are based on the underlying assumption that the tax-refund scheme is politically feasible in Alberta. This indicates that many oilsands firms may not resist such a policy and the government might be willing to implement the policy. However, we need to take a second look at the tax-refund policy from the perspective of both oilsands firms and the provincial government.

To begin with, oilsands firms may not support a tax-refund policy since in practice they have to pay the damaged land tax based on the 2D seismic lines in their operation license region. Some firms may go further to resist such a policy by stating that most of those 2D seismic lines are legacy lines that are built by former firms, not them. But the government should also provide critical information that if oilsands firms implement reclamation and are responsible for forest growth, they are able to get credits.

Furthermore, even if the tax-refund policy is put into effect, some existing firms that are located within caribou ranges may relocate outside of caribou habitat. If they move out of caribou habitats, the legacy seismic lines in their original license region still generate land damage each year. This will inevitably undermine the effectiveness of a tax-refund scheme in caribou recovery in Alberta.

Finally, although a tax-refund scheme might be useful for caribou preservation, the authority may not totally be in favor of such a policy due to its full-refund feature and potential economic impact in the province. The government needs consider the length of 2D seismic lines and output for each project, which might be a daunting task. The authority may also be concerned about the potential decline in bitumen production due to marginal projects being unable to produce bitumen in the tax-refund scheme. In our analysis, when the bitumen price is low, some firms will exit the industry and there will be some adverse economic impacts. In this case, the provincial government may not support the tax-refund scheme considering its negative economic impacts related to the fluctuation in bitumen prices.

6.2.3 Limitations arising from assumptions in the modelling

In this thesis we assume that the damaged land needs around 30 years to be fully reclaimed because it takes 30 years for all trees to reach crown closure. However, tree type, soil compaction, light levels, soil temperature, and other factors could have an impact on the rate of growth (Schneider et al., 2010).

Moreover, we also assume in our static model that the government will reclaim the remaining legacy 2D seismic lines in the beginning period (t=0) if some projects exit due to low bitumen prices and/or the damaged land tax. However, the tax will be collected after production, which makes it difficult for the authority to implement early reclamation in t=0. Furthermore, in practice, several years are required for site preparation, planning and replanting as part of reclamation efforts.

In addition, we assume that the land damage is equal to the tax rate, and the land damage is based on the constant marginal economic benefit of the improvement in caribou and is based on a single study of the economic benefit of caribou conservation. However, the tax rate could be different from the land damage estimate. Sweden adopted a tax rate ten times higher than that used in other European countries, suggesting a tax rate that was much higher than the marginal damage rate. In addition, preserving one caribou in a large herd may not have the same benefit as conserving a caribou in a small herd. Therefore, the benefits of conservation may be herd specific.

Finally, we assume that in their early reclamation firms would only reclaim 2D seismic lines, and that roads and pipelines are permanent until the end of a project. However, recovering existing roads and pipelines would significantly increase caribou preservation cost, and this may change our model results to some extent.

6.3 Recommendations for future study

This study reveals several additional questions and topics that might be worthy of future investigation. In particular, the economic incentive for land reclamation is mainly to deal with stock externalities generated by energy activities. The provision and implementation of a proper incentive mechanism is of great importance to energy firms to address the externality.

Additional research could be directed towards firms' strategic behavior under the tax-refund scheme. For example, the consideration of pre-investment in abatement technology and/or production capital might be ideal, though such an analysis may be faced with limited data. In addition, it would be of great interest to explore the effectiveness of quantity-based counterparts, say an environmental quota where polluters are entitled to property rights to a baseline emission level; if they pollute less, they could sell their quota to other emission extensive firms. Weber and Adamowicz (2002) examine tradable land-use rights (TLRs) as an economic instrument to deal with cumulative environmental effects on public lands, and they find that TLRs increase incentives for intersectional coordination and the adoption of low-impact technologies, both of which would reduce the risk of biodiversity loss. Therefore, it could be interesting and enlightening to discuss the difference between a tax-refund scheme and an environmental quota (or TLRs) in terms of social welfare and political feasibility in the case of caribou recovery.

Furthermore, the static framework used in this thesis could also be extended towards a dynamic one. Specifically, an in-situ oilsands project would make its location decision every well cycle because typical well pairs are assumed to be used for about ten years and projects in the tenth year need to consider whether they still operate within the original license areas or move away to other places that are away from caribou habitats. It would be satisfactory if firms move to other places that are outside caribou habitats because they may not only implement reclamation in t=0 under a tax-refund scheme, but also have no incremental impact on caribou from t=10. Even if they do not entirely move away from their original sites, it is possible for projects to reclaim linear features that are generated within site areas during the first well cycle or the first ten years (from t=0 to t=10). This may result in a more effective tax-refund scheme under which projects are likely to reclaim more linear features than we calculate in our model at present.

Additionally, this analysis shows that caribou do not achieve self-sustaining state (lambda being no less than 1.00), and this indicates that habitat reclamation alone fails to fully recover caribou. This tax-refund scheme provides economic incentives for firms to reclaim their land and restore caribou habitats, and such a method should be combined with habitat protection and/or wolf control for caribou recovery.

In addition, the empirical simulation only examined two of the four possible cases outlined in the theory section. We examine case X1 in terms of firms' profits, caribou outcomes and economic welfare with the assumption that the government do not provide an up-front subsidy to firms. In this case, firms are responsible for the reclamation of legacy linear feature, and their entry decision is treated as a marginal decision (how much bitumen they produce) and the impact of the legacy linear features on their marginal decision. We also examine the tax-refund case X2 regarding its improvement in caribou preservation and economic welfare compared with the competitive case. In X2, the same assumptions as X1 are made and we simulate the tax-refund scheme. In addition, we leave other two of the four possible cases for future research, including the tax case Y1 and the tax-refund case Y2. In these two cases firms are not responsible for legacy linear features reclamation and these lines are treated like a fixed cost of entry. Case Y1 and Y2 will be interesting theoretical cases and may approach optimality if the government can borrow money from taxpayers and subsidize firms for reclamation. Empirical studies for these two cases (Y1 and Y2) are left for future research.

Finally, this study focuses on the future outcomes (including economic welfare and caribou population) of the tax-refund scheme in the context of the in-situ oilsands industry in Alberta if such a scheme would be set at present. In comparison, it would also be interesting to explore what the current situation would be (caribou population, economic welfare, the number of existing projects, and total profit in the oilsands industry) if the tax-refund scheme was established in the 1990s when in-situ oilsands projects initially served as a new way to extract bitumen.

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Appendix

1 Oilsands firm's problem

First Order Conditions

For an in-situ oilsands firms, the first order condition with respect to q_i is

$$\frac{\partial La^{\pi}}{\partial q_i} = \sum_{t=1}^{90} \beta^t (p-\omega) - (\frac{3c^{3D}}{\delta_i} + \frac{c^{4D}}{\delta_i} + \frac{I_i}{q_i^{max}} + \mu_i^{pipe}\left(\frac{P_{i0}}{q_i^{max}} + \rho_i^{pipe}\right) + \mu_i^{r}\left(\frac{R_{i0}}{q_i^{max}} + \rho_i^{r}\right) + \mu_i^{2DL}\frac{E_{i0}^{2DL}}{q_i^{max}} + \mu_i^{2D}(\frac{E_{i0}^{2D}}{q_i^{max}} + \rho_i^{2D}) + \mu_i^{3D}(\frac{E_{i0}^{3D}}{q_i^{max}} + \frac{3}{\delta_i}) + \mu_i^{4D}(\frac{E_{i0}^{4D}}{q_i^{max}} + \frac{1}{\delta_i}) - \mu_i^{q} \leq 0,$$

$$\frac{\partial La^{\pi}}{\partial q_i} = 0 \text{ if } q_i > 0 \qquad (30)$$

and we have

$$\mu_i^{q} \geq \sum_{t=1}^{90} \beta^t (p-\omega) - \left(\frac{3c^{3D}}{\delta_i} + \frac{c^{4D}}{\delta_i} + \frac{I_i}{q_i^{max}}\right) + \mu_i^{pipe}\left(\frac{P_{i0}}{q_i^{max}} + \rho_i^{pipe}\right) + \mu_i^{r}\left(\frac{R_{i0}}{q_i^{max}} + \rho_i^{r}\right) + \mu_i^{2DL}\frac{E_{i0}^{2DL}}{q_i^{max}} + \mu_i^{2D}(\frac{E_{i0}^{2D}}{q_i^{max}} + \rho_i^{2D}) + \mu_i^{3D}(\frac{E_{i0}^{3D}}{q_i^{max}} + \frac{3}{\delta_i}) + \mu_i^{4D}(\frac{E_{i0}^{4D}}{q_i^{max}} + \frac{1}{\delta_i}) \qquad (30')$$

and this shows that μ_i^{q} is larger than or equal to bitumen price (p) minus production cost (ω) and the construction cost before adding benefits from linear feature reclamation. Note that firms do not account for caribou damage. Again, μ_i^{q} could be interpreted as the cost of the right to extract bitumen per barrel per year.

The first-order condition with respect to μ_i^{q} for profit maximization is similar to (27).

The first-order conditions with respect to f_{is} for profit maximization are:

$\frac{\partial La^{\pi}}{\partial f_{i1}^{k}} \leq 0, -\beta^{30}p^{k} \leq u_i$, $\frac{\partial La^{\pi}}{\partial f_{i1}^{k}} = 0$ if $f_{i1}^{k} > 0$

$(f_{i1}^{k} = f_{i1}^{pipe}, f_{i1}^{r}, f_{i1}^{2DL}, f_{i1}^{2D}, f_{i1}^{3D}, f_{i1}^{4D})\ (p^{k} = p^{pipe}, p^{r}, p^{2DL}, p^{2D}, p^{3D}, p^{4D})$ (31)

$\frac{\partial La^{\pi}}{\partial f_{i0}^{k}} \leq 0, -p^{m} \leq u_i$, $\frac{\partial La^{\pi}}{\partial f_{i0}^{m}} = 0$ if $f_{i1}^{m} > 0$

$(f_{i0}^{m} = f_{i0}^{2DL},\ f_{i0}^{2D})\ (p^{m} = p^{2DL}, p^{2D})$ (32)

The left side term ($\beta^{30}p^{k}$ or p^{m}) is the cost of reclamation and the right side term (u_i) represents the net benefit of reclamation.

Here, we present the proof that under the competitive equilibrium, firms produce more output than is socially optimal level, and create more linear features and caribou damage than the socially optimal level.

In Competitive Equilibrium Firms Produce more output than is Socially Optimal:

Proof of $\boldsymbol{\sum_i^n \hat{q}_i > \sum_i^n q_i^*}$

Since the social planner's problem is linear at an optimal solution $q_i^* = 0$ or $q_i^* = q_{imax}$, for $q_i^* = q_i^{max}$, we have

Case 1: $\mu_i^{q*} > 0$, we have $\frac{\partial La^{W}}{\partial q_i} = 0$, and

$$\mu_i^{q*} = \sum_{t=1}^{90} \beta^{t}(p-\omega) - \left(\frac{3c^{3D}}{\delta_i} + \frac{c^{4D}}{\delta_i} + \frac{I_i}{q_i^{max}}\right) - \sum_{t=1}^{90} \beta^{t}\theta\varphi\left(\frac{3}{\delta_i} + \frac{1}{\delta_i}\right) > 0$$

Therefore,

$$0 < \sum_{t=1}^{90} \beta^t (p - \omega) - \left(\frac{3c^{3D}}{\delta_i} + \frac{c^{4D}}{\delta_i} + \frac{I_i}{q_i^{max}} \right) - \sum_{t=1}^{90} \beta^t \theta \varphi \left(\frac{3}{\delta_i} + \frac{1}{\delta_i} \right)$$

$$< \sum_{t=1}^{90} \beta^t (p - \omega) - \left(\frac{3c^{3D}}{\delta_i} + \frac{c^{4D}}{\delta_i} + \frac{I_i}{q_i^{max}} \right) = \mu_i^{\hat{q}}$$

In this case, $\hat{q}_i = q_i^* = q_i^{max}$.

Case 2: $\mu_i^{q*} = 0$, we have $q_i^* = 0$, $\frac{\partial L^W}{\partial q_i} < 0$. In this case $q_i^* \leq q_i^{max}$ is nonbinding and the equations show that the marginal value of bitumen p does not exceed the sum of production costs, construction costs, and the damage to caribou. We have

$$\sum_{t=1}^{90} \beta^t (p - \omega) - \left(\frac{3c^{3D}}{\delta_i} + \frac{c^{4D}}{\delta_i} + \frac{I_i}{q_i^{max}} \right) - \sum_{t=1}^{90} \beta^t \theta \varphi \left(\frac{3}{\delta_i} + \frac{1}{\delta_i} \right) < 0 = \mu_i^{q*}$$

$$< \sum_{t=1}^{90} \beta^t (p - \omega) - \left(\frac{3c^{3D}}{\delta_i} + \frac{c^{4D}}{\delta_i} + \frac{I_i}{q_i^{max}} \right) = \mu_i^{\hat{q}}$$

In this case, $\hat{q}_i = q_i^{max}$ and $q_i^* = 0$.

Therefore, if the land damage arising from impacts on caribou (φ) is sufficiently high, then we will have at least some $q_i^* = 0$ when $\hat{q}_i = q_i^{max}$, and we can say that $\sum_i^n \hat{q}_i > \sum_i^n q_i^*$.

In Competitive Equilibrium Firms Create more Linear Features and Caribou Damage than is Socially Optimal:

Proof of $\hat{\boldsymbol{L}}_s > \boldsymbol{L}_s^*$, $\hat{\boldsymbol{D}}^{\boldsymbol{T}}(\boldsymbol{L}_s) > \boldsymbol{D}^{\boldsymbol{T}*}(\boldsymbol{L}_s)$

We define $\hat{L}_s, s = 1,2,3$ as the total linear features under the no-tax case and L_s^* , $s = 1,2,3$ as the total linear features from solutions of the social planner's problem. We define $\widehat{D}^T(L_s), s = 1,2,3$ as the total land damage arising from the negative impact of total linear features on caribou under the no-tax case and $D^{T*}(L_s), s = 1,2,3$ as the total land damage arising from the negative impact of total linear features on caribou in the social planner's problem.

In the proof above for project i where $\hat{q}_i = q_i^{max}$ but $q_i^* = 0$, these projects will not produce any additional linear features under the social planner's situation. Therefore, we have $L_{is}^* < \hat{L}_{is}$ for these projects i. In addition, equation 32 shows that all firms will set reclamation equal to zero in the competitive case but the social planner could set reclamation to be positive to drive firms to implement reclamation. Therefore, the socially optimal levels of the individual linear feature components $(P_{is}, R_{is}, E_{is}^{2DL}, E_{i1}^{2D}, E_{i1}^{3D}, E_{i1}^{4D})$ will be less than the levels in the no-tax case, and we have $\hat{L}_s > L_s^*, s = 1,2,3$.

Based on the definition of land damage $D^T(L_1, L_2, L_3)$ that is linear and increasing in L_s and $\hat{L}_s > L_s^*, s = 1,2,3$, we have $\widehat{D}^T(L_s) > D^{T*}(L_s), s = 1,2,3$.

2 The tax case

First Order Conditions

$$\frac{\partial La^{tax}}{\partial q_i} = \sum_{t=1}^{30} \beta^t (p-\omega) - \left(\frac{3c^{3D}}{\delta_i} + \frac{c^{4D}}{\delta_i} + \frac{I_i}{q_i^{max}}\right) - \sum_{t=1}^{90} \beta^t \tau \left[\frac{P_{i0}}{q_i^{max}} + \rho_i^{pipe} + \frac{R_{i0}}{q_i^{max}} + \rho_i^r + \frac{E_{i0}^{2DL}}{q_i^{max}} + \theta\left(\frac{E_{i0}^{2D}}{q_i^{max}} + \rho_i^{2D} + \frac{E_{i0}^{3D}}{q_i^{max}} + \frac{3}{\delta_i} + \frac{E_{i0}^{4D}}{q_i^{max}} + \frac{1}{\delta_i}\right)\right]$$

$$+\mu_i^{pipe}\left(\frac{P_{i0}}{q_i^{max}} + \rho_i^{pipe}\right) + \mu_i^r\left(\frac{R_{i0}}{q_i^{max}} + \rho_i^r\right) + \mu_i^{2DL}\frac{E_{i0}^{2DL}}{q_i^{max}} + \mu_i^{2D}\left(\frac{E_{i0}^{2D}}{q_i^{max}} + \rho_i^{2D}\right) + \mu_i^{3D}\left(\frac{E_{i0}^{3D}}{q_i^{max}} + \frac{3}{\delta_i}\right) + \mu_i^{4D}\left(\frac{E_{i0}^{4D}}{q_i^{max}} + \frac{1}{\delta_i}\right) - \mu_i^{qX} \le 0\,,\ \frac{\partial La^{tax}}{\partial q_i} = 0 \text{ if } q_i > 0 \qquad (34)$$

For case Y1, the difference lies in that all terms having $1/q_i^{max}$ are not present for the first order condition. In addition, we define the lagrange multiplier as μ_i^{qY1} rather than μ_i^{qX1}.

When $q_i > 0$, the first order condition may be expressed as:

(Case X1)

$$\mu_i^{qX1} = \sum_{t=1}^{30} \beta^t (p-\omega) - \left(\frac{3c^{3D}}{\delta_i} + \frac{c^{4D}}{\delta_i} + \frac{I_i}{q_i^{max}}\right) - \sum_{t=1}^{90} \beta^t \tau \left[\frac{P_{i0}}{q_i^{max}} + \rho_i^{pipe} + \frac{R_{i0}}{q_i^{max}} + \rho_i^r + \frac{E_{i0}^{2DL}}{q_i^{max}} + \theta\left(\frac{E_{i0}^{2D}}{q_i^{max}} + \rho_i^{2D} + \frac{E_{i0}^{3D}}{q_i^{max}} + \frac{3}{\delta_i} + \frac{E_{i0}^{4D}}{q_i^{max}} + \frac{1}{\delta_i}\right)\right] + \mu_i^{pipe}\left(\frac{P_{i0}}{q_i^{max}} + \rho_i^{pipe}\right) + \mu_i^r\left(\frac{R_{i0}}{q_i^{max}} + \rho_i^r\right) + \mu_i^{2DL}\frac{E_{i0}^{2DL}}{q_i^{max}} + \mu_i^{2D}\left(\frac{E_{i0}^{2D}}{q_i^{max}} + \rho_i^{2D}\right) + \mu_i^{3D}\left(\frac{E_{i0}^{3D}}{q_i^{max}} + \frac{3}{\delta_i}\right) + \mu_i^{4D}\left(\frac{E_{i0}^{4D}}{q_i^{max}} + \frac{1}{\delta_i}\right) \qquad \text{(34-X1)}$$

(Case Y1)

$$\mu_i^{qY1} = \sum_{t=1}^{30}\beta^t(p-\omega) - \left(\frac{3c^{3D}}{\delta_i} + \frac{c^{4D}}{\delta_i}\right) - \sum_{t=1}^{90}\beta^t\tau\left[\rho_i^{pipe} + \rho_i^r + \theta\left(\rho_i^{2D} + \frac{3}{\delta_i} + \frac{1}{\delta_i}\right)\right] + \mu_i^{pipe}\rho_i^{pipe} + \mu_i^r\rho_i^r + \mu_i^{2D}\rho_i^{2D} + \mu_i^{3D}\frac{3}{\delta_i} + \mu_i^{4D}\frac{1}{\delta_i}, \qquad (34\text{-Y1})$$

Lagrange multipliers $\mu_i^{qX1} \geq 0$ or $\mu_i^{qY1} \geq 0$ can be interpreted as the maximum that a project i could pay for extracting all the bitumen resources. For either case X1 or case Y1, the first term on the right is the net operating value (price minus operating cost), the second term is the construction cost, the third term is the tax based on the caribou damage from linear features, and the final several (six for case X and five for case Y) terms are benefits or reduction in tax arising from the reclamation of these linear features.

The first-order condition with respect to μ_i for profit maximization is similar to (27).

The first-order conditions with respect to f_{is} for profit maximization are:

$$\frac{\partial La^{tax}}{\partial f_{i1}^{pipe}} \leq 0, -\beta^{30}p^{pipe} + \sum_{t=61}^{90}\beta^t\tau \leq \mu_i^{pipe}, \ \frac{\partial La^{tax}}{\partial f_{i1}^{pipe}} = 0 \text{ if } f_{i1}^{pipe} > 0 \qquad (35\text{-}1)$$

$$\frac{\partial La^{tax}}{\partial f_{i1}^{r}} \leq 0, \ -\beta^{30}p^{r} + \sum_{t=61}^{90}\beta^t\tau \leq \mu_i^{r}, \ \frac{\partial La^{tax}}{\partial f_{i1}^{r}} = 0 \text{ if } f_{i1}^{r} > 0 \qquad (35\text{-}2)$$

$$\frac{\partial La^{tax}}{\partial f_{i0}^{2DL}} \leq 0, \ -p^{2DL} + \sum_{t=31}^{90}\beta^t\tau \leq \mu_i^{2DL}, \ \frac{\partial La^{tax}}{\partial f_{i0}^{2DL}} = 0 \text{ if } f_{i0}^{2DL} > 0 \qquad (35\text{-}3)$$

$$\frac{\partial La^{tax}}{\partial f_{i1}^{2DL}} \leq 0, \ -\beta^{30}p^{2DL} + \sum_{t=61}^{90}\beta^t\tau \leq \mu_i^{2DL}, \ \frac{\partial La^{tax}}{\partial f_{i1}^{2DL}} = 0 \text{ if } f_{i1}^{2DL} > 0 \qquad (35\text{-}4)$$

$$\frac{\partial La^{tax}}{\partial f_{i0}^{2D}} \leq 0, \ -p^{2D} + \sum_{t=31}^{90}\beta^t\tau\theta \leq \mu_i^{2D}, \ \frac{\partial La^{tax}}{\partial f_{i0}^{2D}} = 0 \text{ if } f_{i0}^{2D} > 0 \qquad (35\text{-}5)$$

$$\frac{\partial La^{tax}}{\partial f_{i1}^{2D}} \leq 0, \ -\beta^{30}p^{2D} + \sum_{t=61}^{90}\beta^t\tau\theta \leq \mu_i^{2D}, \ \frac{\partial La^{tax}}{\partial f_{i1}^{2D}} = 0 \text{ if } f_{i1}^{2D} > 0 \qquad (35\text{-}6)$$

$$\frac{\partial La^{tax}}{\partial f_{i1}^{3D}} \leq 0,\ -\beta^{30}p^{3D} + \sum_{t=61}^{90}\beta^{t}\tau\theta \leq \mu_i^{3D}\ ,\ \frac{\partial La^{tax}}{\partial f_{i1}^{3D}} = 0 \text{ if } f_{i1}^{3D} > 0 \qquad (35\text{-}7)$$

$$\frac{\partial La^{tax}}{\partial f_{i1}^{4D}} \leq 0,\ -\beta^{30}p^{4D} + \sum_{t=61}^{90}\beta^{t}\tau\theta \leq \mu_i^{4D},\ \frac{\partial La^{tax}}{\partial f_{i1}^{4D}} = 0 \text{ if } f_{i1}^{4D} > 0 \qquad (35\text{-}8)$$

For 35-8, the first term ($\beta^{30}p^{4D}$) is the cost of reclamation and the second term ($\sum_{t=61}^{90}\beta^{t}\tau\theta$) is the saved tax over the years that the reclamation has an effect. When τ equals φ, the 35-1 to 35-8 are the same as 28-1 to 28-8, and we get social optimality. The Lagrange multiplier (μ_i^{4D}) represents the net benefit of reclamation of 4D seismic and it will only be positive when the benefits exceed the costs (i.e. when the marginal saved tax from reclamation τ in equations 35-1 to 35-4 and $\tau\theta$ in equations 35-4 to 35-8 is sufficiently large).

Proof of $\boldsymbol{\mu_i^{qY}} > \boldsymbol{\mu_i^{qX}}$(a departure from the socially optimal allocation)

$\mu_i^{qY} - \mu_i^{qX}$

$= \sum_{t=1}^{90} \beta^t \tau \left[\frac{P_{i0}}{q_i^{max}} + \frac{R_{i0}}{q_i^{max}} + \frac{E_{i0}^{2DL}}{q_i^{max}} + \theta\left(\frac{E_{i0}^{2D}}{q_i^{max}} + \frac{E_{i0}^{3D}}{q_i^{max}} + \frac{E_{i0}^{4D}}{q_i^{max}}\right)\right]$

$-\left[\mu_i^{pipe}\ \frac{P_{i0}}{q_i^{max}} + \mu_i^{r}\ \frac{R_{i0}}{q_i^{max}} + \mu_i^{2DL}\ \frac{E_{i0}^{2DL}}{q_i^{max}} + \mu_i^{2D}\ \frac{E_{i0}^{2D}}{q_i^{max}} + \mu_i^{3D}\ \frac{E_{i0}^{3D}}{q_i^{max}} + \mu_i^{4D}\ \frac{E_{i0}^{4D}}{q_i^{max}}\right]$

$= \ \sum_{t=1}^{90} \beta^t \tau \left[\frac{P_{i0}}{q_i^{max}} + \frac{R_{i0}}{q_i^{max}} + \frac{E_{i0}^{2DL}}{q_i^{max}} + \theta\left(\frac{E_{i0}^{2D}}{q_i^{max}} + \frac{E_{i0}^{3D}}{q_i^{max}} + \frac{E_{i0}^{4D}}{q_i^{max}}\right)\right]$

$+[\left(\beta^{30} p^{pipe}\ - \sum_{t=61}^{90} \beta^t \tau\right) \frac{P_{i0}}{q_i^{max}} + (\beta^{30} p^{r} - \sum_{t=61}^{90} \beta^t \tau) \frac{R_{i0}}{q_i^{max}} + (p^{2DL} - \sum_{t=31}^{90} \beta^t \tau) \frac{E_{i0}^{2DL}}{q_i^{max}}$

$+(p^{2D} - \sum_{t=31}^{90} \beta^t \tau\theta) \frac{E_{i0}^{2D}}{q_i^{max}} + (\beta^{30} p^{3D} - \sum_{t=61}^{90} \beta^t \tau\theta) \frac{E_{i0}^{3D}}{q_i^{max}}$

$+(\beta^{30} p^{4D} - \sum_{t=61}^{90} \beta^t \tau\theta) \frac{E_{i0}^{4D}}{q_i^{max}}]$

$= \beta^{30} p^{pipe}\ \frac{P_{i0}}{q_i^{max}} + \beta^{30} p^{r}\ \frac{R_{i0}}{q_i^{max}} + p^{2DL}\ \frac{E_{i0}^{2DL}}{q_i^{max}} + p^{2D}\ \frac{E_{i0}^{2D}}{q_i^{max}} + \beta^{30} p^{3D}\ \frac{E_{i0}^{3D}}{q_i^{max}} + \beta^{30} p^{4D}\ \frac{E_{i0}^{4D}}{q_i^{max}}$

$+ \sum_{t=1}^{90} \beta^t \tau \left[\frac{P_{i0}}{q_i^{max}} + \frac{R_{i0}}{q_i^{max}} + \frac{E_{i0}^{2DL}}{q_i^{max}} + \theta\left(\frac{E_{i0}^{2D}}{q_i^{max}} + \frac{E_{i0}^{3D}}{q_i^{max}} + \frac{E_{i0}^{4D}}{q_i^{max}}\right)\right]$

$- \sum_{t=61}^{90} \beta^t \tau \left[\frac{P_{i0}}{q_i^{max}} + \frac{R_{i0}}{q_i^{max}} + \frac{E_{i0}^{2DL}}{q_i^{max}} + \theta\left(\frac{E_{i0}^{2D}}{q_i^{max}} + \frac{E_{i0}^{3D}}{q_i^{max}} + \frac{E_{i0}^{4D}}{q_i^{max}}\right)\right]$

$- \sum_{t=31}^{60} \beta^t \tau [\frac{E_{i0}^{2DL}}{q_i^{max}} + \theta\, \frac{E_{i0}^{2D}}{q_i^{max}}]$

$= \beta^{30} p^{pipe}\ \frac{P_{i0}}{q_i^{max}} + \beta^{30} p^{r}\ \frac{R_{i0}}{q_i^{max}} + p^{2DL}\ \frac{E_{i0}^{2DL}}{q_i^{max}} + p^{2D}\ \frac{E_{i0}^{2D}}{q_i^{max}} + \beta^{30} p^{3D}\ \frac{E_{i0}^{3D}}{q_i^{max}} + \beta^{30} p^{4D}\ \frac{E_{i0}^{4D}}{q_i^{max}}$

$+ \sum_{t=1}^{60} \beta^t \tau \left[\frac{P_{i0}}{q_i^{max}} + \frac{R_{i0}}{q_i^{max}} + \frac{E_{i0}^{2DL}}{q_i^{max}} + \theta\left(\frac{E_{i0}^{2D}}{q_i^{max}} + \frac{E_{i0}^{3D}}{q_i^{max}} + \frac{E_{i0}^{4D}}{q_i^{max}}\right)\right]$

$- \sum_{t=31}^{60} \beta^t \tau \left[\frac{E_{i0}^{2DL}}{q_i^{max}} + \theta\, \frac{E_{i0}^{2D}}{q_i^{max}}\right] > 0$

Figure 2.1 Proof of $\mu_i^{qY1} > 0 > \mu_i^{qX1}$

3 The tax-refund scheme

First Order Conditions

$$\frac{\partial La^{tr}}{\partial q_i} = \sum_{t=1}^{90} \beta^t (p-\omega) - \left(\frac{3c^{3D}}{\delta_i} + \frac{c^{4D}}{\delta_i} + \frac{I_i}{q_i^{max}}\right)$$

$$- \sum_{t=1}^{90} \beta^t \tau \left[\frac{P_{i0}}{q_i^{max}} + \rho_i^{pipe} + \frac{R_{i0}}{q_i^{max}} + \rho_i^r + \frac{E_{i0}^{2DL}}{q_i^{max}} + \theta\left(\frac{E_{i0}^{2D}}{q_i^{max}} + \rho_i^{2D} + \frac{E_{i0}^{3D}}{q_i^{max}} + \frac{3}{\delta_i} + \frac{E_{i0}^{4D}}{q_i^{max}} + \right.\right.$$

$$\left.\left.\frac{1}{\delta_i}\right)\right] + \mu_i^{pipe}\left(\frac{P_{i0}}{q_i^{max}} + \rho_i^{pipe}\right) + \mu_i^r\left(\frac{R_{i0}}{q_i^{max}} + \rho_i^r\right) + \mu_i^{2DL}\frac{E_{i0}^{2DL}}{q_i^{max}} + \mu_i^{2D}\left(\frac{E_{i0}^{2D}}{q_i^{max}} + \rho_i^{2D}\right) +$$

$$\mu_i^{3D}\left(\frac{E_{i0}^{3D}}{q_i^{max}} + \frac{3}{\delta_i}\right) + \mu_i^{4D}\left(\frac{E_{i0}^{4D}}{q_i^{max}} + \frac{1}{\delta_i}\right)$$

$$+ \sum_{t=1}^{30} \beta^t \tau d \left[\frac{P_{i0}}{q_i^{max}} + \rho_i^{pipe} + \frac{R_{i0}}{q_i^{max}} + \rho_i^r + \frac{E_{i0}^{2DL}}{q_i^{max}} + \theta\left(\frac{E_{i0}^{2D}}{q_i^{max}} + \rho_i^{2D} + \frac{E_{i0}^{3D}}{q_i^{max}} + \frac{3}{\delta_i} + \frac{E_{i0}^{4D}}{q_i^{max}} + \right.\right.$$

$$\left.\left.\frac{1}{\delta_i}\right)\right] \frac{q_i}{q_i + \sum_{j\neq i}^n \bar{\bar{q}}_j} + \tau_1^T\left(L_{i1} + \sum_{j\neq i}^n \bar{\bar{L}}_{j1}\right) d \frac{\sum_{j\neq i}^n \bar{\bar{q}}_j}{\left(q_i + \sum_{j\neq i}^n \bar{\bar{q}}_j\right)^2} - \mu_i^{qX2} \leq 0,$$

$$\frac{\partial La^{tr}}{\partial q_i} = 0 \text{ if } q_i > 0 \qquad (37)$$

For case Y2, relative to X2, the difference lies in that all terms having $1/q_i^{max}$ are not present for the first order condition. For example, $\frac{P_{i0}}{q_i^{max}}$ does not appear in the Laglange equation above for Case Y2. In addition, we define the lagrange multiplier as μ_i^{qY2} rather than μ_i^{qX2}. When $q_i > 0$, the first order condition may be expressed as:

(Case X2)

$$\mu_i^{qX2} = \sum_{t=1}^{30} \beta^t (p-\omega) - \left(\frac{3c^{3D}}{\delta_i} + \frac{c^{4D}}{\delta_i} + \frac{I_i}{q_i^{max}}\right) - \sum_{t=1}^{90} \beta^t \tau \left[\frac{P_{i0}}{q_i^{max}} + \rho_i^{pipe} + \frac{R_{i0}}{q_i^{max}} + \rho_i^r + \frac{E_{i0}^{2DL}}{q_i^{max}} + \theta\left(\frac{E_{i0}^{2D}}{q_i^{max}} + \rho_i^{2D} + \frac{E_{i0}^{3D}}{q_i^{max}} + \frac{3}{\delta_i} + \frac{E_{i0}^{4D}}{q_i^{max}} + \frac{1}{\delta_i}\right)\right] + \mu_i^{pipe}\left(\frac{P_{i0}}{q_i^{max}} + \rho_i^{pipe}\right) + \mu_i^r\left(\frac{R_{i0}}{q_i^{max}} + \rho_i^r\right) + \mu_i^{2DL}\frac{E_{i0}^{2DL}}{q_i^{max}} + \mu_i^{2D}\left(\frac{E_{i0}^{2D}}{q_i^{max}} + \rho_i^{2D}\right) + \mu_i^{3D}\left(\frac{E_{i0}^{3D}}{q_i^{max}} + \frac{3}{\delta_i}\right) + \mu_i^{4D}\left(\frac{E_{i0}^{4D}}{q_i^{max}} + \frac{1}{\delta_i}\right)$$

$$+ \sum_{t=1}^{30} \beta^t \tau d \left[\frac{P_{i0}}{q_i^{max}} + \rho_i^{pipe} + \frac{R_{i0}}{q_i^{max}} + \rho_i^r + \frac{E_{i0}^{2DL}}{q_i^{max}} + \theta\left(\frac{E_{i0}^{2D}}{q_i^{max}} + \rho_i^{2D} + \frac{E_{i0}^{3D}}{q_i^{max}} + \frac{3}{\delta_i} + \frac{E_{i0}^{4D}}{q_i^{max}} + \frac{1}{\delta_i}\right)\right] \frac{q_i}{q_i + \sum_{j\neq i}^n \bar{\bar{q}}_j} + \tau_1^T \left(L_{i1} + \sum_{j\neq i}^n \bar{\bar{L}}_{j1}\right) \frac{\sum_{j\neq i}^n \bar{\bar{q}}_j}{\left(q_i + \sum_{j\neq i}^n \bar{\bar{q}}_j\right)^2} \geq 0 \qquad \text{(37-X2)}$$

Under heterogeneity in the parameters showing the relationship between q_i and linear features, $\mu_i^{qX2} > 0$ at least for some of them.

(Case Y2)

$$\mu_i^{qY2} = \sum_{t=1}^{90} \beta^t (p-\omega) - \left(\frac{3c^{3D}}{\delta_i} + \frac{c^{4D}}{\delta_i} + \frac{I_i}{q_i^{max}}\right) - \sum_{t=1}^{90} \beta^t \tau \left(\frac{3\theta}{\delta_i} + \frac{\theta}{\delta_i} + \rho_i^{pipe} + \rho_i^r + \rho_i^{2D}\right) + \mu_i^{pipe}\rho_i^{pipe} + \mu_i^r \rho_i^r + \mu_i^{2D}\rho_i^{2D} + \mu_i^{3D}\frac{3}{\delta_i} + \mu_i^{4D}\frac{1}{\delta_i} + \sum_{t=1}^{30} \beta^t \tau d \left[\rho_i^{pipe} + \rho_i^r + \theta\left(\rho_i^{2D} + \frac{3}{\delta_i} + \frac{1}{\delta_i}\right)\right] \frac{q_i}{q_i + \sum_{j\neq i}^n \bar{\bar{q}}_j} + \tau_1^T \left(L_{i1} + \sum_{j\neq i}^n \bar{\bar{L}}_{j1}\right) d \frac{\sum_{j\neq i}^n \bar{\bar{q}}_j}{\left(q_i + \sum_{j\neq i}^n \bar{\bar{q}}_j\right)^2} \geq 0 \qquad \text{(37-Y2)}$$

We notice that $\mu_i^{qX1} \geq 0$ or $\mu_i^{qY1} \geq 0$ can be interpreted as the maximum that an oilsands project i could pay for extracting all the bitumen resources. For either case X1 or case Y1, the first term on the right is the net operating value (price minus operating cost), the second term is the construction cost, the third term is the tax based on the caribou damage from linear features, and the next several (six for case X and five for case Y) terms are benefits or reduction in tax arising from the reclamation of these linear features. The final term is the refund that an in-situ project i gains per unit of output.

In case X2, legacy linear features are present in the first order conditions for production (q_i) as an additional marginal cost of production, and therefore, firms' entry decisions are affected (i.e. whether $q_i > 0$ or $q_i = 0$). In Y2, where firms are not responsible to reclaim legacy features, there might be separate reclamation firms that are subsidized by governments (pay negative taxes) when reclamation benefits arise and exceed reclamation costs. This arises because it is socially optimal to reclaim the legacy features, but it is not the firm's responsibility.

The first-order condition with respect to μ_i for profit maximization is similar to (27).

The first-order conditions with respect to f_{is} for profit maximization are:

$$\frac{\partial La^{tr}}{\partial f_{i1}^{pipe}} \leq 0, -\beta^{30} p^{pipe} + \sum_{t=61}^{90} \beta^t \tau \leq \mu_i^{pipe}, \frac{\partial La^{tr}}{\partial f_{i1}^{pipe}} = 0 \text{ if } f_{i1}^{pipe} > 0 \qquad (38\text{-}1)$$

$$\frac{\partial La^{tr}}{\partial f_{i1}^{r}} \leq 0,\ -\beta^{30} p^{r} + \sum_{t=61}^{90} \beta^t \tau \leq \mu_i^{r}\ ,\ \frac{\partial La^{tr}}{\partial f_{i1}^{r}} = 0 \text{ if } f_{i1}^{r} > 0 \qquad (38\text{-}2)$$

$$\frac{\partial La^{tr}}{\partial f_{i0}^{2DL}} \leq 0,\ -p^{2DL} + \sum_{t=31}^{90} \beta^t \tau \leq \mu_i^{2DL}\ , \frac{\partial La^{tr}}{\partial f_{i0}^{2DL}} = 0 \text{ if } f_{i0}^{2DL} > 0 \qquad (38\text{-}3)$$

$$\frac{\partial La^{tr}}{\partial f_{i1}^{2DL}} \leq 0,\ -\beta^{30} p^{2DL} + \sum_{t=61}^{90} \beta^t \tau \leq \mu_i^{2DL}\ , \frac{\partial La^{tr}}{\partial f_{i1}^{2DL}} = 0 \text{ if } f_{i1}^{2DL} > 0 \qquad (38\text{-}4)$$

$$\frac{\partial La^{tr}}{\partial f_{i0}^{2D}} \leq 0,\ -p^{2D} + \sum_{t=31}^{90} \beta^t \tau\theta \leq \mu_i^{2D}\ , \frac{\partial La^{tr}}{\partial f_{i0}^{2D}} = 0 \text{ if } f_{i0}^{2D} > 0 \qquad (38\text{-}5)$$

$$\frac{\partial La^{tr}}{\partial f_{i1}^{2D}} \leq 0,\ -\beta^{30} p^{2D} + \sum_{t=61}^{90} \beta^t \tau\theta \leq \mu_i^{2D},\ \frac{\partial La^{tr}}{\partial f_{i1}^{2D}} = 0 \text{ if } f_{i1}^{2D} > 0 \qquad (38\text{-}6)$$

$$\frac{\partial La^{tr}}{\partial f_{i1}^{3D}} \leq 0,\ -\beta^{30}p^{3D} + \sum_{t=61}^{90} \beta^t \tau\theta \leq \mu_i^{3D}\ ,\frac{\partial La^{tr}}{\partial f_{i1}^{3D}} = 0 \text{ if } f_{i1}^{3D} > 0 \qquad (38\text{-}7)$$

$$\frac{\partial La^{tr}}{\partial f_{i1}^{4D}} \leq 0,\ -\beta^{30}p^{4D} + \sum_{t=61}^{90} \beta^t \tau\theta \leq \mu_i^{4D},\ \frac{\partial La^{tr}}{\partial f_{i1}^{4D}} = 0 \text{ if } f_{i1}^{4D} > 0 \qquad (38\text{-}8)$$

We explain 38-8 as an example, and the rest of equations are similar in terms of economic implications of reclamation costs and benefits. The first term ($\beta^{30}p^{4D}$) is the cost of reclamation and the second term ($\sum_{t=61}^{90} \beta^t \tau\theta$) is the saved tax over the years that the reclamation has an effect. The third term is the loss of saved tax arising from the decrease in linear features because of firms' reclamation. The Lagrange multiplier (μ_i^{4D}) represents the net benefit of reclamation of 4D seismic and it will only be positive when the benefits exceed the costs (i.e. when the marginal saved tax from reclamation τ in equations 35-1 to 35-4 and $\tau\theta$ in equations 35-4 to 35-8 is sufficiently large). In addition, based on empirical facts, we have $p^{pipe} > p^r > p^{2DL}$, and several possibilities are as follows:

1) If the τ is lower relative to the reclamation cost of 2D legacy seismic lines (p^{2DL}) $\frac{\tau}{p^{2DL}} < \frac{1}{\sum_{t=31}^{90} \beta^t}$, firms do not reclaim 2D seismic lines, roads, or pipelines;

2) With a higher level of tax $\frac{1}{\sum_{t=31}^{90} \beta^t} < \frac{\tau}{p^{2DL}}$, firms reclaim 2D seismic lines, but do not reclaim roads or pipelines;

3) With a higher level of tax $\frac{1}{\sum_{t=61}^{90} \beta^t} < \frac{\tau}{p^r}$, firms reclaim 2D seismic lines and roads, but do not reclaim pipelines;

4) If we have $\frac{1}{\sum_{t=61}^{90} \beta^t} < \frac{\tau}{p^{pipe}}$, firms will reclaim 2D seismic lines, roads, and pipelines.