# Essays on Theoretical Methods for Environmental and Developmental Economics Policy Analysis

by

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Dissertation submitted in partial fulfillment of
the requirements for the degree of Doctor
of Philosophy in the Department of
Civil and Environmental Engineering in the Graduate School
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# ABSTRACT

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# Abstract

This dissertation contributes to the fields of environmental, natural resource and development economics. It contains three essays, each tackling related but different sets of questions by developing theoretical, analytical and econometric methods for policy relevant analysis. In the first essay I develop theoretical models to discuss how fossil fuel firms may respond to anticipated climate friendly policies by intensifying resource extraction from existing reserve bases (green paradox) and/or by reducing investments in expansion of the pool of extractable reserves. In the second essay I construct theoretical models to discuss the design of institutions for regulation of novel climate altering geoengineering technologies by first exploring the dangers of a lack of carbon policy commitment and then suggesting institutional solutions that draw from the monetary policy literature. Finally in the third essay, I consider the design of a multiple cut-off regression discontinuity design and show how it can be used to answer policy relevant questions in development economics in situations involving multiple treatments and treatment conditions. Collectively, the studies involve theoretical ideas and concepts that help understand the impact of policy

uncertainty, think about the design of institutions for policy governance and estimate the impacts of past implemented policies.

In many ways this dissertation is a product of my love for mathematics and those seeds of love were sown several years ago by my grandfather, as he patiently and diligently sat with me, over many summers, making me understand the value of algebra and calculus. I dedicate this to my grandfather.

I also want to dedicate this to my parents who have made me the person I am today and taught me the value of persistence and tenacity, qualities that were essential to finishing a PhD.

# Acknowledgements

First and foremost, I would like to thank my advisor Dr. Mark Borsuk. Through all these years Mark had the confidence and faith in me to pursue my independent ideas, even those that weren't necessarily associated with a traditional engineering school. During setbacks and dark times, he was a pillar of support both emotionally and rationally. He supported my ideas, encouraged me and regularly challenged me to think deeper and harder, all while demonstrating deep empathy and great leadership. This work would be not have been possible without his guidance.

I wish to thank Dr. Martin Smith for introducing me to the world of optimal control and dynamic programming. I also want to thank Dr. Georgia Mavrommati for her enduring support and guidance during the initial years of my PhD at Dartmouth. I want to thank my lab members for their gracious support and need when bouncing off ideas, critiquing them and challenging me to be better. Finally I wish to thank my committee for their support and guidance in this process.

# Contents

# List of Figures

# Chapter 1

# Introduction

This dissertation describes three chapters to comprise a doctoral dissertation in the Department of Civil and Environmental Engineering at Duke University. It contains three self-contained papers, all related to natural resource, energy, environmental and development economics and develops theoretical and analytical methods drawing from optimal control, game theory and causal inference.

The first chapter is titled "Reconciling the effects of divestment and the green paradox on resource extraction" and develops a theoretical model to determine how fossil fuel firms make decisions regarding extraction of natural resources when acting under the anticipation of future climate policy. Carbon taxes are often discussed as a solution to internalize the costs associated with greenhouse gases and as a strategy to disincentive the use of fossil fuels. In the real world however, implementation is often uncertain and firms typically find themselves making decisions under uncertainty over when carbon taxes will actually be implemented. The extant literature discusses two distinct behavioural responses to the imposition of future climate friendly policies. On the one hand, and as a response to the likelihood of losing their future business, firms may act pre-emptively and extract even more. This phenomenon is known as the green paradox and increases emissions in the short to medium run. On the other hand, firms may start reducing investments in irreversible and durable assets associated with fossil fuel extraction. For example, the prospect of a future tax means firms are reluctant to drill new oil rigs or sink investments into new coal mines. This phenomenon is known as divestment and reduces emissions in the medium to long run. For the most part, these two behavioural responses have been discussed separately in the literature. While analytical models have most often been used to characterize the green paradox, numerical approaches are typically used to characterize divestment. In this paper, I propose an analytical and theoretical characterisation that accounts for the presence of both of these effects. I discuss the conditions under which the green paradox and reduced investment effects occur, and how these might then be linked to the type of natural resource under consideration. For the most part, I show that concerns over the green paradox are inflated and the consideration of more realistic representations of reserve additions strengthens the reduced investment effect.

The second chapter is titled “Geoengineering and institutional design for credible carbon policies” and develops an institutional framework for governance of solar radiation management (SRM), when its use is coupled with a mitigation policy such as a carbon tax. If efforts towards mitigation fail to achieve the intended goal of emissions reduction, drastic measures like solar radiation management may be used to offset temperature increases. While mitigation addresses the source of the climate change problem by reducing concentrations of greenhouse gases, solar radiation management only alters the temperature impacts associated with a given concentration of greenhouse gases by altering the amount of incoming solar radiation. Hence, solar radiation management should ideally be used alongside mitigation and adaptation as a portfolio of strategies to address the probabilities and impacts associated with climate change damages. However, there is concern that the prospect of solar radiation management (SRM) may change the incentives of actors involved in the system. If firms know that governments have the ability to implement SRM, they might respond by underinvesting in abatement technology. This may especially be true in a world where governments fail to make credible commitments on future climate policy. In this paper, I ask two questions. First, I ask how do incentives for mitigation by private actors change when time inconsistent governments have the ability to implement geoengineering (SRM), and second, what institutional solutions can ensure that incentives for mitigation are not lost in a world with the prospect of geoengineering? I show that firms' response to potential future SAI is to either overinvest or underinvest in abatement technology, depending on the slope of their marginal abatement curve. In either scenario, the result induces governments to lower carbon taxes, increases firms' overall emissions, and consequently increases SAI levels to mitigate damages from excess emissions. To address this problem,I propose the design of an institutional arrangement, much like a central bank, in which control over SAI is handled by an independent environmental authority (IEA). I show that commitment to SAI policy leads to lower emissions, lower levels of SAI, and consequently lower climate damages. Questions regarding contract design between government and the IEA in the presence of informational asymmetry and adverse selection are left for future research.

The third chapter is titled "Multiple treatments with partial effects in a generalized regression discontinuity design". In this essay I extend the standard regression discontinuity (RD) design to multiple treatments in a generalized set-up. This is done by considering an RD design with two cutoffs, at least one of which is a fuzzy discontinuity. I generalize the one score RD and other multiple RD designs in the following ways: (i) allow the consideration of multiple assignment variables with cutoffs that are either fuzzy or strict discontinuities (ii) disentangle the estimation of partial effects from total effects in a fuzzy discontinuity design. I establish identification conditions for this generalized model and also show equivalence with instrumental variables regressions. I also discuss its application to the context of evaluating the joint impacts of electrification status and groundwater availability on various labor market outcomes. I do this by proposing a study to estimate the causal impacts of rural electrification and groundwater availability on various developmental outcomes in the Indian context. The method I have developed in this essay can be used to address a key overarching question in development economics: What necessary conditions besides access to electricity are required for electrification to demonstrate its' potential in facilitating economic development in rural village economies? Availability of water and electricity are key plausible inputs to stimulate rural development in both agricultural and non-agricultural sectors. Especially in the case of the agricultural sector, easy access to groundwater is inextricably linked to electrification, arguably making electricity an indirect but critical driver for generating growth and employment in the short to medium run. In the context of India, where electricity for agriculture is heavily subsidized, access to the electric grid can strongly incentivize private adoption of technologies for ground and surface water irrigation, driving growth in the agricultural sector. The adoption of these technologies could however depend on the depth to groundwater at the time of electrification, driving differences in impacts between regions that vary on groundwater depth. Further, depending on the type and extent of adoption, regions with more or less depth to groundwater, and regions with or without access to electricity could see different developmental pathways over time. Application of the method developed here to answering this question is likely to shed light on the role of groundwater alongside electrification in stimulating rural economic development.

The collection of the above essays contain theoretical ideas and concepts to help us understand the impact of climate policy uncertainty using optimal control methods, think about institutional design using game theory for governance of geo engineering technologies and econometric methods to estimate causal impacts of multiple treatments in the context of development economics.

# Chapter 2

# Reconciling the Effects of Reduced Investment and the Green Paradox on Resource Extraction

This essay is currently under submission in the **Australian Journal of Resource and Agricultural Economics**. The article has been reformatted for the purposes of this dissertation.

### Authorship:

**Varun Mallampalli** - Idea generation, deriving the mathematical calculations and proofs, performing numerical simulations, drafting the article

**Mark Borsuk** - Funding the study, draft revisions, finalizing the article

## 2.1 Introduction

Climate change is the result of a market failure in which greenhouse gases are overproduced beyond the socially optimal level. Since there exists no market to internalize the costs associated with emitting greenhouse gases, the largest burden can fall on those not responsible for generating the most emissions. Over the years, a few mechanisms have been suggested that internalize the costs of these emissions: carbon taxes and cap-and-trade schemes. Since, the accumulation of carbon emissions creates uncertain damages over time, the price level of future emissions is uncertain. Despite this uncertainty, several integrated assessment models examine the optimal level and time path of carbon pricing (Nordhaus, 1993a; 2017).

While pricing mechanisms do offer hope for reducing future emissions, some studies have also looked at how real world implementation of these policies might create feedback mechanisms that erode the effectiveness of the intended policy (Barker et al., 2007). One such mechanism is the ”green paradox”, which has recently received a lot of attention (Sinn, 2008; 2012). The idea behind the green paradox is that if fossil fuel owners are threatened with climate friendly policies, they are likely to preempt the threat and extract more, thereby worsening the problem of climate change. In a market where the supply of fossil fuels is fairly inelastic, this problem could become even more severe (Hoel, 2013). This effect is easily demonstrated with a theoretical Hotelling model that accounts for increasing taxes (Gerlagh, 2011). In contrast, other studies have looked at reinforcing effects of anticipated climate policies. Notably, the reduced investment effect predicts that in response to anticipated climate policies, investors would decrease investment in fossil fuel related infrastructure, thus effectively reducing carbon emissions in the medium and long run (Bauer et. al., 2018; Johnson et. al., 2015).

Sinn (2008) first identified the 'Green Paradox', although the mechanism governing the paradox was introduced well before that (Sinclair, 1992; 1994). Sinclair (1992; 1994) used a standard Hotelling framework to show that a carbon tax is effective only when it decreases over time. Unlike the present paper however, Sinclair resorted to the use of ad-valorem taxes, which is why his optimal tax decreases over time. Similarly, Ulph and Ulph (1994) use a Hotelling rule with extraction and climate damage costs to find the optimal policy that smoothes out fossil fuel use through high taxes at peak consumption. It was not until 2008 that the term 'Green Paradox' was coined and gained significant attention (Sinn, 2008; Strand, 2007). Sinn (2008) showed under several scenarios that markets always favor advanced extraction, and carbon tax plans worsen the problem. He further argued for a need to consider supply side policies in addition to those that try to reduce consumer demand. At around the same time Strand (2008) showed that an international agreement on development of clean energy technologies increases short run emissions. In case of an unsuccessful effort, net climate damages increase substantially. Hoel (2009) showed that investment in a future clean backstop that is perfectly substitutable and made cheaper through technological change also leads to a green paradox.

More recently, a host of more specific conditions have been analyzed by economists to better understand conditions under which the green paradox may or may not occur. Gerlagh (2011) uses the term 'weak green paradox' to refer to a situation in which near term emissions rise and 'strong green paradox' to refer to a situation where net climate benefits are negative. Hoel (2013) studies the effect of supply side climate policies and concludes that 'wrong' supply side climate policies can also lead to a green paradox. A recent paper by Osterle (2016) looks at the effect of costly exploration on the green paradox. He concludes that a fairly high initial tax rate with a low or high growth rate insures against a green paradox. Several other papers have tried to identify the green paradox in partial equilibrium with perfect as well as imperfect substitution and others have sought to identify the green paradox in general equilibrium (Michielsen, 2014; Eichner and Pethig, 2011; Van der Ploeg and Withagen, 2012). Second best tax regimes have also been studied with open economies studying joint effects of carbon leakage and the green paradox (Van Der Ploeg, 2016)

In comparison to the literature on the green paradox, which is confined to the use of theoretical models, the literature on reduced investment is sparse and mainly uses numerical models. Bosetti, Carraro and Tavoni (2009) use the WITCH integrated assessment model to show that the anticipated effects of potential climate policy lead to investments in clean fuels and technologies. Similarly, Blanford, Richels and Rutherfod (2009) use the MERGE model to show how the anticipation of climate policies allows firms to avoid the economic losses associated with making investments in emissions intensive technologies that are likely to reduce the potential for future abatement. Additionally, to the best of my knowledge, only two papers focus on the effect of both reduced investment and the green paradox within the same model. Bauer, McGlade, Hilaire and Elkins (2018) use a numerical approach with two integrated assessment models to show downstream reduced investment in fossil fuel infrastructure in addition to the effect of increased extraction through the green paradox, as a response to a credible policy announcement. Venables (2014) develops a model that fully endogenizes the reserve addition decision thus permitting both extraction as well as reduced upstream investment.

Our characterization of these two opposing effects is different in that we focus primarily on upstream reduced investment at the point of extraction of the resource, characterize these effects using theoretical models and consider the role of uncertainty in the date of implementation of a tax. These are readily handled in an analytical framework. This paper contributes to the literature on extensive margin choices for resource development in the context of carbon taxes (Venables, 2014; Dasgupta and Heal, 1979; Pindyck, 1978). However, unlike Venables (2014), where extensive margin choices are fully integrated via the decision regarding when to sink capital to open a new field, we model additions to the stock of extractable reserves as a continuous variable that reduces reserve depletion costs (Pindyck, 1978) and add to production capacity (Anderson, Kellog and Salant, 2018). This model allows us to evaluate how uncertainty in the timing of future taxes may impact extraction and drilling. Novelty also lies in being able to isolate the responses of exploration/drilling and extraction to the announcement of a future tax. In principle, we are therefore able to establish that even though extraction along the intensive margin is accelerated in response to an announced future tax, drilling and/or exploration are decelerated. Our framework also allows us to better understand the mechanisms driving intensive and extensive margin choices and how these choices drive decisions regarding investment and pre-emptive extraction.

For all future uses of the term in this paper, we define investment as any activity that expands the base of ”proven developed reserves” (PD reserves). For the most part, this includes the costs incurred for setting up infrastructure such as drilling wells and digging mines etc. to convert proven undeveloped reserves into developed reserves. This also includes costs incurred in technological progress that allow certain ”unproven reserves” to be classified as ”proven developed reserves” as well as exploration activities that expand the base of ”unproven” and ”proven” reserves. Reduced investment is therefore the investment away from activities that expand the base of

PD reserves along the extensive margin of adjustment.

We think of the imposition of a carbon tax and its effects on firms' decisions as a problem that can be divided into three separate time regimes: (1) Carbon taxes are unannounced and firms act as if they will never be imposed (2) Carbon taxes are announced to occur at some uncertain date and firms act under the expectation of their future imposition (3) Carbon taxes are imposed and firms internalize their externality costs. This paper focuses on the second regime as our goal is to understand how firms behave in anticipation of carbon taxes and other climate policies.

Section 2.2 presents a basic model of a resource extracting firm with stock effects that faces a carbon tax in the future. Adjustment is only permitted to occur along the intensive margin such that firms' responses are restricted to more intensive resource extraction from existing PD reserves. Section 2.3 extends the same model to account for investments that add to PD reserves in addition to resource extraction from existing PD reserves. Adjustments are therefore permitted along both the intensive as well as the extensive margins. Firms can respond both by extracting more intensively from existing PD reserves and by determining additions to existing PD reserves.

Section 2.4 presents numerical simulations on extraction from existing PD reserves and additions to PD reserves in the presence and absence of a tax announcement. Section 2.5 studies reduced investment in the context of an empirically relevant oil drilling model where adjustment is permitted only along the extensive margin and Sections 2.6 and 2.7 present directions for future research and conclude.

## 2.2 Exhaustible resources: Intensive margin adjustment

Consider a model of the resource market with stock dependent extraction costs $C(x, u) = uC(x)$, such that cost is linear in the amount extracted $u(t)$ and increases as reserves $x(t)$ are depleted (Fisher, 1981). This can be represented as follows:

$$C_x(x, u) < 0 \tag{2.1}$$

$$C_{xx}(x, u) > 0 \tag{2.2}$$

$$C_u(x, u) > 0 \tag{2.3}$$

$$C_{uu}(x, u) = 0 \tag{2.4}$$

$$C_{xu}(x,u) < 0 \tag{2.5}$$

The inverse demand function is assumed to be linear and has the form:

$$p(t) = c - bu(t) \tag{2.6}$$

where, $p(t)$ is the market price of the resource, $c$ is the choke price and $-b$ is the associated slope. Profit before the implementation of the tax in any period is the difference between net revenues $p(t)u(t)$ and costs $C(x,u)$. The time path of reserves is characterized as a continuous time deterministic process as follows:

$$\dot{x(t)} = -u(t) \tag{2.7}$$

The implementation date of taxes is uncertain and unknown to the profit maximizer. This can be understood in the context of a policy maker who lacks commitment to future policies, but has announced that a carbon tax ($\tau$) is likely to be implemented in the future. This tax is imposed on the per unit quantity of the resource extracted. After the implementation of the tax, the profit is the difference between net revenues $p(t)u(t)$ and costs $C(x,u)$ including the tax per unit times the amount of resource extracted $\tau u$. Here we characterize the firms' response in anticipation of a future carbon tax. This intuition is formalized by assuming that the date T at which the tax is implemented is a random variable with marginal density $\omega_T$ . In other words, we maximize the expected present value net profits derived from extracting and selling the resource, where the expectation is taken with respect to the probability distribution over possible values of T. Under the assumption that markets are perfectly competitive, producers maximize the present expected value of net profits by determining the optimal extraction path $u(t)$ given by:

$$V = Max \quad \int_0^\infty \omega(T)[\int_0^T (p(t)u(t) - C(x(t), u(t)))e^{-rt}dt + e^{-rT}V^F(x(T), \tau)]dT \tag{2.8}$$

subject to

$$x(t) \geq 0, u(t) \geq 0 \tag{2.9}$$

$$\dot{x(t)} = -u(t), \quad x_0 \ \ given, \tag{2.10}$$

In the above problem, the expected profit maximizing expression for a particular value of $T$ is given by the expression inside the square brackets. We then maximize this expectation overall all possible values of $T$ drawn from the marginal density

$\omega(T)$. The $V^F$ is the expected net present value after the tax change has occurred. The associated problem after time $T$ is therefore:

$$V^F = Max \quad \int_T^{\infty} (p(t)u(t) - C(x(t), u(t)) - \tau u(t))e^{-rt}dt \tag{2.11}$$

subject to

$$x(t) \geq 0, u(t) \geq 0 \tag{2.12}$$

$$\dot{x(t)} = -u(t), \quad x_T \ \ given, \tag{2.13}$$

Integrating by parts (Appendix 1), expression (8) can be reformulated as:

$$V = Max \quad \int_0^{\infty} [(p(t)u(t) - C(x(t), u(t)))\Omega(t) + \omega(t)V^F(x(t), \tau)]dt \tag{2.14}$$

where, $\Omega(t) = \int_t^{\infty} \omega(s)ds$. Note here that 1 - $\Omega(t)$ is the cumulative distribution function associated with the probability density function $\omega(t)$.

We restrict our analysis to the case in which a tax occurrence is announced by a policy maker that cannot commit to a certain date in the future. Further, firms' ability to adjust production is only permitted along the intensive margin. Practically, this translates to a firm that can only extract resources more intensively from existing PD reserves, but is not permitted to expand its PD reserve base. Firms form expectations over the probability of this tax occurring and change their behavior and market response accordingly. The usual solution to this problem would require solving the optimal control problems in (2.8) and (2.11) as two different regimes, before and after the tax change. Since our focus in the present paper is to understand the behavior of firms in anticipation of a tax change, we restrict our attention to the first phase of the problem before the tax change occurs as in equations (2.8) and (2.14). This means we assume that firms live in anticipation of a tax change that never really occurs, since we are solving till the point of resource exhaustion.

In equilibrium, markets for the extracted resource clear and the solution to the above problem gives us price, extraction and resource stock paths. The current value Hamiltonian of the competitive allocation associated with equation (2.8) is given as:

$$H = (p(t)u(t) - C(x(t), u(t)))\Omega(t) + \omega(t)V^F(x(t), \tau) - \lambda_1(t)u(t) \tag{2.15}$$

where $\lambda_1(t)$ is the co-state variable associated with $x(t)$. The complementary slackness conditions are:

$$u(t) \geq 0, \quad (p(t) - C(x(t)))\Omega_t - \lambda_1(t) \leq 0, \tag{2.16}$$

The other first order conditions are as follows:

$$\dot{\lambda_1(t)} - r\lambda_1(t) = uC_x(x(t))\Omega(t) - \omega(t)V_x^F(x(t)) \tag{2.17}$$

$$\dot{x(t)} = -u(t), \quad x(0) \;\; given \tag{2.18}$$

$$\lambda_1(t)e^{-rt} \geq 0, \;\; u(t)\lambda_1(t)e^{-rt} \to 0 \;\; as \;\; t \to \infty \tag{2.19}$$

Note that $\lambda_1(t)$ is the scarcity rent associated with depleting an additional unit of reserves. As resource extraction ensues, $u(t)$ approaches zero such that the transversality condition (19) holds in the limit and $x(t)$ never approaches zero (Appendix for Essay 1). This means that extraction of the resource will cease before the resource stock is fully exhausted. The solutions to the above conditions give us unique time paths for extraction, price and resource stock. Similarly, we can reformulate the optimal control problem as stated in (2.11),(2.12) and (2.13) to derive the current value

Hamiltonian and associated first order conditions and use them to evaluate the co-state $\lambda_1^F(t)$ associated with $x(t)$ after the tax change. The associated complementary slackness conditions are:

$$t \geq T, \quad u(t) \geq 0, \quad (p(t) - C(x(t)) - \tau) - \lambda_1^F(t) \leq 0, \tag{2.20}$$

From equivalence between the Hamilton-Jacobi-Bellman and Hamiltonian formulations, we know that the future co-state associated with $x(t)$ is the same as the future shadow value associated with a marginal change in $x(t)$.

$$\lambda_1^F(t) = V_x^F(x(t), \tau) \tag{2.21}$$

Using (2.16),(2.17),(2.20) and (2.21) and a simplification that the marginal density $\omega(t)$ follows an exponential distribution with mean arrival rate $\eta$ , we can derive the price path as follows (Appendix 3):

$$E_t[\dot{p(t)}] = r(p(t) - C(x(t))) + \eta\tau \tag{2.22}$$

Using equation (6) the extraction path is therefore:

$$E_t[\dot{u(t)}] = -\frac{1}{b}[r(p(t) - C(x(t))) + \eta\tau] \tag{2.23}$$

Mathematically, the above formulation implies that $\tau \geq 0$ and $\eta \geq 0$. Additionally, because the tax is never actually implemented, T $= \infty$, and we solve until extraction effectively ends, assuming firms continue to operate under the regime of a tax announcement. We can derive the anticipated price and extraction paths in the absence of an anticipated tax policy by formulating the optimal control problem above without considering the tax announcement. This is equivalent to saying that $\tau = 0$. This assumption would lead to the following optimal control problem:

$$V = Max \quad \int_0^\infty (p(t)u(t) - C(x(t), u(t)))e^{-rt}dt \tag{2.24}$$

subject to

$$x(t) \geq 0, u(t) \geq 0 \tag{2.25}$$

$$\dot{x(t)} = -u(t), \quad x_T \;\; given, \tag{2.26}$$

In the absence of an anticipated tax policy, the price and extraction paths can be solved and are as follows:

$$\dot{p(t)} = r(p(t) - C(x(t))) \tag{2.27}$$

$$\dot{u(t)} = -\frac{1}{b}[(p(t) - C(x(t))] \tag{2.28}$$

Equations (2.22) and (2.23) are indicative of the familiar green paradox effect. The announcement of a future tax incentivizes firms to extract more of the resource in the first few periods, depressing prices in the short run. Extraction is greater than the baseline in the first few periods and is subsequently lower in the later periods. The total amount of resource extracted relative to the baseline is ambiguous and depends on the date of actual implementation of the tax. Assuming emissions are proportional to the amount of resource extracted, the severity of this problem however, is dependent on the net present sum of damages as a consequence of this announcement. Further, short term increases in emissions are still a cause for concern and must be accounted for when designing appropriate climate policies. In the following sections we consider various extensions and formulations of this basic problem to allow for the divestment effect.

## 2.3 Inexhaustible but non-renewable resources: Intensive and extensive margin adjustment

In this section we supplement our model and consider that resource owners not only extract resources from existing PD reserves but also make investments to add to their existing pool of PD reserves (Pindyck, 1978). Adjustments are therefore permitted to occur along both the intensive as well as the extensive margins. The exploratory effort to undertake reserve addition per period is represented by $a(t)$ and the cumulative reserve additions are represented by $R(t)$. $a(t)$ is exploratory effort in the sense that it captures drilling of both developmental and exploratory wells. The function $f(a, R)$ is the reserve addition per period and is related to both exploratory activity $a$ as well as cumulative discoveries $R$. In addition we assume that the function $f(a, R)$ has the following properties:

$$f_a(a, R) > 0, f_{aa}(a, R) < 0, f_R(a, R) < 0 \tag{2.29}$$

For simplicity, we assume that $f_a(a, R) = f_a$, $f_{aa}(a, R) = f_{aa}$ and $f_R(a, R) = f_R$. The tractability of the model is maintained by assuming that reserve additions fall as cumulative discoveries increase. There is no physical limit associated with reserve discovery, however there are decreasing returns associated with exploratory activity. This assumption is consistent with Pindyck (1978). As far as the results of the model are concerned, this implies that the inter-temporal trade-off in exploration will dictate whether further exploration takes place, or exploration and extraction are both halted. Price will increase until the choke price is reached, just as exploratory activity, extraction and profits all fall to zero. At the terminal point, there is no benefit in exploring additional reserves. The model and data we use in this section are the same as used by Pindyck (1978) except that we consider the role of announced future taxes in the behavior of firms' extraction and drilling behavior and compare outcomes to the Pindyck (1978) baseline model. Our optimal control problem is therefore:

$$V = Max \quad \int_0^\infty \omega(T)[\int_0^T (p(t)u(t) - C_1(x(t), u(t)) - C_2(a(t)))e^{-rt}dt + e^{-rT}V^F(x(T), R(T), \tau)]dT \quad (2.30)$$

subject to

$$x(t) \geq 0, u(t) \geq 0, a(t) \geq 0 \tag{2.31}$$

$$\dot{x(t)} = \dot{R(t)} - u(t), \quad x_0 \ \ given, \tag{2.32}$$

$$\dot{R(t)} = f(a(t), R(t)), \quad R_0 \ \ given, \tag{2.33}$$

As with Pindyck (1978), $C_1(x(t), u(t))$ represents the cost associated with resource extraction and $C_2(a(t))$ represents the cost associated with effort undertaken to drill developmental and exploratory wells. Drilling and extraction are both represented as irreversible processes. As discussed in the previous section, we focus on the portion of the problem after the tax is announced but before its actual implementation. Using integration by parts (Appendix for Essay 1), equation (2.30) can be reformulated as:

$$V = Max \quad \int_0^\infty [(p(t)u(t) - C_1(x(t), u(t)) - C_2(a))\Omega(t) + \omega(t)V^F(x(t), R(t), \tau)]dt \tag{2.34}$$

where, $\Omega(t) = \int_t^\infty \omega(s)ds$. The current value Hamiltonian associated with this problem is given as :

$$\begin{aligned} H = (p(t)u(t) - C_1(x(t), u(t)) - C_2(a(t)))\Omega(t) + \omega(t)V^F(x(t), R(t), \tau) + \\ \lambda_1(t)(f(a(t), R(t)) - u(t)) + \lambda_2(t)(f(a(t), R(t)) \quad (2.35) \end{aligned}$$

where $\lambda_1(t)$ and $\lambda_2(t)$ are the co-states associated with $x(t)$ and $R(t)$ respectively. The complementary slackness conditions are as follows :

$$u(t) \geq 0, \quad (p(t) - C_1(x(t)))\Omega_t - \lambda_1(t) \leq 0, \qquad (2.36)$$

$$a(t) \geq 0, \quad -C_{2a}(a(t))\Omega(t) + (\lambda_1(t) + \lambda_2(t))f_a(a(t), R(t)) \leq 0, \qquad (2.37)$$

The other first order conditions are as follows:

$$\dot{\lambda_1} - r\lambda_1 = uC_{1x}(x(t))\Omega(t) - \omega(t)V_x^F(x(t), R(t), \tau) \qquad (2.38)$$

$$\dot{x(t)} = \dot{R(t)} - u(t), \quad x(0) \ \ given \qquad (2.39)$$

$$\dot{\lambda_2} - r\lambda_2 = -\omega(t)V_R^F(x(t), R(t), \tau) - (\lambda_1 + \lambda_2)f_R(a(t), R(t)) \qquad (2.40)$$

$$\dot{R(t)} = f(a(t), R(t)), \quad R(0) \ \ given \qquad (2.41)$$

$$u(t)\lambda_1(t)e^{-rt} \to 0 \;\; and \;\; f(a(t), R(t))(\lambda_1 + \lambda_2)(t)e^{-rt} \to 0 \;\; as \;\; t \to \infty \tag{2.42}$$

Note here that $\lambda_2(t)$ is the marginal value associated with cumulative exploration or drilling $R(t)$. Exploratory effort $a(t)$ ceases in the limit, so that extraction also ceases. This is easy to understand as instantaneous profit is driven down to zero in the limit. For the rest of the problem, we continue with our assumption that $T$ follows an exponential distribution $\omega(t)$ with mean arrival rate $\eta$. Using equations (2.36) and (2.38) and the fact that the future shadow value associated with marginal extraction is equivalent to the co-state for $x(t)$, i.e $V_x^F(x(t), R(t), \tau) = \lambda_1^F(t)$, we can solve for the producer's price and extraction paths (Appendix for Essay 1):

$$E_t[\dot{p(t)}] = r(p(t) - C_1(x(t))) + f(a(t), R(t))C_{1x}(x(t)) + \eta\tau \tag{2.43}$$

$$E_t[\dot{u(t)}] = -\frac{1}{b}[r(p(t) - C_1(x(t))) + f(a(t), R(t))C_{1x}(x(t)) + \eta\tau] \tag{2.44}$$

These results are similar to those in Pindyck (1978) except that we now see the effect of a tax $\tau$ highlighting a green paradox effect. The strength of this effect depends on how drilling responds to, and consequently impacts, the effective amount of reserves available for extraction. Similarly, we can use equations (2.36), (2.37) along with equations (2.42), (2.38) and (2.40) to derive the drilling path (Appendix for Essay 1):

$$E_t[\dot{a(t)}] = \frac{C_{2a}(a)[\frac{f_{aR}}{f_R}f - f_R + r] + uC_{1x}(x(t))f_a}{C_{2aa}(a(t)) - C_{2a}(a(t))\frac{f_{aa}}{f_w}} \tag{2.45}$$

Note that equation (2.45) looks exactly the same as that derived by Pindyck (1978). Even though the expression for the rate of drilling does not directly depend on tax $\tau$, the tax still has an effect on it. This is because $\tau$ has an effect on the extraction path which affects the stock of resource $x(t)$. Drilling depends on the stock $x(t)$ and is therefore indirectly impacted by the tax $\tau$. The effect of the tax however is hard to determine directly from the expressions listed above. Further, changes in reserve additions will also feed back and impact the price and extraction paths in ways that are not easy to conceptualize without a numerical assessment. On the one hand, firms may preemptively drill and/or mine more and build up a larger stock of PD reserves to reduce the costs associated with extraction in the future when a tax is introduced. On the other hand, firms may find it more profitable to extract more now and simultaneously reduce the cumulative amount of PD reserves added. To clarify the effect of the tax, we numerically simulate the model in the next section to illustrate the effect of the tax on price, extraction and drilling paths and compare it to a baseline without an announced tax.

## 2.4 Numerical assessment of anticipated taxes

The goal of this section is to evaluate the implications of our modelling assumptions in an empirical context in which we compare the outcomes associated with an anticipated tax relative to the outcomes in the absence of a tax. Note that the purpose of this numerical assessment is not to test the empirical predictions of the model but to understand the trends associated with extraction, price and drilling dynamics in the presence and absence of a tax. The model we developed would need to be adapted and expanded if we were to model different regions with and without a tax, and is left for future work. To ease comparison, like Pindyck (1978) we use data from the Permian region of Texas between 1965 and 1975 and calibrate our functional forms $f(a, R)$ , $C_1(x)$ and $C_2(a)$ to this dataset as follows:

$$C_1(x(t)) = m/x(t) \tag{2.46}$$

$$f(a(t), R(t)) = 10.9a(t)^{0.6}e^{-0.0002258R(t)} \tag{2.47}$$

$$C_2(a(t)) = 0.067a(t) + 103.2 \tag{2.48}$$

$$u(t) = 660 - 20p(t) \tag{2.49}$$

We assume, $m = 8960$ million \$ , $x(0) = 7170$ million barrels and $R(0) = 0$ million barrels and an anticipated tax $\tau = 1.5$ \$ per barrel (about 4.75 \$ per tonne of $CO^2$) that has a mean time to arrival of $\frac{1}{\eta} = 10$ years, so that the mean hazard rate of the process is $\eta = 0.1$. We assume that this tax is first announced in the year 1966. Also, $a$ is in units of number of wells, $u$ is in units of million barrels and $p$ is in units of \$ per barrel so that $C_1(x)u$ and $C_2(a)$ are in units of millions of 1966 \$ . We first solve the problem without drilling to highlight the role of the green paradox. This is obtained by solving (2.22) with (2.18) (with anticipated tax) and comparing it to a baseline in which we solve (2.27) with (2.18) (no anticipated tax). This can be reformulated as:

$$E_t[\dot{p(t)}] = 0.05p(t) - \frac{450}{x(t)} + 0.10 * 1.5 \tag{2.50}$$

$$\dot{x(t)} = -(660 - 20p(t)) \tag{2.51}$$

With boundary conditions:

$$p(T_f) = 33 \quad , \quad x(0) = 7170 \tag{2.52}$$

In equation (2.50) above, $0.10 * 1.5$ is the product of mean arrival rate and the anticipated tax. The boundary condition on $p(t)$ is also the choke price associated with resource extraction calculated from (2.49) by substituting $u(t) = 0$. Note that equations (2.50), (2.51) and (2.52) form a free boundary problem, where the boundary at $T_f$ is free and needs to be endogenously determined. $T_f$ is the time at which $u(T_f)$ and average profit both fall to 0 but a certain amount of the resource stock is left in the ground. Stock effects prevent the resource from being physically exhausted but the level of the stock at $T_f$ is known as the point of economic exhaustion. These free boundary problems may seem hard to solve at first glance, but can be solved by repeatedly varying the initial condition on $p(0)$ until satisfying the terminal condition that $u(T_f)$ and average profit are simultaneously 0, while $x(T_f)$ is larger than 0. In our code, we varied the initial conditions to achieve convergence as discussed here.

As predicted, firms react to the announcement of a tax with an uncertain imple-

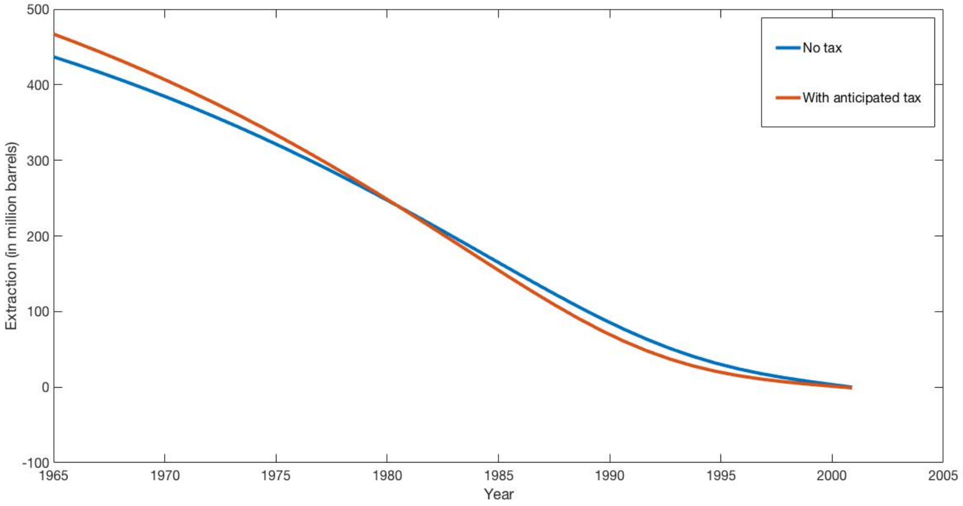

**Figure 2.1**: Extraction for exhaustible resources

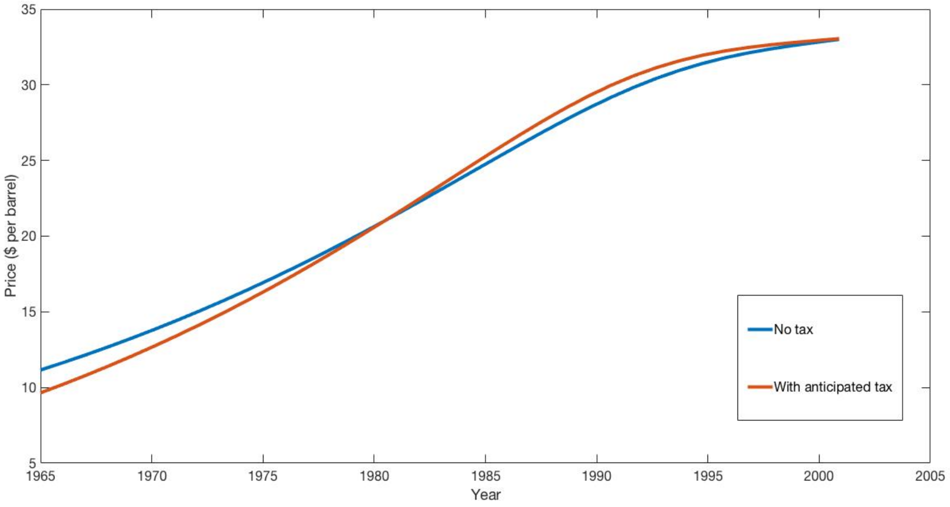

**Figure 2.2**: Price for exhaustible resources

mentation date and advance extraction from their existing reserves. Figures 2.1 and 2.2 show that from the date of announcement, extraction under an announced tax exceeds the baseline for about fifteen years, when in year 1980 extraction with the anticipated tax falls below the case with no tax. Both cases predict that extraction ceases at about the same time around 2002-2003. In this instance, the effect of the green paradox is the effect of excess extraction between 1965 and 1980, as a consequence of anticipated carbon taxes. This is also the period when prices are lower as compared to a baseline without announced taxes.

We now solve the problem with and without a tax by including drilling as an additional control variable and compare our outcomes to the case with no drilling. This is obtained by solving a coupled system of (2.43),(2.45),(2.39) and (2.41), which is reformulated as:

$$E_t[\dot{p(t)}] = 0.05p(t) - \frac{450}{x(t)} - \frac{9.81 * 10^4}{x(t)^2}(a(t)^{0.6})e^{-0.0002258R(t)} + 0.10 * 1.5 \tag{2.53}$$

$$\dot{x(t)} = -(660 - 20p(t)) + 10.9a(t)^{0.6}e^{-0.0002258R(t)} \tag{2.54}$$

$$E_t[\dot{a(t)}] = 0.125a(t) - \frac{2.196 * 10^6(660 - 20p(t))}{x(t)^2}(a(t)^{0.6})e^{-0.0002258R(t)} \tag{2.55}$$

$$\dot{R(t)} = 10.9a(t)^{0.6}e^{-0.0002258R(t)} \tag{2.56}$$

With boundary conditions:

$$p(T_f) = 33 \quad , \quad x(0) = 7170 \quad , \quad R(0) = 0 \quad , \quad a(T_f) = 0, \tag{2.57}$$

Using methods we discussed for the case with no drilling, we repeatedly start at different values of $p(0)$ and $a(0)$, until we find a time point $T$ at which $u(0)$, $a(0)$ and average profit are simultaneously zero. Alternatively, we can use the ossolve code from the CompEcon toolbox in MATLAB to derive the following price and extraction paths.

Figures 2.3 and 2.4 show that the big difference between the case with drilling compared to the case without drilling is that the presence of drilling shortens the time period associated with the green paradox outcome.

While in the case with no drilling, the effect of advanced extraction lasted for around fifteen years, this effect is substantially shortened to seven years with the introduction of drilling, weakening the effect of the green paradox. Figures 2.3 and 2.4 show that the divergence between the amounts extracted grows over time in the

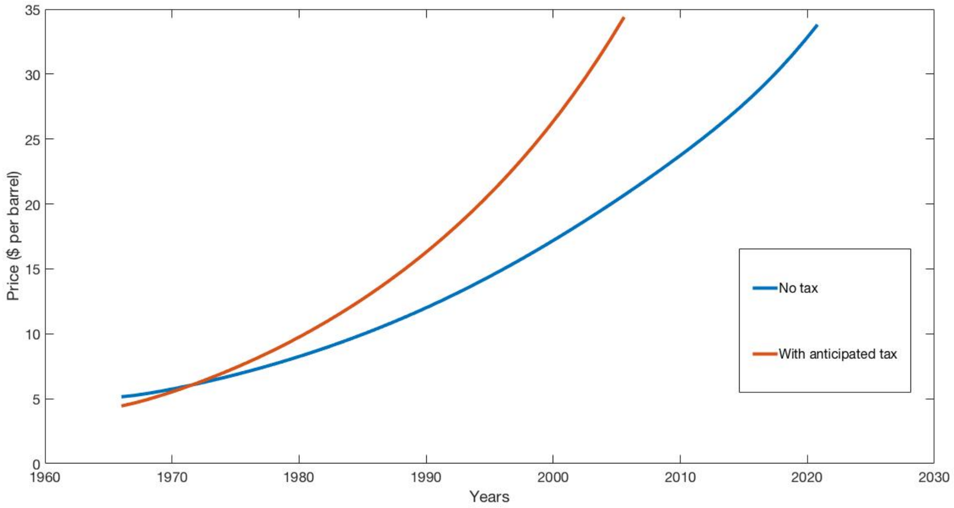

**Figure 2.3**: Price for inexhaustible but non-renewable resources

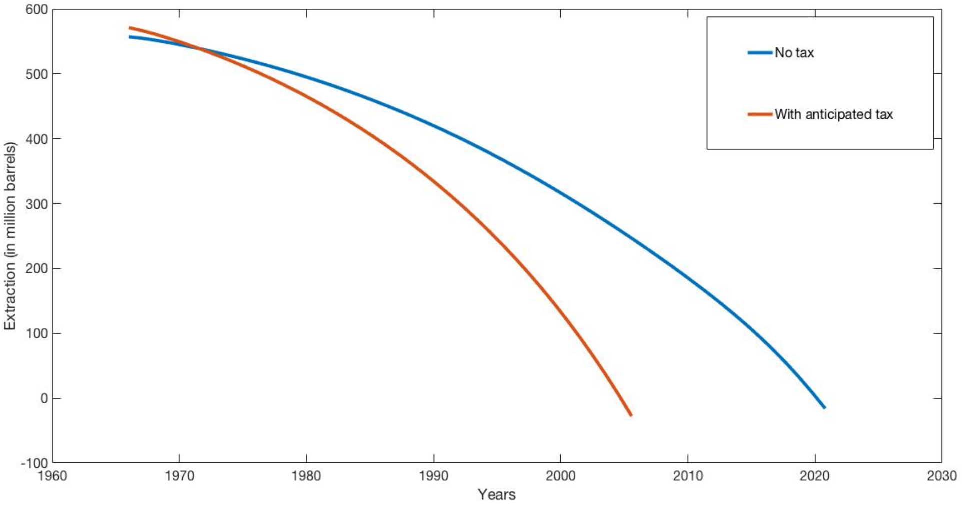

**Figure 2.4**: Extraction for inexhaustible but non-renewable resources

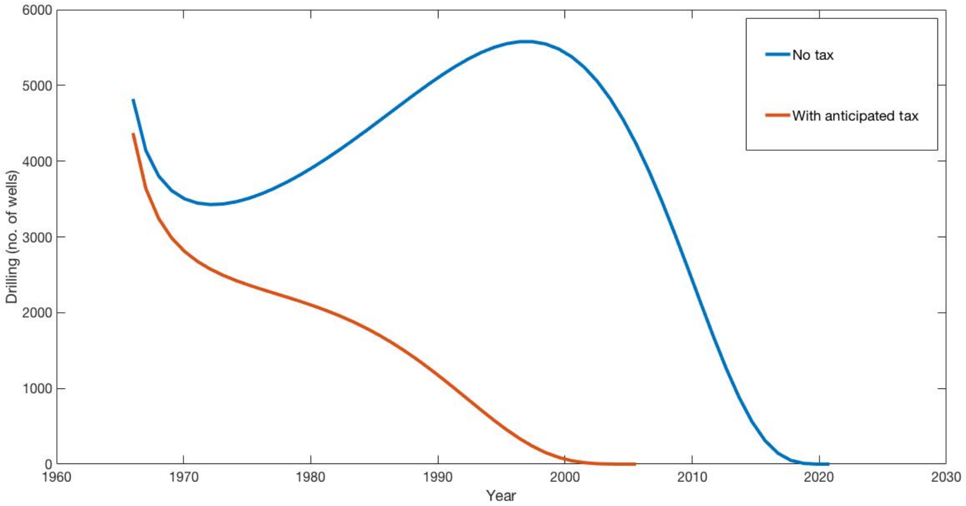

**Figure 2.5**: Drilling for inexhaustible but non renewable resources

case with drilling, implying that drilling responds in a way that decreases the effective amount of reserves available for extraction. To understand the effect of drilling, we look at the drilling paths for the case with and without an anticipated tax.

Figure 2.5 shows that an anticipated tax has the effect of reducing investment in drilling, thereby reducing the effective amount of reserves available for extraction. Not only do firms always drill less right from the beginning in the case with an anticipated tax, drilling also terminates about fifteen years prior to the case without a tax announcement. The growing divergence in extraction and price paths can be explained by the reduced amount of cumulative exploration over time in the case with a tax announcement. There are therefore two effects that simultaneously take place and feed back with each other: (i) Firms increase extraction from existing reserves, but (ii) Firms drill less right from the beginning. The cumulative effect is a much weaker green paradox effect that is brief (seven years and lasts till 1972) and increases extraction along the intensive margin and a strong reduced investment effect along the extensive margin that starts at the point of announcement of the tax. It is worth noting that the presence of the reduced investment effect is conditional on the existence of stock effects. It can be seen from (45) that in the absence of stock effects, depletion and marginal depletion costs would disappear such that only the green paradox effect would remain. In the presence of reserve depletion costs however, the implications are that the net effect of tax announcements are far less pessimistic when one considers the role of reduced investment in conjunction with the green paradox. Thus far we have shown that allowing firms to adjust production by varying PD reserves along the extensive margin, in addition to the standard model of adjustment along the intensive margin weakens the green paradox by strengthening the reduced investment effect. In the next section we consider an empirically relevant oil extraction model where adjustment is restricted to the extensive margin.

## 2.5 Hotelling as a drilling problem: Extensive margin adjustment

Using data from oil reserves in Texas, we reiterate the result demonstrated by Anderson, Kellog and Salant (2018). The authors discuss that recent evidence from oil drilling and extraction in Texas demonstrates two main features: 1) Production is strictly determined by a physical process and, 2) drilling responds to changes in prices. Based on this evidence, they developed a modified Hotelling model where drilling is the only control variable and extraction is a stock variable that depends on the number of drilled wells. In line with Anderson, Kellog and Salant (2018), we make a further empirically consistent assumption that production always occurs at the constraint. These modifications and assumptions effectively restrict PD reserve adjustments to occur only along the extensive margin. Since production is always at the constraint, the only way it can change is through the number of wells drilled. Note that unlike the model in Section 2.3, variable a(t) here corresponds to drilling activity and not exploratory effort. Additionally, consistent with empirical evidence, the cost of extraction is very low in relation to costs associated with setting up drilling infrastructure and is therefore assumed away. We extend the same model and assume that the representative firm faces the prospect of a carbon tax in the future.

$$V = Max \quad \int_0^\infty \omega(T)[\int_0^T (p(t)u(t) - D(a(t)))e^{-rt}dt + e^{-rT}V^F(x(T), R(T), \tau)]dT \tag{2.58}$$

subject to

$$0 \leq u(t) \leq x(t), \quad R(t) \geq 0 \tag{2.59}$$

$$\dot{x(t)} = a(t)X - \mu u(t), \quad x_0 \ \ given, \tag{2.60}$$

$$\dot{R(t)} = -a(t), \quad R_0 \ \ given, \tag{2.61}$$

We solve the model for the interim between announcement and actual implementation of the tax. We consider two scenarios, one where the firm drills in the absence of a tax announcement and the other where firms drill anticipating a tax change in the future. Following Leonard-Long(1992), the current value Hamiltonian is as follows:

$$H = (p(t)u(t) - D(a(t)))\Omega(t) + \omega(t)V^F(x(t), R(t), \tau) +$$

$$\lambda_1(t)(a(t)X - \mu u(t)) - \lambda_2(t)(a(t)) + \phi(t)(x(t) - u(t)) \quad (2.62)$$

where $\lambda_1(t)$ and $\lambda_2(t)$ are the co-states associated with $x(t)$ and $R(t)$ respectively and $\phi(t)$ is the shadow cost associated with the oil flow constraint. We assume that $\frac{d(D(a(t))}{da} = d(a(t))$. The complementary slackness conditions are as follows :

$$u(t) \geq 0, \quad p(t)\Omega_t - \mu\lambda_1(t) - \phi(t) \leq 0, \quad (2.63)$$

$$a(t) \geq 0, \quad -d(a(t)) + \lambda_1(t)X - \lambda_2(t) \leq 0, \quad (2.64)$$

The other first order conditions are as follows:

$$\dot{\lambda_1}(t) - r\lambda_1(t) = -\omega(t)V^F_x(x(t), R(t), \tau) - \phi(t) \quad (2.65)$$

$$\dot{x}(t) = a(t)X - \mu u(t), \quad x(0) \;\; given \quad (2.66)$$

$$\dot{\lambda_2}(t) - r\lambda_2(t) = -\omega(t)V^F_R(x(t), R(t), \tau) \quad (2.67)$$

$$\dot{R}(t) = -a(t), \quad R(0) \;\; given \tag{2.68}$$

$$x(t) - u(t) \geq 0, \quad \phi(t) \geq 0, \;\; c.s \tag{2.69}$$

$$x(t)\lambda_1(t)e^{-rt} \rightarrow 0 \;\; and \;\; R(t)\lambda_2(t)e^{-rt} \rightarrow 0 \;\; as \;\; t \rightarrow \infty \tag{2.70}$$

The solution to these conditions is unique under weak sufficiency. Like Anderson, Kellog and Salant (2018) we assume that firms operate under an empirically relevant production constraint where $\phi(t) = 0$ and $u(t) = x(t)$. In other words, production is always at capacity and does not respond to prices. We further assume that the price path $p(t) = P$ is exogenous and independent of time. Using the property of equivalence for, $\lambda_1^F(t) = V_x^F(x(t), R(t), \tau)$ and, $\lambda_2^F(t) = V_R^F(x(t), R(t), \tau)$, and assuming $\omega(t)$ is drawn from the marginal density of an exponential distribution, we solve (63), (65) and (67) to derive:

$$\lambda_1^F(t) = \frac{P}{r + \mu} \tag{2.71}$$

$$\lambda_1(t) = (\frac{P}{r + \mu} - \frac{\eta\tau}{(r + \mu)(r + \mu + \eta)})e^{-\eta t} \tag{2.72}$$

$$\lambda_2^F(t) = \gamma_0 e^{rt} \tag{2.73}$$

$$\lambda_2(t) = \gamma_0 e^{-\eta t} e^{rt} \tag{2.74}$$

Assuming $a(t) \geq 0$, we can now solve (2.72) and (2.74) with (2.64) to derive the drilling paths with and without the announced tax:

$$d(a(t)) = (\frac{P}{r+\mu} - \frac{\eta\tau}{(r+\mu)(r+\mu+\eta)})X - \gamma_0 e^{rt} \tag{2.75}$$

$$d(a(t)) = (\frac{P}{r+\mu})X - \gamma_0 e^{rt} \tag{2.76}$$

The rate of drilling declines over time and ceases at the point at which $R(T_f) = 0$ (the stock of drillable wells is exhausted). This condition uniquely determines $\gamma_0$ and implies that the time of exhaustion $T_f$ must satisfy (2.75) and (2.76) where $a(T_f) = 0$. To determine both $T_f$ and $\gamma_0$, we solve (2.75) or (2.76) with $-R_0 = \int_0^{T_f} a(t)dt$.

Comparing (2.75) and (2.76) we can see that well drilling under an anticipated tax will be lower than without an announced tax. Also, since drilling is lower with an

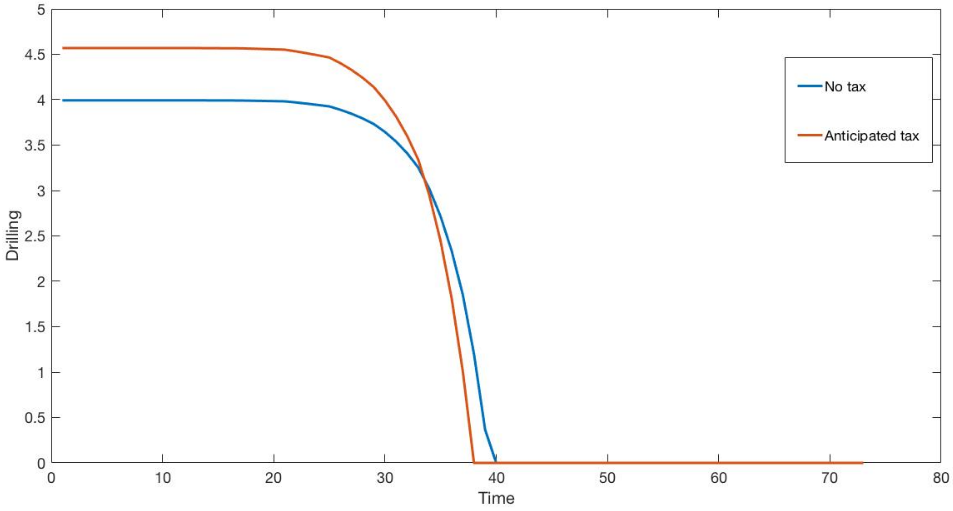

**Figure 2.6**: Drilling dynamics with and without a tax
We assume p(t) = 100\$, x0 = 0, R0 = 100, $\mu$ = r = 0.1, X = 0.05, $\tau$ = 20\$ and $\eta$ = 0.40. Further, we assume d(a(t)) = 1 + 5a(t)

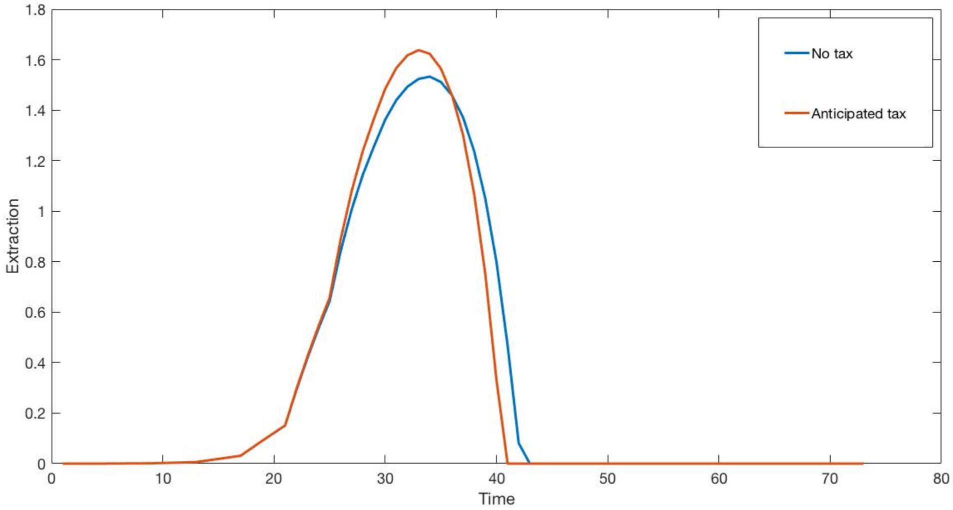

**Figure 2.7**: Extraction dynamics with and without a tax
We assume p(t) = 100\$, x0 = 0, R0 = 100, $\mu$ = r = 0.1, X = 0.05, $\tau$ = 20\$ and $\eta$ = 0.40. Further, we assume d(a(t)) = 1 + 5a(t)

announced tax, the time to exhaustion of the stock will be longer as seen in Figure 2.7. In other words, the announcement effect of a tax makes firms delay investment in drilling and as a result extraction is also lower and delayed under an anticipated tax. The effect of advanced extraction (the green paradox) is not seen because firms always operate at production capacity. Our formulation assumes that production capacity is a stock variable that can only be adjusted through drilling. If firms could adjust both production as well as drilling as control variables then the results of the model would look similar to the previous example. In our current formulation firms' production paths are naturally constrained (as is often the case with oil wells), and therefore only the reduced investment effect matters for the firms' anticipated response which reduces emissions in the short and medium run. Emissions in the longer run may however be higher, as firms now have an incentive to delay PD reserve additions until the end of the planning horizon, as there is less value to holding a larger stock of reserves.

Another key point of comparison between the results of this formulation and the previous one is the distinction between the planning horizons. While the planning horizon in this case is longer under the anticipated tax scenario, it is shorter in the previous example. This difference is attributable to the response margins and the extraction cost functions for firms in both cases. In the previous case, the anticipated tax directly affects the intensive margin response. This causes a green paradox effect in the short run that leads to lower drilling and more cumulative extraction over the first few periods. As can be judged from the numerator in (2.45), this short run response leads to lower cumulative reserve additions and a more rapidly falling extraction path in the longer run through its effect on the marginal depletion cost $C_1(x)$. Consequently, extraction and drilling cease much earlier with an anticipated tax. In the extreme case with no stock effects, only the green paradox effect would persist while the reduced investment effect would vanish such that the planning horizons for the tax and no tax scenarios would be the same. In the present formulation, an anticipated tax effects the extensive margin response through its direct effect on drilling (2.72). This in combination with the fact there is no cost associated with extraction means firms drill less and delay extraction so that the time to exhaustion of the resource is longer.

It is useful to reflect on how the type of natural resource may influence the likelihood of the green paradox and reduced investment effects. In case of production constrained oil wells, the green paradox is unlikely as adjustment is impossible along the intensive margin of production. In case of a natural resource like coal however, we could still see a small green paradox effect as the behavior of the firm is most likely to resemble a profit maximizing agent that is able to adjust production both along the intensive as well as the extensive margins, like the model we discussed in Section 2.

## 2.6 Downstream divestment and the green paradox

Our discussion so far has focused on extraction and investment dynamics upstream at the point of mining/drilling of the resource, however downstream investments in fossil fuel infrastructure are also likely to be affected by anticipated climate friendly policies (Bauer et. al, 2018). This is especially relevant in the context of coal which is a major source of fossil fuel emissions but has little use outside of electricity generation. Most coal that is produced in the U.S is used for electricity generation, and some of it is exported (EIA, 2017). We present here some empirical results on the production and consumption of coal in the U.S.

The decline in consumption of coal in the electricity sector coincides with the decline in coal production and divestment from coal power plants in the electricity sector. These results can be rationalized with a model of an electricity generating coal power plant owner who makes dynamic decisions on investing and maintaining capital for electricity generation. Additional modelling assumptions can be made by observing that the decline in U.S coal generation is determined by two main trends: (1) declining average utilization in coal plants and, (2) a reduction in total coal generation capacity due to retirements. These trends however are also, coincident with a flattening of electricity demand since 2010 . Additionally, much empirical evidence has shown that the abundance of coal as a resource means that it does not behave as a Hotelling resource under scarcity. A rich characterization of the model would also consider competition between energy sources, such as natural gas and renewables with coal in the electricity sector.

The consideration of these features would only strengthen our conclusion by demonstrating downstream reduced investment in addition to the upstream reduced investment effect we have shown. A countervailing effect may exist however if we see a future increase in demand for coal. This is unlikely in the context of coal use for the U.S but may be a possibility if U.S exports of coal grow over time to feed the growing demand for coal in India and sub-Saharan Africa (Thuber and Morse, 2015). In such a scenario, both the reduced investment and the green paradox effects are likely to be weaker. The green paradox effect will weaken as the prospect of increasing future demand will mitigate the need to extract pre-emptively while the prospect of larger demand in the future will incentivize making investments that expand the base of PD reserves. These and other extensions are left for future research.

## 2.7 Conclusion

Most theoretical characterizations of the green paradox use the basic version of the Hotelling model and fail to demonstrate the divestment effect. We show that if we supplement the basic Hotelling model with more realistic representations of extraction and drilling/ mining dynamics the effect of reduced investment becomes significant and weakens the long term effect of the green paradox. We accomplish this by first integrating drilling/ mining as a simultaneous control alongside extraction and show that even though the green paradox persists, its effect is substantially weakened and the time duration of its existence is shortened. Further, when we consider an empirically consistent oil extraction model with a physical constraint on oil production, the effect of the green paradox vanishes in favor of reduced investment from drilling.

This framework can be extended in several logical ways. First, we consider future uncertainty in the time of arrival of the tax. While the arrival date of future carbon policies is certainly uncertain, the magnitude of these taxes and their time paths are also unknown and should be considered in future extensions of the model. While we consider irreversible investments in PD reserve additions (mining/drilling infrastructure), a more realistic representation would model these as fixed cost investments like Venables (2014). In this case, each unmined resource site and undrilled well can be characterized as a real option. Incorporating uncertainty in the value associated with making these fixed cost investments would add further realism to the model. A useful addition could be the consideration of the electricity generation sector as discussed in the previous section. Further, the integration of a model for used capital could allow us to model retirements of coal power plants and other fossil fuel based infrastructure.

# Chapter 3

# Geoengineering and institutional design for credible carbon policies

This essay is currently under submission in **Socio-Environmental Systems Modelling**. The article has been reformatted for the purposes of this dissertation.

### Authorship:

**Varun Mallampalli** - Idea generation, deriving the mathematical calculations and proofs, drafting the article

**Mark Borsuk** - Funding the study, draft revisions, finalizing the article

## 3.1 Introduction

The prospect of climate intervention has gained particular attention from policy makers and researchers in the past few years. The two approaches – (i) capturing and storing carbon, and (ii) changing the reflectivity of earth (solar radiation management), are not a substitute for cutting the probabilities of damages and impacts associated with $CO_2$ emissions and other green-house gases, but are likely to become an alternative to climate mitigation and adaptation. While capturing and storing carbon addresses the issue directly, by lowering the atmospheric concentration of $CO_2$, it is technologically expensive and solar radiation management (SRM) via stratospheric aerosol injection (SAI) is now being seen as a cheaper, quicker and more scalable alternative (Smith and Wagner, 2018). SAI is the injection of particles in the stratosphere that reflect the incoming solar radiation and can in principle be cheaply and easily conducted with airplanes and/or balloons (Hulme, 2012). With research being devoted to understanding the effects of SAI, it is no longer a distant reality that we might soon be able to manipulate the climate and temperature on a global scale (Victor et. al, 2009). The increasing likelihood of SAI implementation is seen by many as a factor that could delay or reduce the incentive to mitigate by relevant actors (Heutel et. al, 2016). A large part of a successful mitigation strategy involves incentivizing firms to make investments that allow for a transition towards cleaner technology (Acemoglu and Rafey, 2018). Even if SAI is a feasible strategy, given the uncertainty associated with government's ability to commit to various climate change response strategies, it is unclear how effective current mitigation efforts through firms' investment decisions will be (Acemoglu and Rafey, 2018).

Geoengineering (SRM) is an appealing third option because of its ability to readily deal with temporary temperature overshoots. In fact, a recent IPCC report (Bongaarts, 2019) reiterated this point highlighting that drastic measures such as SRM may be used in conjunction with mitigation and adaption, in particular to deal with extreme temperatures, sea level rise and intense tropical cyclones. There is a small and growing literature looking at the environmental economic implications of geoengineering (Heutel et. al, 2016; Moreno-Cruz, 2015; Acemoglu and Rafey, 2018). Most of the past literature can be divided into two branches. A first branch looks at the governance of geoengineering (Barret, 2014) . Barrett argues that the idea of geoengineering reducing current mitigation assumes that geoengineering implementation by a single actor imposes no drastic side effects that might lead to strategic counter behaviour by others. While countries most likely to use geo-engineering have a reduced incentive to mitigate, other countries have the opposite incentive and may increase mitigation. This may in turn, remove the incentive for the deployment of geoengineering in the future. Morten and Moreno Cruz (2018) discuss that this counter behavior could also result because countries have different preferences for their desired temperatures and may actively engage in a climate conflict by choosing to reverse others' geoengineering efforts. Emmerling and Tavoni (2017) construct an analytical model for a social planner's two-period decision on mitigation (1st stage) and mitigation and geoengineering (2nd stage), with learning about the uncertainty of geoengineering's effectiveness and the climate sensitivity. Applying both cost effectiveness and cost benefit analysis, and conducting further analysis with the WITCH integrated assessment model, they find that a geoengineering response substitutes for mitigation and decreases in the probability of its own success. Moreno-Cruz (2015) considers the strategic interaction between countries to understand if geoengineering potentially increases the free riding effect of mitigation. He finds that geoengineering could reduce mitigation with similar countries, but induces inefficiently high levels of mitigation with asymmetric countries. Acemoglu and Raffey (2018) study incentives by energy producers to adopt clean technologies when governments impose carbon taxes without commitment. They show how geoengineering advances reduce future carbon taxes and thereby incentives to invest in clean technology, effectively reducing societal welfare. A second branch looks at the optimal use of SRM. Heutel et al., (2018) consider the implications of uncertainty over geo-engineering damages and climate sensitivity to determine the optimal use of geo-engineering. They find that uncertainty over climate sensitivity increases both mitigation as well as geo-engineering efforts, and uncertainty over the damages associated with geo-engineering reduce its deployment. Heutel, Moreno-Cruz and Shayegh (2016) incorporate geo-engineering into the DICE Integrated assessment model, with climate tipping points and show that the capacity of geoengineering to deal with climate damages depends on the type of tipping point.

Most integrated assessment models that are used to price carbon assume the structure of a central social planner, who is able to commit to climate policies like carbon taxes in the long run (Schneider and Kuntz-Duriseti, 2001). The core idea in these models is to solve inter temporal optimization problems, where the time path associated with carbon taxes is fully known by the social planner at the start of the planning horizon. In fact, several real world examples highlight how governments make and then revise environmental policies: (i) Canada's withdrawal from the Kyoto Accord in 2011 (ii) Australia's repeal of a carbon tax in 2014 (iii) Rollback of E.P.As clean power plan in 2017. These examples may be highlighting cases where governments, and hence their preferences, changed or even cases where governments were acting in a non-benevolent fashion. However, economic theory highlights that even benevolent governments who lack the ability to commit to the future will deviate from their past promises if they feel such deviation is in society's best interest. The seminal work on this was by Kydland and Prescott (1977), who studied lack of commitment by a government on inflation and firms' responses leading to higher unemployment and inflation in the longer run. In this context, a time inconsistent social planner is one that prefers one policy in advance and another one when the time to implement a policy arrives. Unanticipated outcomes may then arise if other rational actors respond to the government's inability to commit and act in ways that subsequently reduce overall societal welfare.

There is a related but small literature on environmental policy without commitment (Karp and Newbery, 1993). Laffont and Tirole (1996) study how the usual hold-up problem arises in a two-period setting when there is asymmetric information in innovation and pollution permit markets. Harstad (2012) and Battaglini and Harstad (2016) study bargaining in the presence of multiple regulators. They show that each regulator underinvests in clean technology in fear of a weakened bargaining position with respect to other regulators. Also Harstad (2016) studies an environmental policy maker that makes time inconsistent choices because of hyperbolic discounting, and finds that time inconsistency rationalizes subsidies at a similar level to other kinds of market failures like externalities and technological spillovers. Acemoglu and Raffey (2018) show how the presence of geo-engineering technologies may actually reduce welfare by disincentivizing firms' clean energy investments. This paper is most similar to the work by Acemoglu and Raffey (2018) except that I model the decision to use SRM as an endogenous and continuous variable. I develop a theoretical model of government and firm behavior and ask two questions: 1) How do incentives for mitigation by private actors change when time inconsistent governments have the ability to implement geo engineering? and, 2) What institutional solutions can ensure that incentives for mitigation are not lost with the prospect of geo-engineering? To do this, I develop a 2 stage game theoretic framework with strategic interaction between government and firms. Section 3.2 lays out the main assumptions regarding the costs of investment in abatement technology and geoengineering, the damage function and the objective functions for both the firms and the government. Section 3.3 solves and characterizes the equilibrium solution and compares outcomes between a time inconsistent and a time consistent government in the presence and absence of geoengineering. Section 3.4 discusses implications and lessons from monetary policy and lays out next steps regarding institutional design of an independent environmental authority. Section 3.5 develops a model with an independent environmental authority and compares its equilibrium outcomes with the model in Section 3.3. Finally Section 3.6 concludes.

## 3.2 Base model characteristics

Consider a model with firms and the government. This economy consists of a range of energy related activities that are parsimoniously represented in the form of an abatement cost and environmental damage model. We start by representing environmental damages. Total emissions are a sum of all emissions by firms:

$$E = \sum_{i=1}^{i=n} e_i \tag{3.1}$$

Here, every $i$ represents a firm and $n$ represents the number of firms in the economy. The stock of carbon in the atmosphere $S$ is a function of total emissions $E$, the initial stock of carbon in the atmosphere $S_0$ and the natural depletion rate of carbon $\delta$:

$$S = (1 - \delta)S_0 + E \tag{3.2}$$

Damages are a function of the total stock of carbon and the amount of SRM $0 < \eta < 1$ in the atmosphere:

$$D(S, \eta) = (1 - \eta)D(S) \tag{3.3}$$

$D$ is an increasing, twice continuously differentiable and strictly convex function. For sake of simplicity, we assume all firms are identical $\sum_{i=1}^{i=n} e_i = ne$. We assume the firm's abatement cost function is $C(e, K)$, where $K$ denotes the amount of investment (in non monetary units), and lowers both abatement as well as marginal abatement cost functions. We make the following assumptions:

$$-C_e(e, K) > 0 \;\; for \;\; e < \hat{e} \tag{3.4}$$

$$C_K(e, K) < 0, \;\; -C_{eK} < 0 \;\; for \;\; e < \hat{e} \tag{3.5}$$

$$C_{ee}(e, K) > 0, \;\; C_{KK}(e, K) > 0, \;\; C_{ee}(e, K)C_{KK}(e, K) - [C_{eK}(e, K)]^2 > 0 \tag{3.6}$$

The first property (3.4) states that marginal abatement costs are positive for emissions below some non-regulated baseline emission level $\hat{e}$. Property (3.5) states that investment lowers both abatement and marginal abatement costs and (3.6) guarantees the overall convexity of the cost function. In this economy we introduce divergence between the private and social values associated with investment in abatement technology, such that firms can benefit from the abatement investments of other firms given as:

$$K(k) = (1 + (n-1)\epsilon)k \tag{3.7}$$

Here, $k$ is the amount of private investment whereas $K$ is the total benefit accrued to the firm accounting for inter firm spillovers and $\epsilon$ is the fraction of technological spillovers from other firms. The firm solves the following cost minimization problem:

$$\underset{\mathbf{e,k}}{Min} \quad C(e, K(k)) + pk + \tau e \tag{3.8}$$

Here $p$ is the price per unit of abatement technology investment and $\tau$ is the tax imposed by the government on firms' emissions. We assume that governments are benevolent and they seek to minimize the social welfare cost:

$$\underset{\eta,\tau}{Min} \quad n[C(e,K)+pk]+D(S,\eta)+C(\eta) \tag{3.9}$$

Here C($\eta$) is the cost of SRM such that $C^{'}(\eta) > 0$ and $C^{''}(\eta) > 0$. In this set up firms and the government play a game against each other such that firms choose their emissions $e$ and investment in abatement technology $k$ while governments determine the carbon tax $\tau$ and the level of SRM $\eta$. Note that all uses of the term geoengineering and geoeongineering technology mean the use of SRM and in particular SAI in this paper. Society faces two market failures: (1) greenhouse gas externalities (2) abatement technology investment spillovers. Note that governments in this set up are restricted in the sense that they can only use a single carbon tax to address both market failures. For this reason, the equilibrium outcomes obtained in this game correspond to a second best world.

## 3.3 Solution and equilibrium

The key elements we wish to investigate in order to compare between scenarios are the timing of actions and the presence of geoengineering. To do this, we first solve a baseline case for a time inconsistent government without access to geoengineering. To set the context, we compare the solutions obtained to a time consistent government. This analysis is most similar to the analysis presented in Acemoglu and Raffey (2019). In the next section we solve the model for a time inconsistent government but in the presence of geoengineering and compare the equilibrium outcomes with and without geoengineering. The key question we try to answer here is, how do the behaviors of firms change when they know governments have access to geoengineering technologies ?

### 3.3.1 Time inconsistency without geo-engineering

In this section we solve the model laid out in Section 1, but under the assumption that governments do not have access to geoengineering but still act in a time-inconsistent fashion with respect to the imposition of carbon taxes. This means that governments fail to make commitments and are only able to set carbon taxes after firms have made their abatement investments. The corresponding damage function as presented in (3.3) is therefore modified as follows:

$$D(S,\eta) = D(S) \tag{3.10}$$

Also, the government's objective function in (3.9) is also modified as follows:

$$\underset{\eta,\tau}{Min} \quad n[C(e,K) + pk] + D(S) \tag{3.11}$$

The timing of the game presented above is as follows:

- Firms choose investment in abatement technology $k$
- Given $k$, government chooses carbon tax $\tau$(k)
- Given $\tau$(k) firms choose emissions e($\tau$(k))

This model can be solved by backward induction. In the next section we lay out the steps we take in order to solve the model and the corresponding equilibrium outcomes we obtain. In accordance with the backward induction method, we start by solving the last stage (emissions choice) and work our way to the first stage of the game (abatement investment choice).

### 3.3.2 Emissions stage

In the emissions stage, firms choose their level of emissions given that governments have already set a carbon tax and firms have made their abatement investments. The first order condition with respect to emissions is obtained by differentiating the firms' objective function (3.8) with respect to $e$ assuming all other variables are given. This condition is as follows:

$$C_e(e, K(k)) + \tau = 0 \tag{3.12}$$

The above condition reflects that firms choose to emit up to the point at which the marginal abatement cost equals the tax imposed by the government.

### 3.3.3 Carbon tax stage

In the carbon tax stage, government chooses the carbon tax that minimizes (3.12). While doing so, governments take into consideration the impact their decision will have on the choice of emissions. Mathematically, governments are aware of the relationship between marginal abatement costs and carbon taxes as laid out in (3.13). Note that this set up is different from the set-up by Acemoglu and Raffey (2019).

In their set-up firms did not have an explicit choice over emissions independent from abatement investment.

Arguably, our set-up is more realistic as firms' decisions to invest in abatement technology and firms' decisions to emit are related but independent of each other. Investment in abatement technology is a choice firms make that allows them to move the marginal abatement curve such that marginal abatement costs are lowered overall, while the decision to abate is a choice to move along a certain marginal abatement curve and choose a level of emissions.

The first order condition for the choice of carbon tax by the government in (3.12) is as follows:

$$C_e(e, K(k)) + D_e(ne) = 0 \tag{3.13}$$

The above equation shows that the government takes into consideration the firms' choice over emissions and chooses the marginal damage costs to equal the marginal abatement costs. If we solve (3.14) with (3.13) then we obtain that the tax rate imposed equals the marginal damage costs.

$$\tau = D_e(ne) \tag{3.14}$$

Governments internalize the environmental damage caused by emissions by imposing a tax that equals the marginal damage costs.

### 3.3.4 Investment stage

In the first stage, firms decide on their abatement investments. Since firms' choice of investment in abatement technology happens before governments decide on a carbon tax, firms take government's choice into consideration when making their abatement investments. Firms also have to keep in mind that governments will take emissions into account when deciding on carbon taxes. In addition, firms hold the investment decisions of other firms constant when deciding on their abatement investments. The individual firm will ignore the positive spillovers from investment provided to other firms. The first order condition associated with firms' decision to invest is as follows:

$$C_k(e, K(k)) + p + e\frac{d\tau}{dk} = 0 \tag{3.15}$$

The above equation (3.15) shows that firms decide their abatement investment depending on goverments' choice of a carbon tax. This is also the point at which our model's assumptions make it depart from the conclusions of Acemoglu and Raffey (2019). Since firms know that governments can penalize low abatement investments by imposing a higher tax, they do not necessarily underinvest categorically. In fact, they choose an optimal level of abatement investment such that the government is made to choose a carbon tax level that also lowers the cost of emissions. By differentiating (3.13) w.r.t $k$ and using (3.15) and solving together we can show that the signs for $\frac{d\tau}{dk}$ and $\frac{de}{dk}$ are both negative (Appendix 1). This means that firms invest more in anticipation of a tax than they would without a tax. This makes intuitive sense as firms try to reduce the cost associated with emissions by enticing governments to lower the carbon taxes they impose. In the next section, we discuss what happens when we governments have the option to geoengineer.

### 3.3.5 Time inconsistency with geo-engineering

In this section we give governments the option to engineer. Governments still act in a time inconsistent fashion but can now use geoengineering to deal with excessive emissions by firms. The corresponding damage function and the government's objective function are as in (3.3) and (3.9) respectively.

The timing of this new game is as follows:

- Firms choose investment in abatement technology $k$
- Given $k$, government chooses carbon tax $\tau(k)$
- Given $\tau(k)$ firms choose emissions $e(\tau(k))$
- given $e$, government chooses SRM level $\eta(e(\tau(k)))$

For the purposes of this model and the model presented in Section 3.5, we make the following assumption regarding the relationship between climate damages and geoengineering costs:

$$D(ne) - C_\eta(\eta(e)) \geq 0 \tag{3.16}$$

The model can be solved by backward induction. In the next sub sections we lay out the first order conditions and the equilibrium outcomes associated with the same. As in the previous section, we start by solving the last stage and work our way backwards to the first stage of the game.

### 3.3.6 Geoengineering stage

Unlike the last model, here the government uses SRM in the last stage of the game to combat the impacts of carbon emissions and reduce climate damages. Here, governments choose SRM levels given that firms have already made their emissions decisions, governments have already set their carbon taxes and firms have already made abatement investments. The first order condition with respect to SRM level $\eta$ is obtained by differentating the governments objective function (3.9) w.r.t $\eta$ and is as follows:

$$D(ne) = C_{\eta}(\eta) \tag{3.17}$$

Since damages are positive in the amount of emissions, SRM levels $\eta$ increase with increasing emissions. Governments choose SRM levels upto the point at which the marginal costs or damages from the use of geoengineering equal the marginal benefit of reduced climate damages from emissions.

### 3.3.7 Emissions, carbon tax and abatement stages

The subsequent equations for the emissions stage look exactly the same as the previous in equation (3.12). For the carbon tax stage the associated first order condition for the governments problem is as follows:

$$C_e(e, K(k)) + (1 - \eta) D_e(ne) = 0 \tag{3.18}$$

We can then derive the tax rate imposed by the government if we solve (3.12) with (3.17) to obtain:

$$\tau = (1 - \eta) D_e(ne) \tag{3.19}$$

The first order condition associated with firms decision to invest is as follows:

$$C_k(e, K(k)) + p + e\frac{d\tau}{dk} = 0 \tag{3.20}$$

The key difference between this model and the last arises because of equation (3.20) and the fact that the presence of geo-engineering makes the sign of $\frac{d\tau}{dk}$ ambiguous. For the sake of simplicity and to make generalised statements we assume climate damages exceed geoengineering costs for equivalent levels of SRM and emissions. This leads to the following assertion:

$$D_e(ne)^2 \geq (1-\eta)D_{ee}(ne)$$

Given the above assertion regarding climate damages and geoengineering costs, we can make the following proposition:

**Proposition 1:** i) If $C_{ee}(e, K(k))C_{\eta\eta}(eta) \geq n[D_e(ne)^2 - (1-\eta)D_{ee}(ne)]$ there is underinvestment in abatement technology, the carbon tax falls and emissions rises ii) If $C_{ee}(e, K(k))C_{\eta\eta}(eta) \leq n[D_e(ne)^2 - (1-\eta)D_{ee}(ne)]$ there is overinvestment in abatement technology, the carbon tax falls and emissions rises. In both scenarios, total emissions is higher than the case without geo-engineering.

Proofs for the above proposition are detailed in Appendix for Essay 2. Intuitively, an increase in the slope of the marginal abatement curve induces firms to underinvest in abatement technology. Since cost of abatement is so high, firms choose to underinvest, emit more and therefore induce governments to commit to higher levels of SRM. If the slope associated with marginal abatement is low, firms find it easy to abate and do not mind overinvesting. They do this because they know that if they do not overinvest governments will counter their response with a higher carbon tax. Overinvestment leads to a lower carbon tax and subsequently higher emissions which are handled by the government using SRM.

In both of the above scenarios, emissions increase as firms anticipate governments response with a carbon tax and SRM injection.

### 3.3.8 Timing and time inconsistency

The key assumption in our setup is lack of commitment to future policies by the government, which induces time inconsistent behavior. If a government were to act in a time consistent fashion, they would commit to carbon taxes before firms make their abatement technology investments. We can make the following proposition regarding the governments' preference for a carbon tax in the absence of time inconsistency:

**Proposition 2:** In a second best world a government strictly reduces social costs by committing to a tax $\tau > (1-\eta)D^{'}(S)$ when $\epsilon > 0$ (technological spillovers are positive).

In our second best setup governments would like to use a carbon tax that is higher than a Pigouvian tax in order to correct the two market failures associated with (1) greenhouse gas concentrations as well as (2) positive spillovers from investment. $\epsilon > 0$ means firms do not value their investments as much as the government and therefore underinvest in abatement technology. In our set-up governments are unable to commit to the future.

The tax imposed under commitment is higher than a Pigouvian tax. In this set-up the carbon tax with commitment equals:

$$\tau = (1-\eta)D^{'}(S) + \epsilon(n-1)C_k(e,(1+(n-1)\epsilon)k)\frac{\frac{dk}{d\tau}}{\frac{de}{d\tau}} \tag{3.21}$$

This is a second best tax that can be broken down into two parts. The part to the left of the addition sign is the Pigouvian tax while the part to the right internalizes investment spillovers of firms.

**Proposition 3:** In a second best-word, a government that is unable to pre-commit to carbon taxes imposes a tax $\tau = (1-\eta)D^{'}(S)$ (Pigouvian tax).

Once investments are made, governments have an incentive to deviate to $\tau = (1-\eta)D^{'}(S)$ (Pigouvian tax). Time inconsistency arises because governments' preference for a carbon tax changes once firms have made their investment decisions. Before abatement investments are made by firms, governments can use the carbon tax as an instrument to internalize both the positive spillovers from investment as well as the damages associated with greenhouse gas concentrations. Once abatement investments are made, governments are only able to induce the internalization of climate change damages which it does by implementing a tax that is equal to the Pigouvian tax.

Note that higher emissions are a feature associated with the time inconsistent nature of the government's attitude on carbon taxes and as such is not seen in the absence of SRM. Firms exploit their first mover advantage to tie the hands of the government both in terms of their choice of carbon taxes and in their choice of SRM injection. Governments are then forced to lower carbon taxes and raise the level of SRM as the only solution to reduce climate damages.

The major implication of this result is that lack of credibility shown by governments in their decisions to tax carbon can have unanticipated consequences in the long run. First, we have shown that the equilibrium outcome associated with this time inconsistent government is one where governments have a tendency to deviate, which firms know fully well. Firms therefore act by either underinvesting or overinvesting in abatement technology and consequently force governments to lower carbon taxes and increase the amount of SRM, thereby increasing the stock of greenhouse gases and level of SRM. This lack of credibility may also imply a risk of running into a long-run equilibrium with inoptimally high amounts of emissions and inoptimally high levels of SRM. This result holds even when governments choose to act benevolently and could have adverse consequences especially if we do not fully understand the risks associated with excessive use of SRM. Second, even though our focus so far has been on the actions of a benevolent government, the consequences of non commitment could be even more dire if we consider a non benevolent government. In such a case, lack of credibility could also stem from governments trying to align climate and electoral cycles for the purposes of vote buying, especially if SRM makes it likely that governments can effectively control the climate.

## 3.4 Lessons from monetary policy

Whether governments act benevolently or not, it is important to think about building institutional credibility for SRM governance. The idea of time inconsistency was first discussed in the context of monetary policy (Kydland and Prescott, 1977). In this context, politicans are best off promising lower inflation in the future by increasing interest rates, but when the time comes increasing interest rates may have negative effects, such as reducing consumer spending, decreasing demand and increasing unemployment. If employers understand the policymakers' motives, low inflationary promises lose their credibility such that firms make decisions based on high inflationary expectations, increasing wages without decreasing unemployment. In the long run, this leads to an equilibrium with high inflation and the same level of unemployment. It is easy to see how this situation is synonymous with the time inconsistency problem faced by a government that lacks commitment to future climate policies and therefore suggestive of similar solutions to both problems.

In case of monetary policy, the literature has identified a couple of possible solutions to the time inconsistency problem. Rogoff (1985) suggested the delegation of monetary policy authority to independent central banks that hold a more conservative view on inflation than the government. Similary, Persson and Tabellini (1999) and Walsh (1995) have discussed the design of an optimal contract in a principal agent relationship between the government and the central bank. In either case the delegation of authority to a third party does resolve the time inconsistency problem by changing expectations of other actors in the system. In the following sections I explore how similar delegatory mechanisms with a third party independent environmental authority can help resolve the time inconsistency problem. The rest of the paper will build on this literature by asking two key questions:

1. Can we think of an institutional arrangement with an independent environmental authority?
2. Can this independent environmental authority achieve credibility for climate "monetary" policy - SRM level and climate "fiscal" policy - carbon taxes?

I will build on the framework developed in this paper and write a simple theoretical model that argues for an independent environmental authority with delegation over SRM levels. This model will borrow basic ideas from the principal agent model and framework introduced by Kydland and Prescott (1977) and further explored by Rogoff (1985). Answers to these questions will help address the exacerbated credibility problem of climate policy in the presence of SRM.

## 3.5 Model with independent environmental authority

In this section we consider an extension to the model presented in Section 3.2 and 3.3. We consider that the government is ex- ante able to delegate authority to an independent environmental authority (IEA). The function of this IEA is in nature similar to that of a central bank. Even though control of carbon taxes is still maintained by the government, the control of SRM is assigned to the IEA. In our set-up this is formulated as a contract between a government and the IEA. We continue to assume governments are benevolent but contract with the IEA over the use of SRM. Governments seek to minimize the social welfare cost while determining budget payments to the IEA:

$$\underset{\mathbf{w},\tau}{Min} \quad n[C(e,K) + pk] + D(S,\eta) + w \tag{3.22}$$

Here, $w$ is the wage payment to the IEA in exchange for their service over SRM deployment. The IEA solves to maximize its welfare as a net of the utility gained from wage payment and the cost of deploying SRM and is represented as follows:

$$\underset{\eta}{Max} \quad u(w) - C(\eta) \tag{3.23}$$

In this set-up the IEA chooses the amount of $\eta$ which is observable by the government. The government on the other hand pays a wage $w$ to the IEA. We also assume $u(w)$ is strictly concave and strictly increasing and the IEA has a reservation utility $\underline{\mathrm{U}}$. Given that $w$ is verifiable a first best solution to the above problem can be found by solving the following system:

$$\underset{\mathbf{w},\eta}{Min} \quad n[C(e,K) + pk] + D(S,\eta) + w \tag{3.24}$$

subject to

$$u(w) - C(\eta) \geq \underline{U} \tag{3.25}$$

The solution to the above problem gives us the following result. The government must now solve for $\eta$ to minimize the social welfare cost as follows:

$$\underset{\eta}{Min} \quad n[C(e,K)+pk]+D(S,\eta)+w(\eta,\underline{U}) \tag{3.26}$$

Here $w(\eta,\underline{U}) = u^{-1}(\eta+\underline{U})$.

Now if we assume that ex-ante delegation of authority happens before firms make their investment decisions then this set-up changes the timing of events associated with the game between the government and firms. To effectively delegate authority to an IEA the government must ex-ante decide on its wage payments. However, just as we have shown above, choosing the wage payments for the IEA is equivalent to solving for $\eta$. Hence, the governments decision to sign a contract with an IEA changes the nature of the game such that decisions regarding $\eta$ are made before firms decide on their investment actions. The timing of events are as follows:

- Government delegates authority over SRM to the IEA and chooses $\eta$
- Given $\eta$, firms choose k($\eta$)
- Given k($\eta$), govt chooses carbon tax $\tau$(k($\eta$)
- Given $\tau$(k), firms choose emissions e($\tau$(k),$\eta$(k))

This change in timing of actions ensures that the first mover advantage is now in the hands of the government. Even though the government is unable to fully commit on carbon taxes, it is still able to delegate authority over geo-engineering decisions to the IEA which changes the sequence of events associated with the game.

### 3.5.1 Solution and equilibrium with IEA

This change in sequence of actions is sufficient to address the issue of over geo-enginering because the geoengineering decision is effectively made even before the firms decide on their abatement choices.

### 3.5.2 Emissions, carbon tax and abatement stage

In this version of the game, emissions are the last stage and the first order condition looks identical to (3.12). Carbon taxes are then set keeping firms' emissions decisions in mind. The first order condition for emissions is identical to (3.13). And finally, firms make their investment decisions according to (3.15).

Given that the choice of SRM injection is already known when firms decide on abatement technology investments and emissions, and the government decides on carbon taxes, the sign of both $\frac{d\tau}{dk}$ and $\frac{de}{dk}$ are negative.

### 3.5.3 Geoengineering stage

This is the first stage of the game, where the government considers the future actions of the firms in terms of abatement technology investment and emissions as well as its own response to abatement technology investment in terms of carbon taxes. The first order condition for geoengineering is as follows:

$$C_\eta(\eta) = D(ne) - \epsilon(n-1)C_k(e, K(k))\frac{dk}{d\eta} + e\frac{d\tau}{d\eta} \tag{3.27}$$

We make the following assumption regarding the relationship between marginal geoengineering costs and and climate damages:

$$D(ne(\eta)) - C_\eta(\eta) \geq 0 \tag{3.28}$$

Under the above assumption, we obtain the following propositions regarding SRM injection under commitment.

**Proposition 4:** SRM injection and total emissions under commitment is always lower than without commitment.

The proof for the above is presented in Appendix for Essay 2. Intuitively, since government has the ability to pre-determine SRM injection levels, firms effectively follow their investment decisions based on governments' actions. Governments are aware of this and choose to lower their SRM contributions. Firms' response to lower levels of geoengineering is to lower abatement investment. Governments respond by increasing taxes thus eventually lowering emissions. Emissions therefore fall with a decrease in geo-engineering.

**Proposition 5:** Total climate damages (sum of damages related to emissions and geo-engineering costs) is lower with geo-engineering commitment.

Since climate damages are a function of geo-engineering costs and damages related to emissions, and governments choose geo-engineering investments to offset the damages due to emissions, total damages are lower under the scenario with lower geo-engineering levels. Even though SRM is able to offset the negative effects of increasing emissions it still imposes a cost on the environment. This is shown in Appendix for Essay 2.

## 3.6 Concluding remarks

This paper proposes a theoretical framework to address the adverse outcome associated with geoengineering implementation that arises when governments struggle to make credible policy commitments regarding carbon taxation. In this world, firms underinvest in abatement and force governments to over geoengineer. When firms have knowledge of the existence of geo-engineering technologies and are aware of the government's time inconsistent nature, they intentionally underinvest or overinvest in abatement forcing governments to geoengineer at a high level and employ a low carbon tax.

A solution to this dilemma is to borrow from the monetary policy literature and create an independent environmental authority in charge of geoengineering implementation. Effectively, such delegation changes the timing of decisions associated with geoengineering implementation and results in an outcome in which governments do not under tax and over geoengineer. This is because firms' investment decisions now occur after authority is delegated, effectively leading to the design of a contract such that firms act knowing what geoengineering decisions will occur. This means they do not underinvest and help recover the outcome from a scenario where we inhabit a world with runaway geo-engineering and runaway carbon emissions. This paper does not offer a solution to the time inconsistent nature of carbon policy, rather it presents an institutional framework for better managing runaway emissions assuming lack of commitment on carbon policies. This set up is not sufficient to address the problem of time inconsistency in the enforcement of carbon taxes.

Several extensions of the current framework are possible. At the very least, it will be interesting to investigate what the design of an appropriate contract looks like when there is information asymmetry in the sense of hidden type of the IEA. This adverse selection problem presents an interesting scenario whereby an appropriate contract that induces truth telling may be devised. Also, the current framework is static and does not include dynamic elements such as renegotiation etc. The inclusion of such features could possibly lead to solutions that do not require the need for an IEA. These and other extensions are left for future research.

# Chapter 4

# Multiple treatments with partial effects in a generalized regression discontinuity design

### Authorship:

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## 4.1 Introduction

The regression discontinuity (RD) design was originally introduced by Thistletwaite and Campbell (1960), who used it to evaluate the causal impact of an educational program. Since then, the RD design has been used in several quasi-experimental studies to evaluate causal impacts of a treatment (Black, 1999; Jacob and Lefgren, 2004b; Angrist and Lavy, 1999), however its use only grew after it was realised that the design was not limited in its applications and extends to fields well beyond education research (Caughey and Sekhon, 2011; Chay and Greenstone, 2005). The RD design has received tremendous attention across many fields and has seen growing popularity and applicability since the beginning of this century (Cook, 2008; Chen and Shapiro, 2007; Broockman, 2009).

The simplicity and explicability of the RD design makes it a natural and easy tool to work with. Recovery of causal effects depends on the existence of relatively weak assumptions and an institutional background that is typical of the way policy decisions are made (D. S. Lee and Lemieux, 2010). In "sharp" RD designs, a subject's eligibility for treatment is determined by lying above or below a pre-determined cutoff. This cut-off is often a variable determined by a policy decision such as a government decision to build roads to all villages that have a threshold level of population (Shamdasani, 2016), or a decision to assign pension payments based on a threshold age (Stancanelli, 2017). In "Fuzzy" RD designs, eligibility for treatment is still determined by a cut-off, however the probability of a subject's receipt of treatment does not immediately jump to one at the threshold, and is often a function of the distance from the threshold (D. S. Lee and Lemieux, 2010; Hahn et al., 2001).

In the most typical version of the RD design, a subject is assigned to the treatment group (D = 1) or to the control group (D = 0) depending on whether a single assignment/ scoring variable S crosses a cut-off. The RD works under the assumption that subjects assigned to either side of the cut-off just at the boundary are essentially randomly assigned. A test of this was proposed by McCrary (2008), who reasoned that the marginal density of the assignment/ scoring variable should be continuous at the cut-off. The absence of continuity in the scoring variable indicates manipulation or sorting around the threshold that violates the appropriateness of the RD design. The majority of the literature in RD designs has evaluated the presence of causal effects when a single scoring variable determines treatment eligibility (Black, 1999; D. S. Lee and Lemieux, 2010). There are also a few examples of multiple assignment/scoring variables determining treatment eligibility (Battistin and Rettore, 2008; Clark and Martorell, 2014; Choi and Lee, 2018). To the best of our knowledge, the literature in multiple assignment designs has confined itself to strict RD designs. In our paper, we introduce a generalised multiple treatment RD model with multiple assignments that accommodate both fuzzy as well as strict RD designs, and show how we can use it to estimate both individual/ partial as well as total local treatment effects.

The literature on multiple assignment/scoring variables can be divided into two branches: ‘Multiple-score RD for a single treatment’ and ’ Multiple-score RD for multiple treatments’. The difference between these two types is best illustrated with an example. Certain school districts in the US assign students to summer schools if they fail to obtain cut-off scores in end of year math or reading exams (Jacob and Lefgren, 2004b). Here, there can be two possibilities. Either the performance on both tests determines assignment to one treatment-control contrast or the performance on each test assigns students to a different summer program depending on the test failed. If it is the former, then we have a ’Multiple-score RD for a single treatment design’ (MRD-S), and if it is the latter then we have a ’Multiple-score RD for multiple treatments design’ (MRD-M) (Choi and Lee, 2018). Our work adds to the literature on ’Multiple-score RD for multiple treatments’, which we believe is a generalization over ’Multiple-score RD for a single treatment’. For simplicity, we will refer to our set-up as a ’Multiple-score RD design’ (MRD)

As mentioned, the literature on multiple scores/ assignment variables is small but diverse. Van Der Klaauw (2002) and Angrist and Lavy (1999) use RD designs with multiple cut-offs, but all along a single dimension scoring variable. This is the simplest of all cases and is easily handled by observing one cut-off at a time. Examples also exist where multiple test scores cross a cutoff to determine school graduation or grade advancement (Jacob and Lefgren, 2004b). Another notable example in the literature is of a spatial/geographical RD. Here, the two running variables are functions of the latitude and longitude associated with a co-ordinate (Dell, 2010; Keele and Titiunik, 2015). A dimensional simplification often suggested is the scalar shortest distance to the boundary or discontinuity of interest (Black, 1999; Bayer et al., 2007; Michalopoulos and Papaioannou, 2014). Many other examples of multiple score RDs do not consider all the treatment possibilities and try to reduce the dimensionality of the problem by either taking a weighted average to come-up with a single representative effect (Cattaneo et al., 2016) or by excluding partial/ individual treatment effects (Schmieder et al., 2012). A couple of studies examine partial or individual treatment effects, but restrict their design to strict discontinuities. Choi and Lee (2018) examined a 'Multiple-score RD for a single treatment' with partial effects in a strict RD design. Similarly, Papay et. al (2011) discuss a 'Multiple-score RD for multiple treatments' with individual treatment effects. Our paper is different from the above in that we develop a generalized design for 'Multiple-score RD for multiple treatments' that accommodates "fuzzy" discontinuities and also allows us to estimate partial/ individual treatment effects. Further, we also derive estimators for a two-score scenario with at least one fuzzy discontinuity.

The rest of the paper proceeds as follows. In Section 4.2, we introduce the econometric framework in a strict design with two scores. In section 4.3, we generalize the set-up to include "fuzzy" discontinuities. In Section 4.4, we discuss identification and estimation for a two score set-up with at least one fuzzy discontinuity. In Section 4.5, we discuss how we propose to use the MRD set-up to determine the causal impact of electrification and groundwater access on various labor market outcomes, jointly as well as individually. Finally, in Section 4.6 we conclude with future steps.

## 4.2 Econometric framework

In this section we establish the basic econometric framework for the strict RD design with multiple (two) cut-offs. Like most of the literature, we define causal effects in line with the potential outcomes framework, also known as the Neyman-Fisher-

Rubin causal model (Rubin, 1974; Holland, 1986). We assume there are two distinct treatments $D^1$ and $D^2$, each of which takes binary values depending on the treatment status. In line with common practice, a value of '1' indicates an active treatment and a value of '0' indicates no treatment. These treatments are applied to the same population, from which we observe $n$ units drawn randomly and independently, and indexed as $i = 1, ........n$. We can then define four potential outcomes associated with individual $i$ as follows:

- $Y_i^{11}$ : Both treatments $D^1 = 1$ and $D^2 = 1$ are active.
- $Y_i^{00}$ : Both treatments $D^1 = 0$ and $D^2 = 0$ are inactive.
- $Y_i^{10}$ : One treatment $D^1 = 1$ is active and one treatment $D^2 = 0$ is inactive.
- $Y_i^{01}$ : One treatment $D^1 = 0$ is inactive and one treatment $D^2 = 1$ is active.

Based on the above, the observed outcome for an individual $i$ can be defined as follows:

$$Y_i = Y_i^{00}(1 - D_i^1)(1 - D_i^2) + Y_i^{11} D_1^1 D_2^2 + Y_i^{10} D_i^1 (1 - D_i^2) + Y_i^{01}(1 - D_i^1) D_i^2 \quad (4.1)$$

The fundamental problem of causal inference is then that only one of the four potential outcomes $(Y_i^{11}, Y_i^{00}, Y_i^{10}, Y_i^{01})$ is observable. To obtain an estimate of average individual treatment effects, we take averages of $Y_i^{10} - Y_i^{00}$ and $Y_i^{01} - Y_i^{00}$ over sub populations. The total treatment effect is similarly calculated by averaging over $Y_i^{11} - Y_i^{00}$ and subtracting out the individual treatment effects as follows:

$$(Y_i^{11} - Y_i^{00}) - (Y_i^{10} - Y_i^{00}) - (Y_i^{01} - Y_i^{00})$$

In the RD setting, the relationships between average outcomes are further defined by two forcing variables: $S_1$ and $S_2$. Unlike the single forcing variable setting here we envision the set-up as three dimensional set up the X and Y axes are the two forcing variables $(S_1, S_2)$ and the Z-axis is the outcome variable Y. In this space we define four underlying relationships between Y and $(S_1, S_2)$: $E[Y_i^{11}|S_1, S_2]$, $E[Y_i^{00}|S_1, S_2]$, $E[Y_i^{10}|S_1, S_2]$ and $E[Y_i^{01}|S_1, S_2]$. Let also the cut-offs for treatment status associated with each forcing variable $S_1$ and $S_2$ be $s_1^c$ and $s_2^c$ respectively . If $s_1$ and $s_2$ are each a random number drawn from the set of points in $S_1$ and $S_2$ respectively, we can define the following for activity of treatment status:

- $D^1 = 1$ and $D^2 = 1$ if $s_1 > s_1^c$ and $s_2 > s_2^c$
- $D^1 = 0$ and $D^2 = 0$ if $s_1 < s_1^c$ and $s_2 < s_2^c$
- $D^1 = 1$ and $D^2 = 0$ if $s_1 > s_1^c$ and $s_2 < s_2^c$
- $D^1 = 0$ and $D^2 = 1$ if $s_1 < s_1^c$ and $s_2 > s_2^c$

In this setting we observe $E[Y_i^{11}|S_1, S_2]$ only where $s_1 > s_1^c$ and $s_2 > s_2^c$. Similarly, the other averaged outcomes are observable only when their respective treatment statuses are made active. In this case, the average treatment effects are defined based on observable outcomes. The average individual treatment effects are estimated using the following quantities at the boundaries of their respective cut-offs:

$$\lim_{\epsilon \downarrow 0} E[Y_i|S_{1i} = s_1 + \epsilon, S_{2i} = s_2 < s_2^c] - \lim_{\epsilon \uparrow 0} E[Y_i|S_{1i} = s_1 + \epsilon, S_{2i} = s_2 < s_2^c]$$

$$\lim_{\epsilon \downarrow 0} E[Y_i|S_{1i} = s_1 < s_1^c, S_{2i} = s_2 + \epsilon] - \lim_{\epsilon \uparrow 0} E[Y_i|S_{1i} = s_1 < s_1^c, S_{2i} = s_2 + \epsilon]$$

Similarly, the average total treatment effect is estimated as follows:

$$(\lim_{\epsilon\downarrow 0} E[Y_i|S_{1i} = s_1 + \epsilon, S_{2i} = s_2 + \epsilon] - \lim_{\epsilon\uparrow 0} E[Y_i|S_{1i} = s_1 + \epsilon, S_{2i} = s_2 + \epsilon])$$

$$-(\lim_{\epsilon\downarrow 0} E[Y_i|S_{1i} = s_1 + \epsilon, S_{2i} = s_2 < s_2^c] - \lim_{\epsilon\uparrow 0} E[Y_i|S_{1i} = s_1 + \epsilon, S_{2i} = s_2 < s_2^c])$$

$$-(\lim_{\epsilon\downarrow 0} E[Y_i|S_{1i} = s_1 < s_1^c, S_{2i} = s_2 + \epsilon] - \lim_{\epsilon\uparrow 0} E[Y_i|S_{1i} = s_1 < s_1^c, S_{2i} = s_2 + \epsilon])$$

All the above treatment effects are evaluated near the cutoffs $s_1^c$ and $s_2^c$. Inference according to the potential outcomes framework is made possible in this RD setting if we assume that subjects are ”as good as” randomly assigned to treatment status in close vicinity of the cut-off boundaries. Additionally, continuity of the outcome distributions $E[Y_i^{11}|S_1, S_2]$, $E[Y_i^{00}|S_1, S_2]$, $E[Y_i^{10}|S_1, S_2]$ and $E[Y_i^{01}|S_1, S_2]$ is a direct consequence of randomization (Lee & Lemieux, 2009). In practical terms this holds true if there is no manipulation or sorting around the cutoffs. This also leads to the assertion that the forcing or assignment variables $S_1$ and $S_2$ are independent of the potential outcomes $Y_i^{11}$,$Y_i^{00}$,$Y_i^{10}$ and $Y_i^{01}$, and the curves $E[Y_i^{11}|S_1, S_2]$, $E[Y_i^{00}|S_1, S_2]$, $E[Y_i^{10}|S_1, S_2]$ and $E[Y_i^{01}|S_1, S_2]$ are flat.

## 4.3 Fuzzy MRD with two scores

In this section we discuss the design of a fuzzy MRD with two scores. We impose a couple of simplifying assumptions that allow us to easily derive estimators in the subsequent sections. As a start, we put further structure onto our outcome equation and define the following relationship between the outcome variable $Y$ and the two assignment variables $S_1$ and $S_2$ using the following regression model:

$$E(Y|S_1,S_2)=\beta_1 E(D^1|S_1,S_2)+\beta_2 E(D^2|S_1,S_2)+\beta_D E(D^1|S_1,S_2)E(D^2|S_1,S_2)+m(S_1,S_2) \tag{4.2}$$

In the above formulation, $\beta_1, \beta_2$ and $\beta_D$ are parameters of interest that we want to estimate. While $\beta_1$ and $\beta_2$ signify individual treatment effects, $\beta_D$ measures the total treatment effect. Further, we assume $E(D^1|S_1,S_2)$ and $E(D^2|S_1,S_2)$ are discontinuous at $(S_1 = s_1^c, S_2)$ and $(S_1, S_2 = s_2^c)$ respectively. The discontinuity condition is different from the single score case in the sense that this discontinuity manifests in three dimensions. While in the single score case a discontinuity was a line parallel to the outcome dimension designated by a single point (the cut-off point) along the assignment variable axis, here the discontinuity is along two intersecting planes defined by the following:

- The plane $S_1 = s_1^c$ parallel to the $S_2$ axis
- The plane $S_2 = s_2^c$ parallel to the $S_1$ axis

$m(S_1, S_2)$ is an unknown function that is continuous at $(s_1^c, s_2^c)$. We further assume that the discontinuity defined by the forcing variable $S_1$ is fuzzy such that $D^1$ is no longer a binary variable, but is a probabilistic function of forcing variables $S_1$ and $S_2$ as such:

$$E(D^1|S_1, S_2) = \pi E(\delta|S_1) + \pi_2 E(D^2|S_2) + \pi E(\delta/S_1)E(D^2|S_2) + l_D(S_1, S_2) \quad (4.3)$$

In the above equation, $\delta = 1$ if $S_1 >= s_1^c$ and takes a value $\delta = 0$ if $S_1 < s_1^c$. $\pi$ is our parameter of interest defining the strength of the relationship between treatment likelihood and the assignment variable, and $l_D(S_1, S_2)$ is an unknown function continuous at $(S_1 = s_1^c, S_2)$ and $(S_1, S_2 = s_2^c)$. Based on the above we can derive the following generalized outcome equation by substituting (4.3) in (4.2):

$$E(Y|S_1,S_2) = \beta_1\pi_1 E(\delta|S_1)+\beta_1\pi_2 E(D^2|S_2)+\beta_1\pi E(\delta|S_1)E(D^2|S_2)+\beta_2 E(D^2|S_1,S_2)$$
$$+\beta_D\pi_1 E(\delta|S_1)E(D^2|S_1,S_2)+\beta_D\pi_2 E(D^2|S_2)E(D^2|S_1,S_2)$$
$$+\beta_D\pi E(\delta|S_1)E(D^2|S_2)E(D^2|S_1,S_2)+l(S_1,S_2)+m(S_1,S_2) \quad (4.4)$$

Using the above equation, we define the four outcome surfaces associated with the MRD design as follows:

$$E(Y|S_1 < s_1^c, S_2 < s_2^c) = l(S_1,S_2)+m(S_1,S_2) \quad (4.5)$$

$$E(Y|S_1 > s_1^c, S_2 < s_2^c) = \beta_1\pi_1 + l(S_1,S_2)+m(S_1,S_2) \quad (4.6)$$

$$E(Y|S_1 < s_1^c, S_2 > s_2^c) = \beta_1\pi_2+\beta_2+\beta_D\pi_2+\beta_D l_D(S_1,S_2)+l(S_1,S_2)+m(S_1,S_2) \quad (4.7)$$

$$E(Y|S_1 > s_1^c, S_2 > s_2^c) = \beta_1\pi_1+\beta_1\pi_2+\beta_1\pi+\beta_2+\beta_D\pi_1+\beta_D\pi_2+\beta_D\pi$$
$$+\beta_D l_D(S_1,S_2)+l(S_1,S_2)+m(S_1,S_2) \quad (4.8)$$

In addition to the above equations, we can also derive the forcing variable expressions using (3) on either side of both thresholds associated with $S_1$ and $S_2$ as follows:

$$E(D^1|S_1 < s_1^c, S_2 < s_2^c) = l(S_1, S_2) \tag{4.9}$$

$$E(D^1|S_1 > s_1^c, S_2 < s_2^c) = \pi_1 + l(S_1, S_2) \tag{4.10}$$

$$E(D^1|S_1 < s_1^c, S_2 > s_2^c) = \pi_2 + l(S_1, S_2) \tag{4.11}$$

$$E(D^1|S_1 > s_1^c, S_2 > s_2^c) = \pi_1 + \pi_2 + \pi + l(S_1, S_2) \tag{4.12}$$

The above expressions define the set of four potential outcome surfaces along with the set of four treatment status functions that allow us to estimate the individual and total treatment effects.

## 4.4 Identification and estimation

In this section we discuss the procedure for deriving the estimators $\beta_1$, $\beta_2$ and $\beta_D$. The estimator for $\beta_1$ is derived by taking the difference between (4.6) and (4.5) to first estimate the following equation:

$$E(Y|S_1 > s_1^c, S_2 < s_2^c) - E(Y|S_1 < s_1^c, S_2 < s_2^c) = \beta_1\pi_1 \tag{4.13}$$

We also take the difference between (4.10) and (4.9) to derive the following:

$$E(D^1|S_1 > s_1^c, S_2 < s_2^c) - E(D^1|S_1 < s_1^c, S_2 < S_2^c) = \pi_1 \tag{4.14}$$

The estimator for $\beta_1$ is then as follows:

$$\beta_1 = \frac{E(Y|S_1 > s_1^c, S_2 < s_2^c) - E(Y|S_1 < s_1^c, S_2 < s_2^c)}{E(D^1|S_1 > s_1^c, S_2 < s_2^c) - E(D^1|S_1 < s_1^c, S_2 < S_2^c)} \tag{4.15}$$

As expected, this looks like a 'Wald' type estimator (Angrist and Keueger, 1991). We recall that $\beta_1$ is the treatment effect estimate for the fuzzy discontinuity $S_1$. Analytically, this estimation can be carried out in a 2SLS model (Angrist and Imbens, 1995), just as an instrumental variables regression, where in the first stage we estimate an OLS form of (4.3) as follows:

$$D_i^1 = \alpha_1 + \pi_1\delta_i + l_D(s_{1i}, s_{2i}) + e_i \tag{4.16}$$

In the second stage we use the predicted values of $D_i^1$ in the OLS form of equation (4.2):

$$Y_i = \alpha + \beta_1 D_i^1 + m(s_{1i}, s_{2i}) + \mu_i \tag{4.17}$$

This two stage procedure gives us an estimate for $\beta_1$. The estimator for $\beta_D$ is derived by first taking the difference between (4.8) and (4.7) to estimate the following equation:

$$E(Y|S_1 > s_1^c, S_2 > s_2^c) - E(Y|S_1 < s_1^c, S_2 > s_2^c) = (\beta_1 + \beta_D)(\pi + \pi_1) \tag{4.18}$$

The above equation (4.18) can then be solved with (4.13),(4.12) and (4.11) to derive the estimator for $\beta_D$ as follows:

$$\begin{aligned}\beta_D = &\frac{E(Y|S_1 > s_1^c, S_2 > s_2^c) - E(Y|S_1 < s_1^c, S_2 > s_2^c)}{E(D^1|S_1 > s_1^c, S_2 > s_2^c) - E(D^1|S_1 < s_1^c, S_2 > s_2^c)} \\ &- \frac{E(Y|S_1 > s_1^c, S_2 < s_2^c) - E(Y|S_1 < s_1^c, S_2 < s_2^c)}{E(D^1|S_1 > s_1^c, S_2 < s_2^c) - E(D^1|S_1 < s_1^c, S_2 < s_2^c)}\end{aligned} \tag{4.19}$$

On close observation, it is easy to notice that (4.19) looks like a difference between two 'Wald' estimators. We know from our set-up that $S_2$ is the forcing variable associated with the strict discontinuity. In the above expression, the part to the left of the minus sign is the 'Wald' estimator above the strict discontinuity and the part on the right of the minus sign is the 'Wald estimator' below the discontinuity. This also means that we can simplify our design and estimate two instrumental variables (IV) regressions on either side of the cut-off $s_2^c$, and take the difference between the IV estimates to derive the total treatment effect. We now discuss the analytical procedure to carry out this estimation.

We first use the steps in (4.15) and (4.16) to obtain an estimate of $\beta_1$. Then we estimate another 2SLS model, in which the first stage involves estimating the following OLS equation:

$$D_i^1 = \alpha_1 + \pi_1 \delta_i + \pi_2 D_i^2 + \pi \delta_i D_i^2 + l_D(s_{1i}, s_{2i}) + e_i \tag{4.20}$$

In the second stage we use the predicted values of $D_i^1$ in the OLS form of equation (2):

$$Y_i = \gamma + \beta_1 D_i^1 + \beta_2 D_i^2 + \beta_D D_i^1 D_i^2 + m(s_{1i}, s_{2i}) + \mu_i \tag{4.21}$$

Equation (4.21) gives us an estimate for both $\beta_D$ as well as $\beta_2$.

## 4.5 Application: MRD for causal impact of groundwater and electrification

In this section we discuss how we plan to use the MRD to estimate the causal impact of access to groundwater and electrification on various labor market outcomes in India. Before discussing the details of an empirical specification we present a background on the importance of rural electrification and groundwater access as complementary conditions for simulating economic development. Our goal is to test if the joint total effect of access to groundwater and electrification can stimulate rural economic development.

Evidence on the developmental impacts of rural electrification lack consensus and atleast in the context of India appear to be highly context driven (Burlig and Preonas, 2016; Usmani and Fetter, 2019). This is further complicated by the fact that recovering causal estimates of the impacts of electrification are rather challenging as electricity infrastructure investment decisions are made based on the economic conditions of the target recipients, biasing treatment effect estimates. Dinkelman (2011) and Lipscomb et al. (2013) used an instrumental variables strategy to overcome this econometric bias and identified large positive effects of rural electrification on employment in South Africa and Brazil, respectively. Similarly Chakravorty et.al (2016) also use an instrumental variables strategy and find agricultural productivity gains from rural electrification in Phillipines. Burling and Preonos (2016), and Usmani and Fetter (2019) both use a regression discontinuity design and show that at least in the context of India, electricity by itself is insufficient in stimulating economic growth unless supplemented by other complementary conditions and economic contexts. A key overarching question in development economics is therefore what necessary conditions besides access to electricity are required for electrification to demonstrate its potential in facilitating economic development in rural village economies? A related question to this is what empirical methods and approaches must one use or develop to examine complementary conditions and/or treatments for stimulating rural economic development? Arguably the strict regression discontinuity design requires weaker identifying assumptions than an instrumental variables strategy, but its success is conditional on an appropriate institutional and policy context.

Rural electrification and groundwater access have long been seen as necessary conditions for stimulating economic development (Kirubi et al., 2009; Molden et al., 2001). Even so, around a billion people still lack access to electricity worldwide, and governments and international organizations are taking massive strides in extending electricity access to all (Shyu, 2014). In many rural communities, electricity is a pre-requisite for catalyzing agricultural growth through irrigation (Barnes, 2019). In particular, electrification eases access to groundwater and breaks an economy's reliance on rainfall (Shah and Verma, 2008). This was the premise with which India launched its' green revolution in the 1970s (Parayil, 1992). Since then, the Indian government has incentivized various irrigation related schemes that promote agricultural development (Bathla et al., 2017). Subsidies for electricity use in agriculture were introduced to encourage farmers to adopt electric pump sets to drill for groundwater (Parayil, 1992). Access to the electric grid therefore can strongly incentivize private adoption of technologies for ground and surface water irrigation, driving growth in the agricultural sector. The adoption of these technologies could however depend on the depth to groundwater at the time of electrification, driving differences in impacts between regions that vary on groundwater depth. Further, depending on the type and extent of adoption, regions with more or less depth to groundwater, and regions with or without access to electricity could see different developmental pathways over time.

Both rural electrification and groundwater availability offer contexts for the successful implementation of the MSRD set-up in India (Burlig and Preonas, 2016; Sekhri, 2014). In 2005, the Indian government launched the The Rajiv Gandhi Grameen Vidyutikaran Yojana (RGGVY) to expand electricity access to 400,000 unelectrified and partially electrified Indian villages. Phase 1 of RGGVY was launched between 2005 and 2008, and electrified all villages that were above the 300 persons population cut-off. This strict cut-off offers the perfect scenario to construct a strict regression discontinuity, and has been previously used to explore the benefits of electrification (Burlig and Preonas, 2016; Usmani and Fetter, 2019). Similarly Sekhri (2014) constructed a fuzzy regression discontinuity to study the welfare consequences of groundwater availability. Her design exploits the fact that the technology and hence the cost associated with extracting groundwater changes discontinuously at a depth beyond 8 metres, with well-defined constraint imposed by the laws of physics. Groundwater within 8 metres of depth can be extracted with a simple centrifugal pump, but costlier submersible pumps are required for groundwater at depths greater than 8 metres. This exogenously imposed technological feasibility constraint offers the perfect setting to construct a fuzzy regression discontinuity design. To find the effect of both groundwater availability and electricity access, an appropriate empirical design would integrate both discontinuities into the same econometric design. We believe that the MSRD set up we have developed in this paper is appropriate for addressing such questions and allow us to estimate both individual as well as total treatment effects in the context of electrification and access to groundwater.

In our case the total treatment group corresponds to the sample of villages that are just above the 300 person electrification and the 8 meter technological constraint cut-off. The individual treatment groups correspond to groups crossing only one of the two cutoffs and the control group is below both the electrification and 8 meter technological constraint cut-off. More formally, we rely on the MRD to estimate the following relationship:

$$Y_i = \gamma + \beta_1 W_i + \beta_2 T_i + \beta_D W_i T_i + m(d_i, p_i) + \mu_i \tag{4.22}$$

In the above specification, $Y_i$ is a village level outcome of interest (labor force as a percentage of village population, sectoral composition of workforce, wages by sector, employment by sector) post-electrification. $W_i$ is a variable representing the percentage of farmers using submersible pumps in the village. $T_i$ is an indicator variable representing the status of electrification. It equals 1 if population of village $p_i > 300$. $d_i$ is a variable representing depth of groundwater and $p_i$ is a variable representing village population. The coefficients $\beta_1$, $\beta_2$ and $\beta_D$, represent the individual treatment effects of groundwater availability and electrification and the total treatment effect associated with both groundwater availability and electrification status. In this design, the technical feasibility of pumps changes exogenously at a depth of 8 metres (Sekhri, 2014) (based on industry standards). This creates a fuzzy discontinuity in the sense that our variable of interest $W_i$ is probabilistically linked to the depth of groundwater around 8 metres. In addition to Sekhri (2014), we believe the likelihood of a submersible pump may also depend on electrification status. We estimate the following regression equation as a first stage to evaluate the relationship between $W_i$ (groundwater availability through submersible pump percentage), $\delta$ (indicator for depth of groundwater less than 8 metres) and $T_i$ (electrification status).

$$W_i = \alpha + \pi_1 \delta_i + \pi_2 T_i + e_i \tag{4.23}$$

Estimating (4.23), and using the predicted values in (4.22) we believe will give us the individual and and total causal treatment effects associated with groundwater availability and electrification on various labor market outcomes. This excercise is left for future work.

## 4.6 Discussion

In this paper we have developed a generalized fuzzy double regression discontinuity model to estimate individual and total treatment effects in the presence of more than a single interacting treatment. We used a general specification to derive estimators for the individual and total treatment effects and its' relationship with the 'Wald' estimator. We have also discussed how this method can be applied to estimate the causal impact on groundwater availability and electrification status on various labor market outcomes in an Indian context. The critical difference between our method and earlier methods is the consideration of "fuzzy" discontinuities in an RD setting that allows us to also estimate individual treatment effects in addition to total treatment effects.

The method developed in this essay discusses cases with two treatments, however the same framework can easily be extended to more than two treatment conditions as well. In the presence of three individual treatment conditions, the total number of treatment and control groups will number eight. The biggest issue around multiple treatment conditions will be in the practicality of the method as the statistical power reduces with an increase in the total number of treatment and control groups. Theoretically this extension is easily feasible with the methods discussed in the paper, but practically such extension may offer limited marginal benefit.

This approach does have its limitations and next steps include developing more insight into the criticality of these limitations. Firstly, statistical power could be a key issue as the method is only likely to estimate precisely when there is enough density of points in the joint cut scores. Secondly, external validity is very limited as the effects that are estimated are local to the cut-off and to compliers at the joint cut-off. Nonetheless, with sufficient data the method provides an econometrically robust way of estimating individual and total treatment effects in the presence of multiple interacting treatments.

# Chapter 5

# Conclusion

In this dissertation, I delve into three essays all related to natural resource, environmental and development economics. The common theme across all essays is the development of theoretical methods for answering policy relevant questions numerically, analytically and empirically.

In the field of natural resource economics, the first essay develops analytical and numerical methods for analysis of the uncertainty associated with the timing of future carbon tax impositions. The idea of uncertainty in the timing of future policies is important and spans across several disciplines. The analytical methods developed can be applied to other contexts with similar characteristics in timing uncertainty.

In the area of the economics of geo-engineering, the second essay develops a theoretical analysis of institutional frameworks for governing geo-engineering in ways that do not compromise mitigation efforts. The essay is novel in its proposal to borrow ideas around independent institutions for governance from the monetary policy literature and in demonstrating how a disastrous outcome of runaway carbon emissions can be avoided by addressing the time inconsistency problem in government decision making regarding climate policies.

In the area of econometric methods for resource and development economics, the third essay develops statistical methods to estimate causal impacts in the presence of multiple treatments and treatment conditions. Specifically, the regression discontinuity design developed allows the estimation of causal impacts with multiple treatments in the presence of both fuzzy as well as strict discontinuities. The method developed can easily be extended to multiple treatments and is widely applicable to contexts with multiple treatments and treatment types.

# Appendix of Essay 1

## 1. Integration by parts of objective function

Here we solve for the general problem as in (2.8). The same applies to all the other cases.

$$V = Max \quad \int_0^{\infty} \omega(T)[\int_0^T (p(t)u(t)-C(x(t),u(t)))e^{-rt}dt+e^{-rT}V^F(x(T),\tau)]dT \tag{5.1}$$

The integration by parts rule is given as follows:

$$\int udv = uv - \int vdu \tag{5.2}$$

Equation (5.1) can be also written as follows:

$$V = Max \quad \int_0^{\infty} \omega(T)[\int_0^T (p(t)u(t)-C(x(t),u(t)))e^{-rt}dt]dT+\int_0^{\infty} \omega(T)[e^{-rT}V^F(x(T),\tau)]dT \tag{5.3}$$

Let, $dv = \omega(T)$ and $u = [\int_0^T (p(t)u(t) - C(x(t),u(t)))e^{-rt}dt]$. Now integrating by parts the first part of expression (5.3) between limits 0 and $\infty$ gives us the following:

$$[\Omega(T)\int_0^T (p(t)u(t) - C(x(t),u(t)))e^{-rt}dt]_0^\infty + \int_0^\infty [(p(t)u(t) - C(x(t),u(t)))\Omega(t)]dT \tag{5.4}$$

The first part of (5.4) is zero, and if we combine the second part of (5.4) with the second part of (5.3) then we get (2.14).

## 2. Transversality condition

Let, $e^-rt$H(t) → 0 as t → $\infty$. For the current value Hamiltonian in (2.15) to converge to 0, it must be true that $\lambda_1(t)u(t)$ converges to zero. This is because, we know that profit $p(t)u(t) - C(x(t),u(t))$ is driven down to 0 in the limit. After the tax change, we also know that $\lambda_1^F(t)$ approaches 0. Using (2.21) we can see that all the terms in (2.15) except $\lambda_1(t)u(t)$ naturally converge to zero leading to the transversality condition. In essence, for $e^-rt$H(t) → 0 to hold $\lambda_1(t)u(t)$ will have to converge to zero as t → $\infty$.

## 3. Exhaustible Resources: Intensive margin adjustment

Differentiating (16) w.r.t t gives us:

$$\dot{\lambda_1}(t) = (\dot{p}(t) + uC_x(x(t)))\Omega(t) + (p(t) - C(x(t))\dot{\Omega}(t) \tag{5.5}$$

In (5.5), we know $\dot{\Omega}(t) = -\omega(t)$. Substituting $\dot{\lambda_1}(t)$ from (5.5) in equation (2.17) and solving with (2.18),(2.21) and (2.20) gives us the following price path:

$$\frac{1}{dt}E_t dp = r(p - C(x(t))) + \frac{\omega(t)}{\Omega(t)}\tau \tag{5.6}$$

Under the assumption that the marginal density $\omega(t)$ follows an exponential distribution, we obtain the price path in (2.22).

To derive equation (2.20) we set up the hamiltonian using the optimal control problem forumlated in equations (2.11) - (2.13) as follows:

$$H = (p(t)u(t) - C(x(t), u(t)) - \tau u(t)) - \lambda_1^F(t)u(t) \tag{5.7}$$

Taking the derivative of the (5.7) w.r.t u(t) gives us equation (2.20).

## 4. Inexhaustible but non-renewable resources: Intensive and extensive margin adjustment

In addition to equation (2.27), the optimal control problem after tax implementation is as follows:

$$V^F = Max \quad \int_T^\infty (p(t)u(t) - C_1(x(t), u(t)) - C_2(a(t)) - \tau u(t))e^{-rt}dt \tag{5.8}$$

subject to

$$x(t) \geq 0, u(t) \geq 0, a(t) \geq 0 \tag{5.9}$$

$$\dot{x(t)} = \dot{R(t)} - u(t), \quad x_0 \;\; given, \tag{5.10}$$

$$\dot{R(t)} = f(a(t), R(t)), \quad R_0 \;\; given, \tag{5.11}$$

The Hamiltonian associated with the above problem is as follows:

$$H = (p(t)u(t) - C_1(x(t), u(t)) - C_2(a(t)) - \tau u(t)) + \lambda_1^F(t)(f(a(t), R(t)) - u(t)) + \lambda_2^F(t)(f(a(t), R(t)) \tag{5.12}$$

The co-state associated with the x(t) after the tax change is as follows:

$$u(t) \geq 0, \quad (p(t) - C_1(x(t)) - \tau) - \lambda_1^F(t) \leq 0, c.s \tag{5.13}$$

From equivalence between the Hamilton-Jacobi-Bellman and Hamiltonian formulations,we know that the future co-state associated with x(t) is the same as the future shadow value associated with a marginal change in x(t)

$$\lambda_1^F(t) = V_x^F(x(t), R(t), \tau) \tag{5.14}$$

Also the future co-state associated with R(t) is the same as the future shadown value associated with a marginal change in a(t)

$$\lambda_2^F(t) = V_R^F(x(t), R(t), \tau) \tag{5.15}$$

Differentiating (2.36) w.r.t t gives us the following:

$$\lambda_1\dot{(}t) = (p\dot{(}t) + (f(a(t), R(t))C_{1x}(x(t)))\Omega(t) + (p(t) - C(x(t))\Omega\dot{(}t) \tag{5.16}$$

Now, solve (5.16) with (2.36),(2.38),(5.15) and (4.38) to derive the price path as in (2.43).

Differentiating (2.37) w.r.t t gives us the following:

$$C_{2aa}(a)\dot{a}\Omega(t) = \dot{\Omega(t)}C_{2a}(a(t))+(\dot{\lambda_1(t)}+\dot{\lambda_2(t)})f_a(a,R)+(\lambda_1+\lambda_2)(f_{aa}(a,R)\dot{a}+f_{aR}(a,R)\dot{R}) \tag{5.17}$$

Rearranging (2.37) we can get the following expression:

$$(\lambda_1(t)+\lambda_2(t)) = \frac{C_{2a}(a)\Omega}{f_a(a,R)} \tag{5.18}$$

Further, if we derive the above equation for the time period after the tax is implemented then it is

$$(\lambda_1^F(t)+\lambda_2^F(t)) = \frac{C_{2a}(a)}{f_a(a,R)} \tag{5.19}$$

Now we can solve (5.19) with (5.18), (5.17), (2.38), (2.40) and susbtitute (5.16) and (5.18) to obtain (2.45).

# Appendix of Essay 2

## 1. Time inconsistency without geoengineering

Differentiating (13) w.r.t $k$ and solving with (15) we obtain the following:

$$\frac{de}{dk} = \frac{-(1+\epsilon(n-1))C_{eK}}{C_{ee} + n(1-\eta)D_{ee}(ne)} \tag{5.20}$$

$$\frac{d\tau}{dk} = \frac{-n(1-\eta)D_{ee}(ne)(1+\epsilon(n-1))C_{eK}}{C_{ee} + n(1-\eta)D_{ee}(ne)} \tag{5.21}$$

From the above equations and based on the assumptions laid out in (4), (5) and (6), we can see that $\frac{de}{dk}$ and $\frac{d\tau}{dk}$ are both negative.

## 2. Time inconsistency with geo-engineering

Differentiating (16), (17) and (12) with respect to $k$, we obtain the following equations:

$$C_{ee}(e,K)\frac{de}{dk} + (1+\epsilon(n-1))C_{ek}C_{eK}(e,K) + \frac{d\tau}{dk} = 0 \tag{5.22}$$

$$C_{ee}(e,K)\frac{de}{dk}+(1+\epsilon(n-1))C_{ek}C_{eK}(e,K)+n(1-\eta)D_{ee}(ne)\frac{de}{dk}-(1-\eta)D_e(ne)\frac{d\eta}{dk}=0 \tag{5.23}$$

$$nD_e(ne)\frac{de}{dk}=C_{\eta\eta}(\eta)\frac{d\eta}{dk} \tag{5.24}$$

Solving equations (29), (30) and (31) together we obtain the following relationships:

$$\frac{de}{dk}=-\frac{(1+\epsilon(n-1))C_{eK}(e,K)C_{\eta\eta}(\eta)}{C_{ee}(e,K)C_{\eta\eta}(\eta)-n(D_e^2-(1-\eta)D_{ee}(e,K)C_{\eta\eta}(\eta))} \tag{5.25}$$

$$\frac{d\tau}{dk}=-\frac{n(D_e(ne)^2-(1-\eta)D_{ee}(ne)C_{\eta\eta}(\eta))(1+\epsilon(n-1))C_{eK}(e,K)}{C_{ee}(e,K)C_{\eta\eta}(\eta)-n(D_e^2-(1-\eta)D_{ee}(e,K)C_{\eta\eta}(\eta))} \tag{5.26}$$

$$\frac{d\eta}{dk}=-\frac{(1+\epsilon(n-1))C_{eK}(e,K)nD_e(ne)}{C_{ee}(e,K)C_{\eta\eta}(\eta)-n(D_e^2-(1-\eta)D_{ee}(e,K)C_{\eta\eta}(\eta))} \tag{5.27}$$

Given the assumptions in (4), (5) and (6) hold along with the assumption:

$$D_e(ne)^2 \geq (1-\eta)D_{ee}(ne)$$

We can easily establish that the conditions outlined in Proposition 1 will hold such that:

i) If $C_{ee}(e, K(k))C_{\eta\eta}(eta) \geq n[D_e(ne)^2 - (1-\eta)D_{ee}(ne)]$ then $\frac{de}{dk} < 0$, $\frac{d\tau}{dk} > 0$ and $\frac{d\eta}{dk} < 0$ and,

ii) If $C_{ee}(e, K(k))C_{\eta\eta}(eta) \leq n[D_e(ne)^2 - (1-\eta)D_{ee}(ne)]$ then $\frac{de}{dk} > 0$, $\frac{d\tau}{dk} < 0$ and $\frac{d\eta}{dk} > 0$ and,

## 3. Model with independent environmental authority

In order to prove the results in Proposition 4, we have to find the signs of the derivative $\frac{dk}{d\eta}$ and $\frac{d\tau}{d\eta}$ in equation (26). We can write (26) as follows:

$$C_\eta(\eta) = D(ne) - \epsilon(n-1)C_k(e, K(k))\frac{dk}{d\eta} + e\frac{d\tau}{dk}\frac{dk}{d\eta} \tag{5.28}$$

Now we can substitute $\frac{d\tau}{dk}$ from equation (19) into equation (35) to obtain the following:

$$\frac{dk}{d\eta} = \frac{D(ne) - C_{\eta}(\eta)}{(1 + \epsilon(n-1))C_k(e, K) + p} \tag{5.29}$$

We know the sign of $\frac{d\tau}{dk}$ is $< 0$. We can use $\frac{d\tau}{dk}$ along with $\frac{dk}{d\eta}$ and apply the chain rule to find that the sign of $\frac{d\tau}{d\eta}$ is $< 0$. Based on this we can see that in (36), the level of geo-engineering solved for with commitment is lower than without commitment when solved using (16).

Further we can also apply the chain rule to find the sign of $\frac{de}{d\eta}$. We can combine $\frac{de}{d\tau}$ and $\frac{d\tau}{d\eta}$ using the chain rule to show that $\frac{de}{d\eta}$ is $> 0$. This means that $\eta$ and $e$ move in the same direction such that at lower levels of $\eta$ we find lower levels of total emissions $e$.

To prove Proposition 5 we take the derivative of $((1-\eta)D(ne) + C(\eta))$ with respect to both $k$ as well as $\eta$ to represent the 2 scenarios 1) without commitment and 2) with commitment. We obtain $n(1-\eta)D_e(ne)\frac{de}{dk}$ and $n(1-\eta)D_e(ne)\frac{de}{d\eta}$. Now, we can use the results in Appendix 2 and Section 2.2 (Proposition 1), to show that i) If $C_{ee}(e, K(k))C_{\eta\eta}(eta) \geq n[D_e(ne)^2 - (1-\eta)D_{ee}(ne)]$ there is underinvestment in abatement technology, and ii) If $C_{ee}(e, K(k))C_{\eta\eta}(eta) \leq n[D_e(ne)^2 - (1-\eta)D_{ee}(ne)]$ there is overinvestment in abatement technology.

We also know that, i) If $C_{ee}(e, K(k))C_{\eta\eta}(eta) \geq n[D_e(ne)^2 - (1-\eta)D_{ee}(ne)]$ then $\frac{de}{dk} < 0$, $\frac{d\tau}{dk} > 0$ and $\frac{d\eta}{dk} < 0$ and,

ii) If $C_{ee}(e, K(k))C_{\eta\eta}(eta) \leq n[D_e(ne)^2 - (1-\eta)D_{ee}(ne)]$ then $\frac{de}{dk} > 0$, $\frac{d\tau}{dk} < 0$ and $\frac{d\eta}{dk} > 0$ and,

In both the above cases (i) and (ii), emissions rise and higher SRM levels are used to combat increases in emissions. Based on the above results we know, damages with commitment are lower because total emissions and geoengineering levels are lower with commitment. Higher geoengineering levels are able to counter the effects of higher emissions, but impose their own costs with are higher in the absence of commitment.

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# Biography

Varun Mallampalli earned his bachelors degree in Production and Industrial Engineering (B.Tech., 2013) from the Indian Institute of Technology, Roorkee, India. He then pursued a masters degree in engineering management (M.E.M., 2015) from Dartmouth College. He currently holds three publications which were other projects Varun was involved with during his dissertation studies at Dartmouth as well as at Duke. He was involved with multiple initiatives on Duke's campus including: 1) A D-SIGN grant dedicated to teaching students and policy centres the value of using System Dynamic models for policy analysis and System Design 2) A collaboratory grant dedicated to understanding the risks of using geoengineering as a third option alongside climate mitigation and adaptation.

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