Essays in the Economics of Environmental Policy

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Thesis submitted to the Indian Statistical Institute
in partial fulfilment of the requirements for the degree of
Doctor of Philosophy

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To Arundhati

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Introduction: Motivation and Main Results

We have modified our environment so radically that we must now modify ourselves to exist in this new environment.

Nobert Wiener

It is increasingly being accepted that the planet we live in is unable to fulfill the enormous resource demands that mankind places on it. As a result the environment we live in has undergone rapid changes in the last two centuries - changes that adversely affects human life. Long ago Thomas Malthus and more recently the *Club of Rome* researchers warned that rapid economic and population growth were going to be unsustainable as they are going to create an acute shortage of food and vital metals like mercury. Their predictions never passed the test of time (Sterner, 2003). However their ideas seem to hold true for ecological and environmental resources. The problem of overuse of global commons like earth's atmosphere and hydrosphere and local commons like forests, groundwater reserves, grasslands are a reality in today's world. The unfortunate fate of ecological goods is mainly due to the impure public good nature (rival but not excludable) of ecological goods and services. This ensures over-exploitation of such resources in a regulation free world as the economic man- an individual guided by self interest, does not internalize the externalities associated with such resource use. Hence the need of environmental policies to deal with situations of market failure in the realm of environmental goods and services. In addition to market failures, ill designed government policies are often an important reason for environmental problems. In the light of this, a economic study of various aspects of environmental policy is of great importance.

This dissertation consists of three chapters, each of them dealing with a particular aspect of environmental policy. The first and the third chapters deal with the distributional effects of environmental policy making in South Asia. To the extent that our current environmental problems are outcomes of unsustainable economic growth, it is unethical to have environmental policies that have adverse distributional consequences. It is specially true for developing countries with unequal societies like India and Nepal. Opposition to environmental policies are often on distributional grounds. Hence studying the distributional effects of environmental policies are of importance.

The second chapter of this dissertation deals with climate policy in a situation of dynamic inconsistency. Dynamic inconsistency in the context of climate policy refers to a situation where the policy maker cannot commit to a policy in future. The chapter shows how incentives to invest in research and development of green (emission free) technologies are affected by the presence of such commitment problems. It studies the role of various market instruments- emission taxes, emission caps and investment subsidies, in creating incentives for R & D in green technology.

I will now discuss each of these essays in brief by outlining the motivation and major results. In the chapters that follow, we discuss each of them in greater detail.

1.1 The Incidence of Fuel Taxation in India

In recent years, fuel taxes have returned to centre stage as a potential policy instrument for greenhouse gas abatement. However critics have often complained that a fuel tax would be regressive. Such views are often based on some studies on gasoline taxes in developing countries. As energy use patterns in developing and developed countries are different, it cannot be expected that results obtained in developed countries will hold good for developing countries as well. This chapter uses data from a representative household survey covering more than 124 thousand Indian households to examine this claim. It finds that a fuel tax would be progressive as would a carbon tax. Using an input-output approach, it is found that the progressivity results holds good even when one considers indirect consumption of fuel through its use as an intermediate input. Sensitivity checks allowing for differing price elasticities of demand between rich and poor confirm this result for most of the fuels. A tax on kerosene is the only fuel tax that is regressive in all situations.

1.2 Climate Policy and Innovation in the Absence of Commitment

It is well-recognized that new technology is a crucial part of any solution to the problem of climate change. But since investments in research and development take time to mature, price and quantity instruments, i.e., carbon taxes and cap-and-trade, run into a commitment problem. We assume that the government cannot commit to the level of a policy instrument in advance, but sets the level to be optimal ex-post. Under these assumptions, we show that when the supply curve of dirty (emission-producing) energy is flat, then an emissions tax is ineffective in promoting R & D into green (emission-free) energy while an emissions quota (i.e., cap and trade) can be effective. A subsidy to R & D is welfare-reducing. More realistically, when the supply curve of dirty energy is upward-sloping, then both tax and quota regimes can be effective in promoting R & D into emission-free technology. In this case, a tax generally induces more R & D than a quota. When the supply curve is sufficiently steep compared to the demand curve, a subsidy to R & D can expand the range of parameter values under which R & D occurs and this can be welfare-improving. If there is sufficient uncertainty about whether a climate policy will be adopted ex-post, then subsidizing R & D is an even more attractive policy option since a welfare-improving subsidy to R & D exists under a wider range of circumstances.

1.3 Equity and Communal Control: The Community Forestry Program in Nepal

Environmentalists and environmental activists have often advocated transfer of forests to village communities in order to resist non-judicious use of forest resources that lead to deforestation. It now well established that local involvement in forest management has had an important role in slowing down the rate at which forest resources are collected from forests in South Asia (Edmonds, 2002; Bandhyopadhyay and Shyamsundar, 2004). However the distributional effects of such a change in forest tenure have not been studied properly. The question of interest is not whether inequality in resource extraction exists under a regime where control of forests rests with the *"community"*. In the feudal democracies of South Asia, where societies are highly stratified, any system of resource control is expected to be unequal. What is of interest is to see if how levels of inequality under communal control compares with levels of inequality under other modes of control. This chapter tries to answer this using data from Nepal Living Standards Survey - Round 2. Using firewood collection as an indicator of utility derived from forest resources, it checks if the marginalized and the poor experience a larger decline in firewood consumption as the forest tenure is changed. The chapter finds some evidence for the hypothesis that tenure change has a relatively larger impact on the firewood collection and energy consumption of the poor and the marginalized, but such results are not robust to specification changes. However this chapter does not answer issues that can arise from endogenous location of forests user groups. This chapter is a brief note that acts as a prelude to further research that I want to undertake on this issue.

2

Incidence of Fuel Taxation in India [1]

2.1 Introduction

Climate change is increasingly being accepted as a major problem by policy makers round the world. Emission of carbon dioxide (CO_2) at an alarming rate is the major cause behind such anthropogenic climate change. Carbon accumulates in the atmosphere since natural processes of fixation and absorption in the oceans etc. are quite insufficient to counteract the extremely high current emission levels.

In the developed world, there is a growing realization that the problem of global warming is real and serious and something needs to be done about it. Even to achieve modest carbon-dioxide concentration targets like 550 parts per million by 2050, radical measures are required. Fossil fuels are the most important sources of carbon emissions. According to Raupach, Marland, Ciais, Quere, Canadell, Klepper, and C.B.Field (2007), fossil fuels account for about 90 percent of CO_2 emissions. Thus, their use will have to be controlled to achieve any meaningful reduction in CO_2 emissions.

India is the third largest emitter of CO_2 worldwide and accounts for about 5 percent of world CO_2 emissions in 2007. Figure 2.1.1 shows the rise in total carbon emissions in India in the last century and the early years of this century. It shows that the growth in emissions have increased rapidly in the last quarter of a century and shows no signs of tapering off.

[1] This chapter is based on Datta, A. (2010): "The Incidence of Fuel Taxation in India", *Energy Economics*, 32, S26-S33

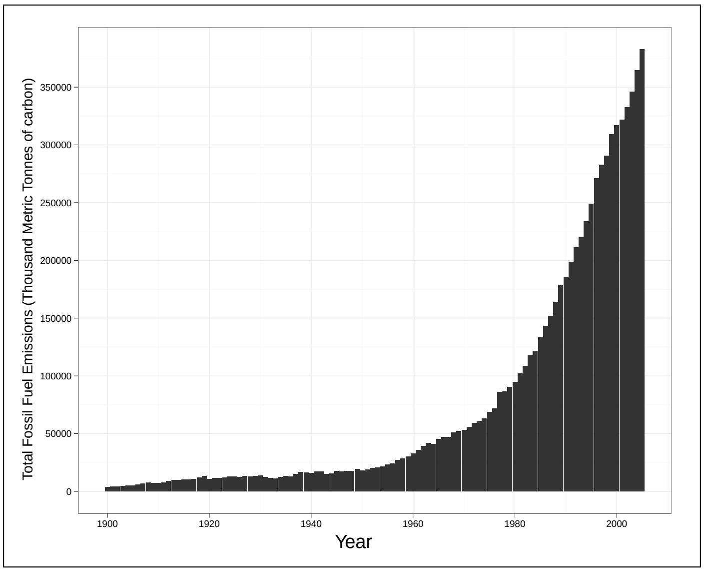

Figure 2.1.1: Total Fossil Fuel Emissions in India 1990-2005
Source: Marland, Boden, and Andres (2008)

Table 2.1.1 shows that fossils fuels are the single most important source of carbon emissions in India. They account for more than 95 percent of the CO_2 emissions in India. Thus any meaningful reduction in emissions from India will require a reduction in fuel use and a rise in fuel prices via taxation or other means can be used to ensure such a reduction. However till date, the government has failed to appreciate the enormity of the problem of climate change and have not done enough to deal with it. In the grab of socially beneficial intervention in the energy sector, it has often pursued policies of subsidization that have created negative incentives for emission abatement.

	(thousand metric tons of CO_2)	Percentage of Total emissions
Solid Fuels	782180	75.90
Liquid Fuels	192950	18.72
Gaseous Fuels	45045	4.37
Gas flaring	3344	0.32
Cement Manufacturing	47339	4.59
Land Use Change	-40307	-3.91
	1030551	

Table 2.1.1: Carbon Dioxide Emissions in India by Source
Source: Carbon Dioxide Emissions by Source 2005, Carbon Dioxide Information Analysis Center (CDIAC), World Resources Institute (WRI)

Although policy makers have often considered environmental taxes to be politically infeasible, Western Europe has for long experimented with environmental taxes: directly in the form of carbon taxes in the 1990s (which was prematurely discarded) and indirectly in the form of fuel taxes. Though fuel taxes in many of these Western European countries were designed for non environmental reasons, it has been shown that they did have a significant environmental impact. Sterner (2007) reviews several studies and concludes: *'Had Europe not followed a policy of high fuel taxation but had low U.S. taxes, then fuel demand would have been twice as large'*. Having calculated the hypothetical transport demand for the whole OECD area, Sterner concludes that fuel taxes are the single most powerful climate policy instrument implemented to date.

However, fuel taxes have sometimes been criticized on distributional grounds. This has generated a popular perception that fuel taxes are regressive. The balance of academic evidence does not favour this view. It was in early the 90's that the question of regressivity in fuel taxation was raised for the first time. A large number of people argued against fuel taxation on the ground that it imposes a larger burden on poor people. Such claims were based on studies that used the US data on gasoline consumption (KPMG Peat Marwick, 1990). Santos and Catchesides (2005) found similar regressivity, but only among car users in the United Kingdom. However, the United States is hardly a representative country in this regard. The USA is a country with very high incomes in which even poor households have cars - in fact it is the poor who own old, energy inefficient cars. Unlike developed nations of Western Europe, many cities of the United States don't have an efficient public transport system. Regressivity in these initial studies is also conditioned by the fact that such studies are based on current income rather than current expenditure. Poterba (1989) and Kasten and Sammartino (1988) suggested that the extent of regressivity of taxation in USA was exaggerated by the year to year fluctuations in income among households at the bottom of the annual income distribution. Poterba (1989) argued that consumption expenditure is a better indicator of a household's long run economic well being as it is less susceptible to shocks and hence incidence measures should be based on expenditure. Once that is done, a gasoline tax ceases to be regressive (Poterba, 1991). Poterba showed that when expenditure based measures are used the maximum incidence of gasoline tax is on middle expenditure deciles.

Recently West (2004) showed that a gasoline tax in the USA is regressive across higher income households only. For low levels of income, it is progressive. Steininger, Friedl, and Gebetsroither (2007) developed a computable general equilibrium model and found that a gasoline tax is progressive in Austria. Santos and Catchesides (2005) showed that if all households (both with and without cars) are considered then the maximum burden of a gasoline tax is on middle income households. Their study is based on income and not on expenditure levels, so their results might be biased in a way similar to the bias found in early studies of the USA.

Only a few papers on the distributional effects of fuel taxation are based on data from developing countries. Working with the Mexican data, Sterner and Lozada (2009) find that fuel taxation is strongly progressive if one takes only direct consumption of gasoline into account. However when indirect consumption through public transport is taken into account, it becomes neutral. Ziramba (2009) shows that fuel taxation is progressive in South Africa whether or not we consider indirect consumption through public transport. Kpodar (2006) shows that in Mali, taking indirect consumption into account, the burden of an oil price hike is highest on the highest income deciles. According to World Bank (2001), the impact of a 33 percent gasoline and diesel price hike is regressive (including indirect consumption) in Pakistan. Thus it is clear that there is no unanimous result on the regressivity issue.

India is characterized by a high level of governmental intervention in the petroleum sector. Even after the abolition of the administered price mechanism in 2002, the government continues to provide fiscal subsidies to cooking and lighting fuels. In addition to fiscal subsidies, both cooking-lighting and transport fuels receive implicit subsidies that take the form of under-recoveries for oil marketing companies. However both the state and central government impose taxes on transport and cooking-lighting fuels. Subsidies outweigh the taxes for cooking-lighting fuels. The situation for transport fuels is not clear. Subsidies for transport fuels mainly take the form of under-recoveries and official statistics don't give any information on under-recoveries per unit of petrol or diesel. Rough calculations reveal that taxes outweigh implicit subsidies for transport fuels [2]. Thus we see that even after the official abolition of the administered price mechanism, there has been substantial government intervention in the fuel sector. In such an environment, it is important to know the distributional impact of additional taxes or removal of existing subsidies.

This chapter studies the incidence of a tax on fuels in India. It specifically tries to check if fuel tax or removal of fuel subsidies adversely affects the poor more than they do the rich. This study is important for two reasons: Firstly, the energy sector in India is highly regulated by the government. The government provides subsidies to various fuels with an aim of helping the poorer sections of the society. It is important to see if the poor really benefit from such subsidization schemes or the removal of such subsidies have a progressive effect. Secondly, India is one of the largest emitters of carbon dioxide worldwide. Emissions in India have been increasing at a rapid rate and are expected to do so in future. If fuel taxes are not regressive, they can be used to restrict fuel emissions without having serious adverse social implications. Besides it is politically easier for governments to justify taxes that are progressive than those that are regressive. Hence, it is important to study the distributional effects of fuel taxes in India.

In comparison to other papers that studies the regressivity issue in underdeveloped or developing countries, this chapter is different in two major ways: Firstly, unlike other papers on developing nations, this chapter looks at the distributional effect of taxes on all major cooking, lighting and transport fuels. Since solid fuels are a major source of emissions in India and a large part of energy produced in India is thermal power, we specifically look at the impact of a coal tax. It is also important to consider all fuels in a single framework as major petroleum products like diesel and kerosene are produced jointly in refineries. Often fuels like kerosene and diesel are used as substitutes [3]. Thus taxing one of them while subsidizing the

[2] Details in Appendix 2.A

[3] According to a study titled "Comprehensive Study to Assess the Demand and Requirement of SKO" carried out by the National Council of Applied Economic Research (NCAER) and commissioned by the petroleum and natural gas ministry, 36 percent of the total amount of kerosene distributed in the country through PDS is diverted. The study further found out that, 20% of diverted kerosene finds its way to households through the open market. Assuming that the whole of the rest is used to adulterate diesel, around 18% of PDS kerosene supplied is used to adulterate diesel. (NCAER, 2005)

other, can lead to problems of adulteration and black-marketing. Secondly, while calculating incidence, this chapter makes full inclusion of all indirect effects through an input output structure. Most papers (Ziramba, 2009; Sterner and Lozada, 2009) restrict their attention to the indirect effects in the public transport sector on the assumption that by doing so substantial part of the indirect effects is captured. It also undertakes sensitivity analysis using elasticity estimates from secondary sources.

2.2 Data and Methods

Would fuel taxes or any other policy that is equivalent in the sense of raising fuel prices in India be regressive in the sense that they would impose a higher percentage burden on the poor compared to the rich? I use information from an all India consumption survey and an Input Output transaction matrix to answer this question.

In a partial equilibrium framework, I first examine the direct effects, then allow for indirect effects and finally perform a sensitivity analysis that allows for differing price elasticities of fuel for rich and poor. There is not enough information available for a credible complete general equilibrium analysis.

I start with the simplest of the measures: a measure of direct tax burden, ignoring indirect consumption of fuel through consumption of commodities that use fuel as an input. The following assumptions are made:

1. The production function of the taxed commodity shows a fixed coefficient technology. Thus the supply curve of the taxed commodity is perfectly elastic. Consumers bear the entire burden of tax [4].

[4] If the supply curve is not perfectly elastic, then a part of the tax burden is shifted to the producers. Calculation of the burden would then require information on the demand and supply elasticities of different industries and the distribution of ownership of firms in those industries. This information is not available. Besides, a number of studies suggest that in the short to medium run, the burden of a carbon tax will be mostly passed forward into higher consumer prices (Bovenberg and Goulder (2001) and Metcalf et al. (2008))

2. The taxed commodity is not an intermediate input and so does not change the price of any other commodity in the economy. This assumption will be relaxed later.

3. Hicksian (compensated) demand for fuel is inelastic. Sensitivity checks will later be performed to check if relaxation of this assumption changes the results.

Under assumptions (1), (2) and (3), I can comment on the progressivity or regressivity of tax just by looking at the budget share of the taxed commodity for different levels of monthly per capita expenditure (MPCE). If a tax on a particular fuel is regressive (progressive), the budget share will fall (rise) as we move from lower to higher deciles.[5].

Data on consumer expenditure on fuel and other commodities is obtained from the consumption schedule of the 61st round of the National Sample Survey conducted by the National Sample Survey Organization of the Government of India during the period July 2004- June 2005. This quinquennial round has a sample size of 124584 households. The rural sample consists of 79258 households and corresponding figures for the urban sample are 45326 households. I measure the incidence of a fuel tax across expenditure classes since, due to consumption smoothing; expenditure is a better measure of long term economic welfare than income. In any case, the NSS does not report income. I use consumption figures that are based on 30 day recall for both non-durables and durables.

The measure discussed above takes only direct consumption of fuel into account. However fuel is an important input into the production of various commodities. When households consume such commodities, they indirectly consume fuel. A tax on fuel increases the price of such fuel-using commodities, which in turn imposes an additional burden on consumers. The second measure that I consider takes such indirect consumption into account. (Assumption 2 is relaxed). This measure of incidence requires the following additional assumptions:

1. A closed economy

2. Unchanged value added per unit output. Primary Factor markets unaffected.

[5]Budget share of a decile is the ratio of the average (weighted) fuel expenditure and average (weighted) total expenditure for that decile

Given these assumptions, I calculate the fuel tax induced price changes in all sectors. Due to the assumption of inelastic compensated demand curves, we can calculate the compensating variation as a percentage of total expenditure. If this percentage increases (decreases) with MPCE deciles, the tax imposed is progressive (regressive)[6].

To calculate the economy wide price changes I at first use the Input Output Coefficient matrix- 2003-2004, published by the Central Statistical Organization. The original matrix for 2003-04 has disaggregated information on 130 sectors. In order to make it compatible with the NSSO data; the 2003-2004 CSO matrix has been aggregated to make an input output matrix which has information on 46 broad sectors. This obviously introduces an element of error, but compatibility between NSSO data and CSO data demands such aggregation. Central Statistical Organization's Input-Output Matrix has fossil fuel sector information at a very aggregative level. The four fuel sectors are: Crude petroleum, Natural gas, Petroleum Products and Coal and Lignite. In order to study the distributional effects of petroleum and gas products separately I use information from the Input Output Table (2003-04) constructed by National Council for Applied Economic Research in the report titled "Study of Macroeconomic Impact of High Oil Prices" (NCAER, 2006). This matrix has 27 sectors of which eight are fuel related sectors. They are Petroleum, oil & lubricants-Crude, Motor gasoline, Diesel, Aviation turbine fuel, Liquefied petroleum gas, Kerosene, Other Petroleum Products and Gas and Water Supply. However, here the coal sector here is merged with the all other minerals to form a sector called "Mining and Quarrying". However the CSO 2003-2004 matrix reveals that coal constitutes about 65 percent of total mineral production in India. Thus this sector can be used to calculate incidence of a coal tax. I combine information from the NCAER matrix and combine it with the CSO matrix to create a new matrix that has energy level information at a disaggregated level [7].

While calculating each of the above measures, I had assumed that the compensated demand

[6] Technical details discussed in Appendix 2.B

[7] The NCAER matrix is not used directly as it is an input-output matrix at factor prices. For this analysis, I need a matrix evaluated at producer prices. The way in which information from this matrix is used in our analysis, is discussed in Appendix 2.B

is inelastic. This is unrealistic but the strength of the progressivity results seem to suggest that the results will remain unaltered even when I allow for elastic demand. I carry out a sensitivity analysis using elasticity estimates from different studies to test if that is indeed the case. The estimates are obtained from different sources and are often not representative at an all India level. Thus they have problems of comparability. However the purpose of these checks is to show that the progressivity results don't change for "reasonable" values of elasticity. One requires extreme values of elasticities to change the results. Since it is not possible to obtain own price, cross price and income elasticity estimates for all the 27 commodities that I have considered earlier, I aggregate further and consider only 5 commodities: Coal, LPG, Transport Fuels, Kerosene and Other goods. Elasticity estimates for these goods for different deciles are obtained from various sources and the unknown ones are calculated using identities on demand elasticities. The regressivity results are then checked by comparing the incidence on the lowest and the highest deciles.

2.3 Results

In a low income country, we may expect transport fuel taxes to be progressive since poor people don't own cars. This is especially true for India where 34% of the population is below Purchasing Power Parity of $1 a day and 27.5% of the population lives below the abysmally low national poverty line . In India, most rural households use biomass-fuels and do not use fossil fuels for cooking purposes. However kerosene -an important petroleum product is widely used as lighting fuel. Thus it cannot be said for sure if cooking and lighting fuels will have distributional impacts different from that of transport fuels.

Figure 2.3.1 shows the distribution of household monthly per capita expenditure in India as a whole. As expected the per capita expenditure distribution for India is highly positively skewed with a median MPCE of Rs. 550 [8]. The figure gives us a clear idea as to where the

[8] Based on new statistical calculations of purchasing power parity (PPP) exchange rates published in 2005 by the International Comparison Program (ICP) of the IMF, the PPP adjusted exchange for India Rs. 14.7 / PPP adjusted US dollar

MPCE deciles stand in respect to absolute levels of consumption.

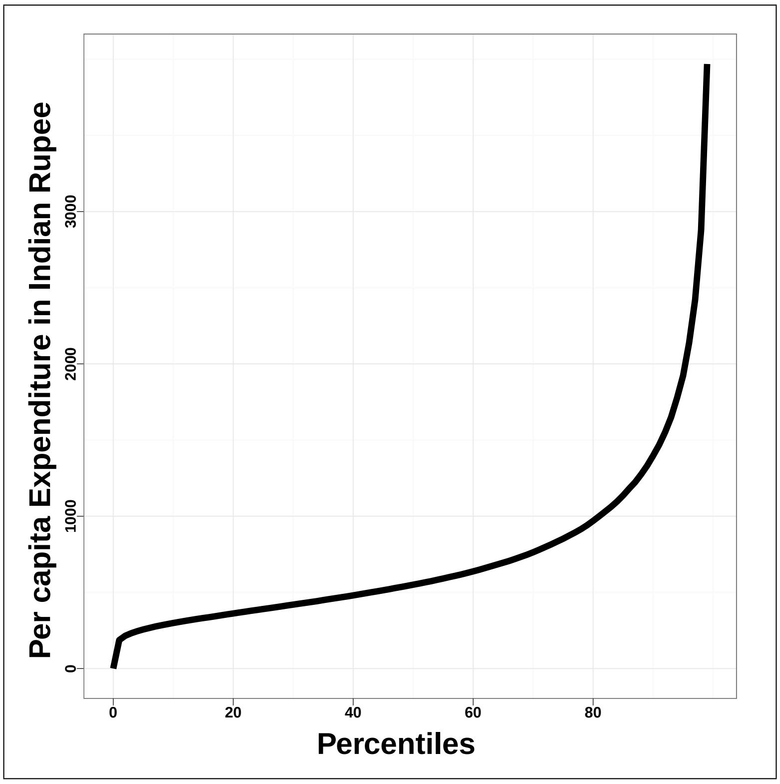

Figure 2.3.1: Distribution of Monthly Per Capita Expenditure

We now look at the incidence results: Figure 2.3.2 shows the direct budget share of fuel [9] as a whole. The combined budget share of all fuel products (Coke-Coal, Petrol, Diesel, Kerosene, Gas etc) is seen to be higher for higher consumption deciles. The budget share of fuels stay constant for the first three deciles, but increases thereafter, indicating that an overall fuel tax would be strongly progressive. There is a difference of around 4% between the budget shares of highest and lowest decile.

It will be interesting to see what is going on behind these figures. To see that I calculate the incidence results separately for transport fuels and cooking-lighting fuels.

From Figure 2.3.3, it is seen that the budget share of all cooking fuels is constant for

[9] Direct Budget Share means directly consumed fuel (excluding indirect consumption through consumption of commodities using fuel as input) as a percentage of total expenditure. Consumption reported in the household consumption survey is treated to be direct consumption. As noted earlier, budget share of a decile is the ratio of the average (weighted) fuel expenditure and average (weighted) total expenditure for that decile.

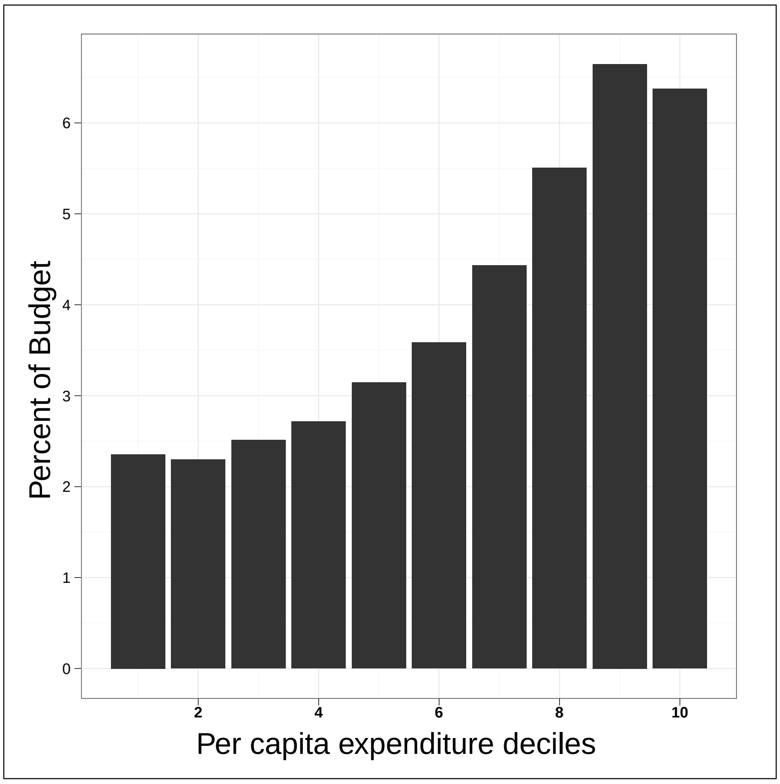

Figure 2.3.2: Budget Share of Fuels across MPCE deciles

the first four deciles, but increases thereafter. It falls substantially for the highest decile. If we consider kerosene and Liquefied Petroleum Gas, then kerosene's budget share decreases with consumption while the budget share of LPG increases with consumption. The budget share for gas falls substantially for the last decile. This is expected because the urban non poor are the major users of gas as a cooking fuel. The budget share curve for coke and coal has an inverted U shape. The budget shares are negligible and hence not shown in the diagram.

In rural India, very few households use gas. Only 0.19 percent of rural households in the poorest decile use gas as their main cooking fuel, the figure increases to 43 percent for rural households of the top decile. Only people in the upper end of the expenditure distribution use gas. The budget shares increase with the level of expenditure. In urban India, LPG is a popular cooking fuel, especially among the middle and high expenditure groups. The percentage of urban households who use LPG as their main cooking fuel rises across expenditure deciles. From 4% for the first decile, the percentage of households using gas as the primary cooking fuel increases to 80% for the top decile. When budget shares of cooking gas across deciles is calcu-

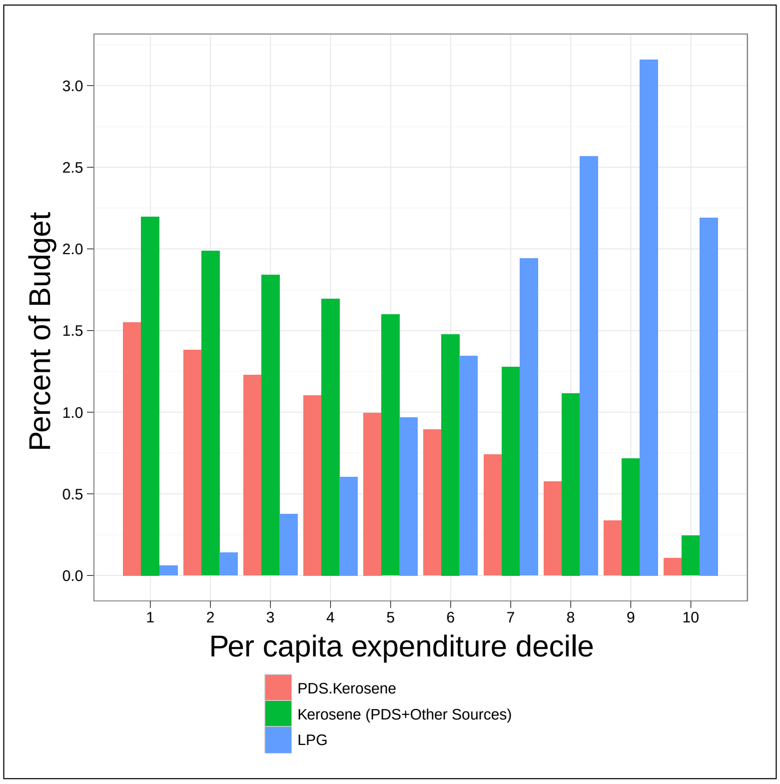

Figure 2.3.3: Budget Share of Cooking & Lighting Fuels across MPCE deciles

lated separately for rural and urban sector (creating separate deciles for the rural and urban distribution), budget shares increase with deciles for the rural sector and budget share curve is inverted U shaped for the urban sector. However the urban sector is richer and smaller than the rural sector. Household that are at the middle of the urban expenditure distribution are in the top end of the overall distribution. This explains fall in budget shares of cooking gas with rise in deciles (Figure 2.3.3). Thus a removal of existing subsidies on cooking gas is progressive.

Kerosene is the popular lighting fuel in rural areas, especially for the poor. As consumption increases, people move towards electricity, subject to its availability in villages. For cooking purposes traditional biomass fuels- firewood, dung and agricultural residue, are generally used. With an increase in income people start shifting towards more convenient fuels like kerosene and gas. The budget shares of kerosene fall with expenditure, indicating the expected regressivity from the use of kerosene as a lighting fuels outweighs the expected progressivity from it's use as a cooking fuel. In the urban sector electricity is used for lighting, almost universally. Only 8% of urban Indian households do not state electricity to be their main lighting fuel.

These urban households (the majority of whom come from the lowest decile) use kerosene. However around 10 percent of urban households use kerosene as their main cooking fuel and they are distributed across the urban deciles. In the urban sector, the budget share of kerosene declines with expenditure. When both sectors are considered, the budget share of kerosene falls with per capita expenditure. When kerosene sold through the public distribution system is considered separately, the budget shares decrease with per capita expenditure. Thus the removal of existing subsidies on kerosene will be regressive.

Most of the literature on the distributional effects of a fuel tax concentrates on transport fuels like gasoline. In figure 2.3.4 below I consider Petrol (Gasoline). Diesel and other transport fuels are rarely used for personal transport in India. Diesel is mainly used for freight and for public transport. It is only in cities like Delhi that the public transport fleet uses cleaner fuels like CNG. It is known that kerosene is used to adulterate diesel (NCAER, 2005). However I cannot make incidence calculations taking that into account as I don't know how such adulterated kerosene is distributed across deciles.

As is evident from figure 2.3.4, the budget shares of transport fuels are strictly increasing with consumption [10]. This is expected as only the very rich can afford private transport and hence require transport fuels. A large majority of Indian households (more than 80% according to 61st round NSS data) do not buy either petrol or diesel.

So far I looked at taxes on individual fuels or a situation where all new fuel taxes were proportional to their existing price. I now examine the incidence of a carbon tax on coal and petroleum and gas products. A carbon tax implies that fossil fuels are taxed according to their emission potential. If the emission factor of one unit of a fuel is 'a' and a carbon tax of 'x' is imposed, then the effective unit tax on the fuel is 'ax'. I assume that only fossil fuels that I have considered so far (coal-coke, LPG, kerosene, diesel, petrol) are taxed according to their carbon content, biomass fuels-firewood, gobar gas, cow dung are not taxed though they also

[10] The curve for diesel is almost flat, showing some upward slope for top consumption deciles. It is very close to zero showing that a negligible amount of Indian households use diesel vehicles for private transport. Hence, it is not shown in the figure 2.3.4

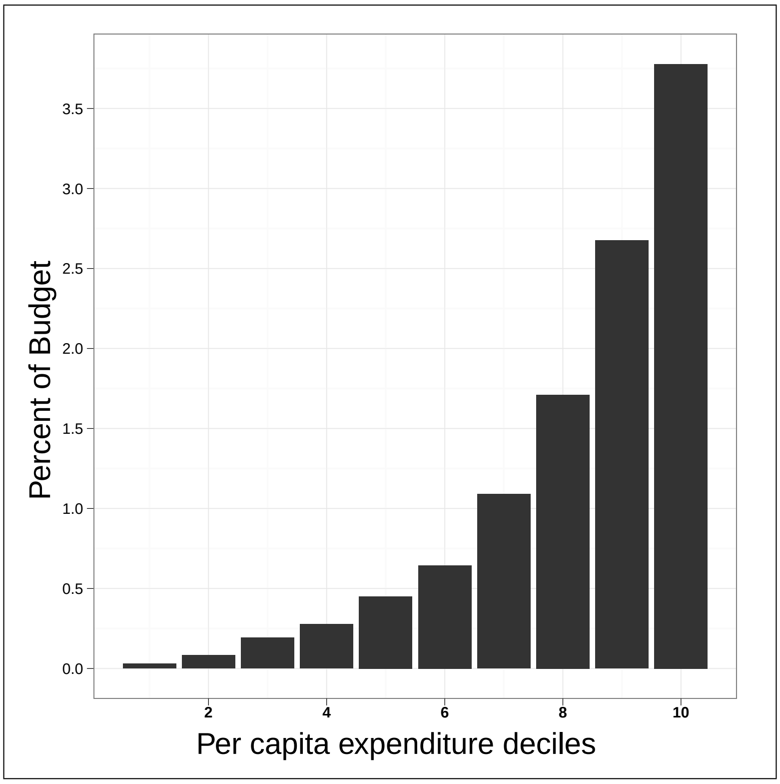

Figure 2.3.4: Budget Share of Transport Fuels across MPCE deciles

cause emissions. The conversion factors used to calculate total emissions are based on IPCC (1996) and U.S. Environmental Protection Agency (2000) [11]. Figure 2.3.5 shows the incidence of Rs 5 per kg [12] of carbon-dioxide tax on different deciles. The burden is constant for the first four deciles and increases thereafter. Thus a carbon tax on fossil fuels is not regressive. It is neutral for lower deciles and becomes progressive for higher deciles. The different colours show the contribution of each fuel in the total burden from fuel tax. It is evident that the two major cooking fuels: kerosene and LPG drive the results.

The results reported so far ignores indirect consumption of fuel. Since coal and diesel is mostly consumed indirectly, it is important to take this into account. According to the $2003-04$ input-output data, inter industry consumption of coal and petroleum products constitutes about 98% and 80% of the sum of total home production and imports respectively.

[11]I obtain conversion factors from $http://www.climatetrust.org/solicitations_2007_Metrics.php$. Coefficients for LPG are expressed per unit volume while in India LPG is sold in kilograms. I use approximate weight of 1 metric ton for 1844. 20 litres of LPG, to calculate emissions. The results remain unchanged when I use emission coefficient obtained from citetGreenpeace07

[12]There is nothing special about the tax rate being considered. The progressivity results will hold true for any tax rate.

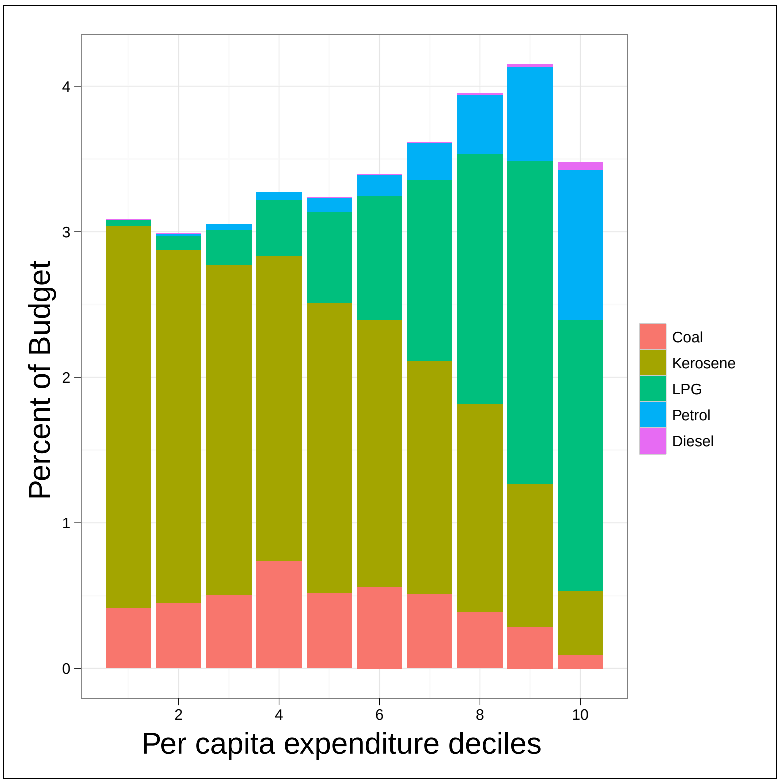

Figure 2.3.5: Direct Effect of a Carbon Tax at Rs. 5 per Kg of Carbon (tax on the 5 fuels in proportion to their emission coefficient)

According to basic statistics published by the Ministry of Oil and Natural Gas, Government of India, diesel sale in India is 5 times the sale of motor gasoline (petrol). This shows that it is important to take indirect effects into account when I calculate incidence. I now report combined budget shares that include both direct and indirect consumption of fuel. Such budget shares equal the compensating variation as a percentage of total expenditure, when fuel taxes rise by a unit amount [13]. An increase in such budget shares with increase in MPCE indicates progressivity. Figure 2.3.6 reports the combined and indirect budget shares that are calculated using CSO's 2003 − 04 input output table.

The figure shows that inclusion of indirect consumption does not change the conclusion that taxation of coal and petroleum products [14] at a rate proportional to the current price

[13]Explanation given in Appendix 2.B

[14]In addition to Diesel, Petrol, Kerosene and LPG, petroleum products also include lubricating oil and other industrial fuels. Coke is no longer a part of coal sector. According to CSO classification, it is a part of the sector coal tar products. While reporting direct budget shares, we had provided the combined share of coke and coal.

would be progressive. Inclusion of indirect consumption reverses some regressivity results that I had obtained earlier. Earlier the direct budget share of coal was highest for the middle deciles and was lower at the two ends. However inclusion of indirect consumption yields progressivity.

This result is quite intuitive. Coal is an important input in the production of energy and manufacturing sector. The rich spend a much bigger proportion of their total expenditure on energy and consumer goods. This in turn changes the earlier result. The budget shares for petroleum products are almost unchanged for the first few deciles. They start increasing thereafter. Thus at an All India level, taxes on petroleum products are progressive.

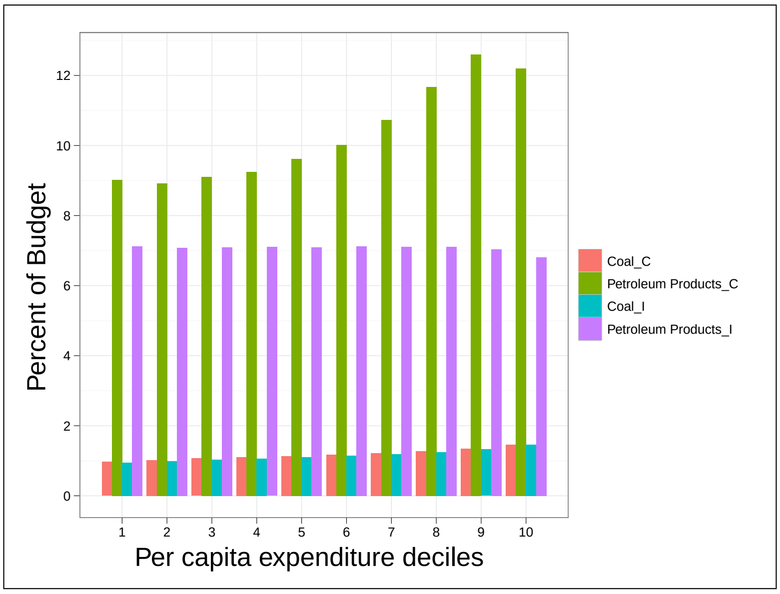

Figure 2.3.6: Combined and Indirect Budget Share of Coal and Petroleum Products

The petroleum products sector of CSO's input output table includes transport fuels like gasoline (petrol) and diesel, cooking fuels like liquefied petroleum gas, lighting fuels like kerosene and various other industrial fuels like fuel oil, bitumen and petroleum wax. Thus, the indirect effects calculated using the matrix aggregates all the effects. However the indirect effects of different fuels can conceivably run in different directions. For example, furnace oil is generally used in the high end manufacturing sector. Kerosene, on the other hand, might be used as an intermediate input in very small scale eateries in the informal sector and can thus have regressive indirect effects. However such differences get lost in the aggregation. To deal with this, I combine the information from NCAER (2006) to create a new matrix with disaggregated information on energy sector. I then use this matrix to calculate incidence results at a disaggregated level. This matrix has disaggregated information on petroleum products. However it does not have a separate sector for coal. Coal is included in a sector called Mining and Quarrying. Using this matrix, I see the impact of a tax on major petroleum products like petrol, diesel, LPG, kerosene and ATF. None of the petroleum products other than diesel and ATF have indirect effects that are non-negligible. For these fuels the combined effects mimic the direct effects. Even after indirect effects have been considered, all of them (except kerosene) continue to be progressive. Kerosene remains regressive. Aviation Turbine Fuel has no direct consumption by households, so the indirect effect coincides with the direct effect. As expected they are progressive. However the budget shares for all the deciles are negligible. Thus Figure 2.3.7 shows only the results for diesel only. Diesel is rarely used by households directly but has significant indirect uses.

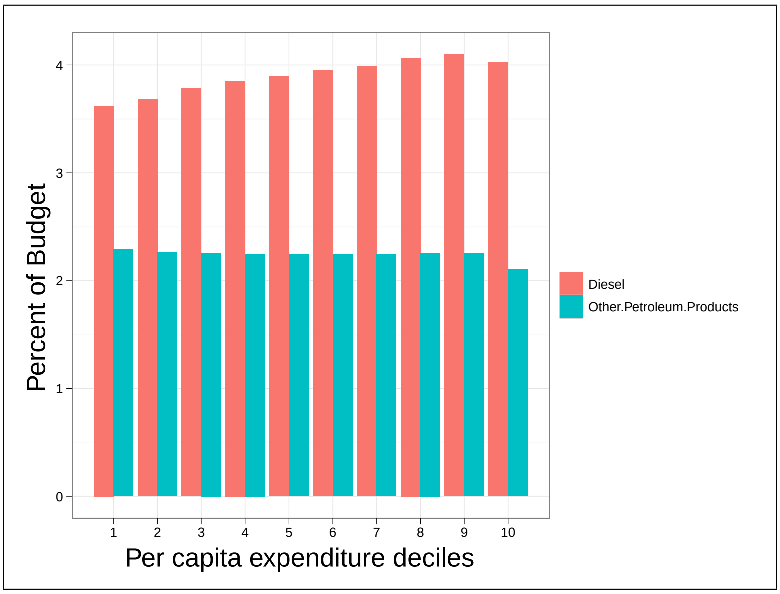

Figure 2.3.7: Combined Budget Share of Petroleum Products
(Calculated using addition information from NCAER matrix)

I now examine the total incidence of a carbon tax on coal and petroleum and gas products taking the effect of indirect consumption into account. I use the CSO matrix for this purpose. Figure 2.3.8 shows the incidence of a carbon-dioxide tax (at the rate of Rs 5 per Kg.

of carbon-dioxide) on different deciles [15]. The burden-expenditure ratio increases with per capita expenditure (MPCE). Thus a carbon tax on fossil fuels is not regressive. The different colours show the contribution of each fuel in the total burden from fuel tax.

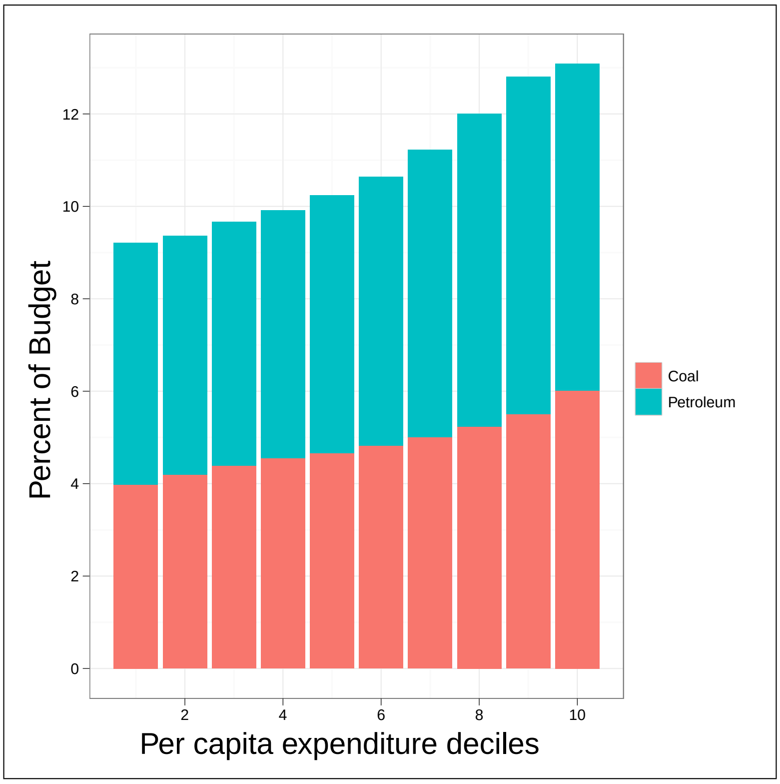

Figure 2.3.8: Burden of a carbon tax (including indirect effects) at rate of Rs. 5 per Kg of CO_2

I now provide some intuition for why the inclusion of indirect effects maintains the progressivity result. We know that the poor have low budget shares for petroleum products (except kerosene) and slightly high budget shares for coal, compared to the rich. In spite of that, the fact that fuel prices affect prices of other commodities and the possibility that the poor might

[15] In order to calculate the incidence of a carbon tax, I assume the price of a Kg of Coal and a litre of petroleum products to be Rs.4.57 and Rs. 25.67 respectively. The emission coefficients of coal and petroleum products are 1.91 Kgs of CO2 per Kg and 2.45 kgs. of CO2 per litre respectively. The price for coal is obtained from NSSO data. The price and emission coefficient of petroleum products are the quantity weighted averages. Prices of petroleum products commodities are obtained from various sources: data published by the Ministry of Petroleum and natural gas, Govt. of India and the two major oil marketing companies: Indian Oil and Bharat Petroleum. The emission coefficients and density values of individual fuels are obtained from http://www.eia.doe.gov/oiaf/1605/coefficients.html and US Greenhouse Gas Inventory (US Environmental Protection Agency)

have high budget shares for such commodities, may change the direction of the incidence results. For example, the poor might be affected adversely if food prices are highly sensitive to fuel prices. The fact that the budget share of food for the poor is high might depress the progressivity result obtained earlier. Table 2.3.1 gives the difference in the budget shares of the last and the first decile for some important sectors. It shows that the "poor" have a higher budget share for food items, forestry and logging, coal and lignite, edible oil and toiletries, compared to the rich. These sectors have the potential to depress the progressivity obtained earlier (by comparing direct budget shares), only if the products of these sectors are highly sensitive to fuel prices. On the other hand textiles, milk products, petroleum products, health, electricity, transport services, other services, education, hotels and restaurants and education have lower budget shares for the poor, compared to the rich.

Sectors	Decile 1	Decile 10	Difference
Major Food Crops and their products	28.94	5.28	-23.66
Other Crops	9.01	4.3	-4.71
Milk and Milk Pdts	2.85	5.21	2.36
other animal products	3.44	1.79	-1.65
Forestry and Logging	5.25	0.3	-4.95
Coal and Lignite	0.03	0.01	-0.02
Sugar	1.84	0.73	-1.11
Edible Oil	4.86	1.75	-3.11
Textiles	1.13	4.19	3.06
Misc. Manufacturing	0.63	2.67	2.04
Petroleum Products	1.89	5.39	3.49
Health	2.6	9.1	6.5
Toiletries	4.76	2.69	-2.07
Electrical, Electronic Machines and Appliances	0.12	1.54	1.41
Transport Equipment	0.11	3.47	3.36
Electricity	1.35	3.82	2.47
Other Services and Communication	3.1	9.99	6.89
Trade	13.43	7.84	-5.6
Hotels and restaurants	0.19	2.08	1.89
Education	0.43	4.22	3.79

Table 2.3.1: Budget Share for the richest and poorest decile.
(After adjusting for trade and transport margins)

Figure 2.3.9 shows the price changes in all sectors in response to an increase in the unit tax on coal (petroleum products) by one unit. Since the initial prices are normalized to one, it can be treated as the percentage change in price in response to an increase in coal/petroleum tax by one unit. Food items, forestry and logging, edible oil and toiletries are not very responsive to a coal tax. On the other hand sectors like electricity are highly responsive to a coal tax. Thus electricity consumption can have an important role in determining the incidence of a coal tax. Now I look at the impact of a petroleum product tax on the prices across the economy. We see that cereals and non cereal food crops, forestry and logging, edible oil and toiletries are not very responsive to a petroleum product tax. On the other hand sectors like electricity and transport services are highly responsive to such a tax. Thus electricity and transport services consumption can have an important role in determining the incidence of a petroleum products tax. I similarly calculate price changes due to taxes on individual petroleum products, using the input output matrix constructed using NCAER (2006). It is high speed diesel oil and other petroleum products (naphtha, bitumen, high sulphur low stock etc.) that are mainly responsible for the additional indirect burden from a petroleum products tax. In other words, diesel and other petroleum products are important intermediate inputs in a large number of sectors.

Till now I had assumed that compensated demand is inelastic. This is highly unrealistic but the strength of the progressivity results seem to suggest that the results will remain unaltered even when we allow for elastic demand. I carry out a sensitivity analysis using elasticity estimates from different studies to test if that is indeed the case. I compare the proportional burden for the top and the bottom decile using different elasticity estimates for the two deciles. Higher proportional burden for the top decile indicates progressivity. Even after allowing for elastic compensated demand, transport fuels and LPG remain progressive. Coal becomes neutral, while kerosene continues to be regressive [16]. The results for LPG, kerosene and transport fuels are robust to small changes in electricity. However the result for coal changes sign for small changes in elasticity. However the difference in the proportional tax burden of the two deciles is extremely close to zero.

[16] Sources of elasticity estimates and the method of sensitivity check are discussed in appendix 2.C & appendix 2.D respectively

Figure 2.3.9: Sectorwise price change due to increase in tax on coal and petroleum products by one unit

2.4 Conclusions

Fuel taxes for environmental purposes have often faced skepticism and criticism on the grounds of regressivity. This chapter shows that such criticisms do not apply to a low-income country like India. When just direct consumption is considered, taxes on transport fuels (petrol and diesel) are highly progressive for both urban and rural sector. Similarly, all cooking fuels, with the exception of kerosene and coal, show definite signs of progressivity. These results remain unchanged when indirect consumption is included in the analysis. A tax on coal is progressive for the country as a whole. While a tax on kerosene is regressive, the results for gas are just the opposite. Transport fuels continue to be progressive even after the inclusion of indirect effects. Allowing for elastic compensated demand, makes the coal tax neutral. Kerosene continues to be regressive and gas and transport fuels continue to be progressive.

These results of this chapter can be used in different ways, depending on the policy objective of the government and tax authority. The objective of an environmental tax is to reduce emissions by reducing consumption of fuel. Thus, unlike a tax imposed for revenue purposes, an environmental tax should be imposed on fuels with elastic demand and on fuels with emission potential. Transport fuels satisfy these criteria and are thus an appropriate case for a fuel tax for environmental purposes. They have high emission potential with each litre of transport fuel emitting around 2.3 kilograms of carbon dioxide per litre of fuel. Although transport fuels demand is inelastic in the short run, it responds to price changes in the long run and have a long-run elasticity of -0.84 (Sterner, 2007). However, Ramanathan and Geetha (1998) report a lower long run elasticity of -0.42, which is still sensitive to price changes. The results presented here show that a tax on transport fuel is progressive. The results hold good even when indirect consumption is considered. Thus a tax imposed on transport fuels achieves the desired objective of emission reduction without having any adverse distributional effects, thus making a strong case for transport fuel taxation.

Coal is the largest emitter of carbon dioxide in India. The results here show that a tax on carbon is neutral or slightly progressive. Given that there is no strong regressivity, there is strong case for taxing coal. Such a tax would encourage innovation and diffusion of non-conventional carbon free energy like solar and wind energy.

The issue of taxing cooking and lighting fuel is more complex and it is difficult to make an unqualified recommendation for a tax. Contrary to popular perception, studies by Gundimeda and Kohlin (2008) show that elasticities of cooking and lighting fuels are not low for all sections of the society. According to their study, the elasticity of gas is close to unity for almost all sections of the society, ranging from -0.92 for the urban rich to -1.05 for the urban poor. However, gas is a cleaner fuel compared to its counterparts and thus the case for a gas tax (or equivalently, the case for a removal of the existing gas subsidy) is not strong in spite of the fact that such a tax is progressive. The case for a gas tax becomes reasonable only when the government can couple it with incentives for using electricity for cooking purpose. Electricity is an efficient cooking fuel. However a large percent of electricity in India is coal based, thus a movement away from gas to electricity might accentuate the emission problem. Thus the case for a gas tax is not strong.

In India, kerosene is an important cooking and lighting fuel. While urban households use kerosene as a cooking fuel, rural households use it for lighting purposes. The demand for kerosene is responsive to prices especially in the rural sector. It ranges from -0.7 for the rural rich to -0.5 for the middle expenditure group. Kerosene is a poor lighting source and more expensive than electricity (Barnes, Plas, and Floor, 1997). The results from this chapter show that a removal of the subsidy on kerosene would be regressive and a major reason for the observed regressivity is that 35% of rural households use kerosene primarily to light their homes. Besides regressivity, a tax on kerosene has other aspects of concern. Any tax on kerosene causes the poor to substitute towards fuelwood, which has strong adverse health and regional climate implications and can also lead to deforestation. According to Gundimeda and Kohlin (2008), a one percent increase in the price for kerosene increases fuel wood use by 0.7 percent for the rural poor and 0.4 percent for the urban poor. Thus, any tax proposal should be preceded by compensatory proposals for the poor. This can take the form of targeted electricity and LPG subsidies for the poor and should be coupled with a program of rural electrification. The targeted gas subsidy might also help in forest conservation as has been pointed out by Baland et. al (2006). The need for gas subsidy can be reduced by subsidizing biogas whenever viable.

A report by Greenpeace India - "Hiding behind the poor" (Ananthapadmanabhan, Srinivas, and Gopal, 2007) concludes that when it comes to CO_2 emissions, a relatively small wealthy class of 1% of the population in India is hiding behind a huge proportion of 823 million poor people and that it is India's poor who keep per capita CO2 emissions really low. Thus it is natural that a policy designed to tackle GHG emission should impose a larger burden on the rich. The evidence from this study shows that an environmental fuel tax would do just that. The progressivity result is robust to the inclusion of indirect fuel consumption. Thus it a bit surprising that people speaking for the Indian underclass in the polity often come down heavily on any proposal of fuel price hike, on the grounds that it imposes a higher burden on the poor than on the rich. While this is true for kerosene, it is not true for any other fuel.

Appendices for Chapter 2

2.A Tax Subsidy Situation in Indian Petroleum Sector

States in India impose taxes on petroleum products at different rates. For illustration of the relative tax-subsidy scenario we use information from the National Capital Territory of Delhi. According to Graczyk (2006), the tax situation in Delhi is as follows:

	Price Without Tax	Customs Duty	Excise Duty	Sales Tax	Total Tax	Retail Price
Kerosene (litre)	8.7	0	0	0.35	0.35	9.05
Diesel (litre)	18.42	1.94	4.93	3.16	10.03	28.45
Petrol (litre)	17.04	1.6	14.74	6.75	23.09	40.13
LPG (14.2 Kg Cylinder)	215.49	0	16.06	18.17	34.23	249.72

Table 2.A.1: Petroleum Retail Price Buildup in New Delhi 2005-2006

According to data published by Petroleum Planning and Analysis Cell, Ministry of Petroleum and Natural Gas, Government of India, subsidy (subsidy from fiscal budget and under recoveries to oil companies) to consumer is Rs.12.92 per litre of PDS kerosene and Rs. 175.04 per cylinder of domestic LPG. Thus for cooking fuels subsidies outweigh the taxes.

According to basic statistics published by the Ministry of Petroleum and Natural Gas, Government of India, the total consumption of Petrol (Mogas) and Diesel (HSDO) was 8647000 tonnes (12010 million litres assuming a density of 0.72 kgs/litre) and 40191000 tones (48000 million litres assuming a density of 0.85kgs/litre) respectively, in 2005-06. Assuming that the tax structure of New Delhi (given in table 2.A.1) prevails across the country, this translates into tax revenue of Rs. 7643240 million. According to data published by Petroleum Planning and Analysis Cell, Ministry of Petroleum and Natural Gas, Government of India, the total under recovery on Petrol and Diesel was Rs.153700 million. Thus the tax revenues outweigh the implicit subsidies. However under-recoveries have grown very fast in the last few years.

2.B Calculation of Direct and Combined Incidence

- Direct Incidence:

For a given product, its budget share corresponds to the price elasticity of total spending, assuming volume of demand constant.

$$\theta_{ij} = \frac{\partial logM_j}{\partial logP_i} \tag{2.B.1}$$

where M_j is money income/total expenditure of j^{th} household, P_i is the price of the i^{th} good and θ_{ij} is the budget share of i^{th} commodity in j^{th} household's budget.

$$\text{Tax Burden due to tax on X} = \frac{(P+t)X}{E} = (1+\frac{t}{P}) * \text{Initial Budget Share of X} \tag{2.B.2}$$

where P is the initial price of X, t is the unit tax, X is the amount purchased and E is the expenditure.

Thus, under assumptions (1)-(3), I can test whether a tax on a particular fuel is regressive, simply by comparing the budget share of that fuel across different expenditure deciles.

- Combined Incidence calculated using Input Output tables

Using the absorption (Use) matrix at producer prices and the make matrix, I create a (130 × 130) input output matrix at producer prices. Each cell (i, j) denotes the total amount (inclusive of taxes paid) of input j used in the production of commodity j. At the end of each column is the gross value added and indirect taxes on each commodity. The sum for each column is thus the sum of value of intermediate input at producer prices, Gross value added and the indirect taxes, which in turn is the total value of output of that commodity at producer prices. By dividing each column by the output for that column, I get the coefficient matrix. Under the assumption that all prices are normalized to one, the cell (i, j) in this coefficient matrix denotes the amount of input i used to produce one unit of input j. In order to make it comparable to the NSSO data, I aggregate the matrix to 46 broad sectors. The sector names can be seen in Figure 2.3.9.

Let $A = [a_ij]_{n\times n}$ be the $(n \times n)$ input output coefficient matrix, where n is the number of commodities considered. a_ij is the quantity of i^{th} commodity output used to produce 1 unit of commodity j.

Let the price formation equation be:

$$P_j = P_i + VA_j + t_j, i = 1, 2, \ldots, n \tag{2.B.3}$$

$$\text{or,} (I - A^T)_{n\times n} P_{n\times 1} = VA_{n\times 1} + t_{n\times 1} \tag{2.B.4}$$

where, I is a $n \times n$ identity matrix, t is a $n \times 1$ column matrix of tax rates and P and VA are column vectors showing prices and value added of the n sectors.

Let us assume that the tax of the i^{th} commodity changes by dt_i. Then,

$$(I - A^T)_{n\times n} dP_{n\times 1} = dt_i e_i \tag{2.B.5}$$

where e_i is a column vector with 1 in the i^{th} place and 0 in every other place.

Taking inverse (assuming inverse exists) we have,

$$dP_{nx1} = (I - A^T)^{-1} dt_i e_i \tag{2.B.6}$$

The tax burden of the k^th household is

$$TB_k = [\frac{X_k (I - A^T)^{-1} e_i}{Y_k}] dt_i \tag{2.B.7}$$

where X_k is the $(1 \times n)$ vector of quantities purchased by household k and Y_k is consumption expenditure of household k. Denote the term within parenthesis by S_k. This can be interpreted as the share of commodity i in household k's expenditure taking all indirect effects into account.

Since the terms outside the parenthesis are same for all households, I only need to calculate the term within to comment of distribution of tax burden. Information on X_k and Y_k is obtained from NSSO data while information about other matrices is obtained from CSO input output table. In NSSO survey, the consumption value of any commodity is at market prices. However the CSO matrix used is at producer prices. The difference between the two arises because of the trade and transport margins. Thus when a consumer reports to buy Rs. X worth of commodity i in the NSSO survey, he is actually buying the output of 3 CSO sectors (commodities): sector i, trade sector and transport sector. Thus a part of the consumer expenditure on sector i should be transferred to trade and transport sector. The CSO provides information on the trade and transport margins for all sectors. I assume that the overall margins for the economy apply to all consumption deciles. After adjusting for trade and transport margins, I obtain X_k required to calculate tax burdens using 2.B.7.

The CSO input output transaction matrix is actually the cost share matrix $\{C_{ij}\}_{n \times n}$ where $C_{ij} = a_{ij}(P_i/P_j)$. I chose physical units in such a way that initially (before tax) $P_1 = P_2 = \ldots = P_n = 1$ .Given this assumption $\{C_{ij}\}_{n \times n}$ is the same as $\{a_{ij}\}_{n \times n}$ and the tax burden can be easily calculated. I can calculate it for each household corresponding to tax changes in coal, natural gas, kerosene and petroleum products.

In order use the information of the 27 sector NCAER matrix, I aggregate the CSO matrix to 22 broad sectors. These 22 sectors are the 21 non petroleum sectors included in NCAER matrix and a broad energy sectors that includes all petroleum products. Since all petroleum products are jointly produced in refineries, it is difficult to know what proportion of a particular input used in the refinery goes into the production of a particular sector. Thus I divide the column for petroleum products into 6 different columns each have the same cell value as the earlier petroleum products sectors. These columns refer to liquefied petroleum gas, kerosene, aviation turbine fuel, gasoline, diesel and other petroleum products. The row for petroleum products is now divided between the six petroleum products according to the ratios obtained from the NCAER matrix.

2.C Source of Elasticity Estimates for Sensitivity Checks

Let rural households of the first decile (of all India distribution) denote rural poor and urban households of the first decile (of all India distribution) denote urban poor. Similarly rural households of the tenth decile (of all India distribution) denote rural rich and urban households of the tenth decile (of all India distribution) denote urban rich. Thus we have 4 mutually exclusive groups: rural poor, rural rich, urban poor and urban rich. Let table 2.C.1 be the matrix of Marshallian price elasticities and income demand elasticities of a particular group. I know the budget shares of the 5 commodities considered: Coal, Petroleum Products, Gas, Kerosene and others, for this group from NSSO data. [17]

	Coal	Pet	Gas	Kerosene	Others	Income
Coal	A11	A21	A31	A41	A51	A1
Pet	A12	A22	A32	A42	A52	A2
Gas	A13	A23	A33	A43	A53	A3
Kerosene	A14	A24	A34	A44	A54	A4
Others	A15	A25	A35	A45	A55	A5

Table 2.C.1: Marshillian Price Elasticities and Income Elasticity

Rural Sector: $B33$, $B34$, $B44$, $B43$, $A3$ and $A4$ are obtained from Gundimeda and Kohlin (2008). They have this information for 3 rural classes: low income, high income and

[17] I aggregate the 27 sectors of the I-O matrix (created using information from NCAER (2006) into 5 sectors: Coal, transport fuel, LPG, Kerosene and Other goods. There is no separate sector for coal in this matrix. Coal is a part of mining and quarrying sector. However CSO's 2003-04 matrix shows that coal constitutes around 65% of all mineral production (excluding petroleum and natural gas). I use the price changes in the mining and quarrying sector as indicative of price changes in coal. To adjust for trade and transport margins, we use information from CSO matrix. Since transport margins are not available separately for kerosene, LPG and transport fuels, we use the transport margin of petroleum products for all the three commodities.

	Coal	Pet	Gas	Kerosene	Others
Coal	B11	B21	B31	B41	B51
Pet	B12	B22	B32	B42	B52
Gas	B13	B23	B33	B43	B53
Kerosene	B14	B24	B34	B44	B54
Others	B15	B25	B35	B45	B55

Table 2.C.2: Hickian Price Elasticities

middle income. I assume our poor have the elasticities corresponding to low income group and our rich have elasticities corresponding to high income group.

No information is available on $B12$, $B32$, $B42$, $B21$, $B23$ and $B24$. I assume then to be 0 since there is no reason to expect strong complementarity or strong substitutability between cooking fuels and transport fuels. I know $A22$ and $A2$ from time series study by Ramanathan and Geetha (1998). Using the Slutsky Equation I have $B22$.

I don't have estimates for $B11$, $B13$, $B14$, $B31$ and $B41$. I assume that the relationship between coal and other goods will be similar to the relationship between firewood and other goods, as both this fuels are generally used by users with similar profiles. I obtain these estimates from Gundimeda and Kohlin (2008). The value for $A1$ is also obtained from Gundimeda and Kohlin (2008) assuming the value is similar to income elasticity of firewood with respect to income.

Now I have values for Bji , $j = 1, 2, 3, 4$ and $i = 1, 2, 3, 4$. We know that the sum of compensated price elasticities are equal to zero. Using this I can easily calculate $B5i, i = 1, 2, 3, 4$.

Now the only thing that is not known is the last row of matrix B. Since I know Bji ($j = 1, 2, 3, 4, 5$ and $i = 1, 2, 3, 4$), Aj ($j = 1, 2, 3, 4$) and the budget shares, I can calculate Aji , $j = 1, 2, 3, 4, 5$ and $i = 1, 2, 3, 4$. Now using the Cournot Aggregation Rule I can calculate $A15$, $A25$, $A35$, $A45$ and $A55$. Using the condition that the sum of income elasticity and Marshallian price elasticities is zero, I obtain $A5$.

Now that I have information on $A51$, $A52$, $A53$, $A54$, $A55$, $A5$ and the budget shares, I calculate $B51$, $B52$, $B53$, $B54$ and $B55$ using the Slutsky equation. Now I have the whole B matrix that is required to do the sensitivity check.

Urban Sector: $B33$, $B34$, $B44$, $B43$ are obtained from Gundimeda and Kohlin (2008). They have this information for 3 urban classes: low income, high income and middle income. I assume our poor have the elasticities corresponding to low income group and our rich have elasticities corresponding to our high income group.

No information is available on $B12$, $B32$, $B42$, $B21$, $B23$, $B24$. I assume them to be 0 since there is no reason to expect strong complementarity or strong substitutability between cooking fuels and transport fuels. I know $A22$ and $A2$ from time series study by Ramanathan and Geetha (1998). Using the Slutsky Equation I have $B22$.

I don't have estimates for $B11$, $B13$, $B14$, $B31$ and $B41$. I obtain estimates for $A11$, $A41$ and $A14$ from the paper by Gupta and Kohlin (2006) on Calcutta. For estimates of $B13$, $B31$ and $A1$, I assume that the relationship between coal and other goods will be similar to the relationship between firewood and other goods, as both this fuels are generally used by users with similar profiles. I obtain these estimates from Gundimeda and Kohlin (2008). The value for $A13$ can also obtained from Gupta and Kohlin (2006). However the estimation this paper shows a counterintuitive sign. I couldn't find any reason for such a result. Thus I make a stronger assumption, and use the Gundimeda and Kohlin (2008) values for $B13$ and $B31$. $B11$, $B41$ and $B14$ are obtained using Slutsky equation (I know $A11$, $A41$, $A14$, $A1$, $A4$ and budget shares).

Now I have values for Bji, $j = 1, 2, 3, 4$ and $i = 1, 2, 3, 4$. I know that the sum of compensated price elasticities are equal to zero. Using this I can easily calculate $B5i$, $i = 1, 2, 3, 4$.

Now the only thing that is not known is the last row of matrix B. Since I know Bji ($j = 1, 2, 3, 4, 5$ and $i = 1, 2, 3, 4$), Aj ($j = 1, 2, 3, 4$) and the budget shares, I can fill in the

Aji , $j = 1, 2, 3, 4, 5$ and $i = 1, 2, 3, 4$ that are not known. Now using the Cournot Aggregation Rule I can calculate $A15$, $A25$, $A35$, $A45$ and $A55$. Using the condition that the sum of income elasticity and Marshallian price elasticities is zero, I obtain $A5$.

Now that I have information on $A51$, $A52$, $A53$, $A54$, $A55$, $A5$ and the budget shares, I calculate $B51$, $B52$, $B53$, $B54$ and $B55$ using the Slutsky equation. Now I have the whole B matrix that is required to do the sensitivity check.

The proportion of rural population in the lowest decile of the all India distribution is 0.94. Let Hicksian Elasticity matrix of "Rural poor" is RP and "Urban poor" be UP. Then the Hicksian elasticity matrix for the "poor" (bottom decile of overall distribution) is $OP = 0.94 * RP + 0.06 * UP$. Similarly, elasticity for the "rich" (top decile of overall distribution) is the weighted average of the urban and rural values where the rural weight is 0.29. These elasticity estimates are used to undertake sensitivity checks. The elasticity estimates obtained for the "poor" and the "rich" are as in table 2.C.3:

	Coal		Transport Fuels		LPG		Kerosene		Others	
	Poor	Rich	Poor	Rich	Poor	Rich	Poor	Rich	Poor	Rich
Coal	-0.118	-0.095	0	0	0.832	0.436	0.671	0.144	-1.385	-0.485
Transport Fuels	0	0	-0.42	-0.363	0	0	0	0	0.42	0.363
LPG	0.6	0.511	0	0	-0.482	-0.517	0.478	0.916	-0.596	-0.909
Kerosene	0.225	0.05	0	0	0.228	0.365	-0.593	-0.204	0.139	-0.212
Others	-0.005	-0.012	0	0.015	-0.005	0.011	0.013	-0.023	-0.002	0

Table 2.C.3: Compensated Demand Elasticities for Poor and Rich

2.D Methodology of Sensitivity Check

From the theory of demand we know that demand elasticities satisfy two conditions:

$$\sum_{j=1}^{n} e_{ji} + e_{mi} = 0 \quad \forall i \tag{2.D.1}$$

$$\sum_{i=1}^{n} d_i e_{ji} + e_{mi} = -d_j \quad \forall j \tag{2.D.2}$$

where e_{ji} is the uncompensated price elasticity of commodity i with respect to price of commodity j. We also have the Slutsky equation,

$$\frac{\partial X_i}{\partial P_j} = \frac{\partial X_i^h}{\partial P_j} - X_j \frac{\partial X_i}{\partial M} \tag{2.D.3}$$

where P_j , X_j and X_j^h are the price , Marshallian demand and Hicksian demand for good i respectively. The tax burden is

$$\begin{aligned} TB &= \frac{\text{Compensating Variation}}{\text{Initial Expenditure}} \\ &= \frac{E(P', U^0) - E(P^0, U^0)}{E(P^0, U^0)} \\ &= \frac{\sum_{i=1}^{n} P_i' X_i^h(P', U^0)}{E(P^0, U^0)} - 1 \end{aligned} \tag{2.D.4}$$

where P^0, P' and U^0 denotes price bundle before tax, price bundle after tax and utility level before tax respectively. Taking total differential of $X_i^h = X_i^h(P, U)$,

$$\begin{aligned} dX_i^h &= \sum_{j=1}^{n} \frac{\partial X_i^h}{\partial P_j} dP_j \\ &= \sum_{j=1}^{n} \alpha_{ji} \frac{X_i^h dP_j}{P_j} \end{aligned} \tag{2.D.5}$$

where α_{ji} is the compensated (Hicksian) price elasticity of commodity i with respect to price of commodity j. Thus,

$$\begin{aligned} X_i^h(P^0 + dP, U^0) &= X_i^h(P^0, U^0) + dX_i^h \\ &= (1 + \sum_{j=1}^{n} \alpha_{ji} dP_j) X_i^h(P^0, U^0) \end{aligned} \quad (2.D.6)$$

[Note: $P_i^0 = 1$ due to normalization.]

Thus,

$$TB = \frac{\sum_{i=1}^n P_i'(1 + \sum_{j=1}^n \alpha_{ji} dP_j) X_i^h(P^0, U^0)}{E(P^0, U^0)} - 1 \quad (2.D.7)$$

Let there be two classes: Rich (R) and Poor (P). For a tax on commodity i to be progressive we require

$$TB_R > TB_P$$

$$\Rightarrow \frac{\sum_{i=1}^n P_i'(1 + \sum_{j=1}^n \alpha_{ji}^R dP_j) X_i^{h^R}(P^0, U^0)}{E^R(P^0, U^0)} - 1 > \frac{\sum_{i=1}^n P_i'(1 + \sum_{j=1}^n \alpha_{ji}^P dP_j) X_i^{h^P}(P^0, U^0)}{E^P(P^0, U^0)} - 1$$

$$\Rightarrow \sum_{i=1}^{n} P_i' \big[(1 + \sum_{j=1}^{n} \alpha_{ji}^R dP_j) D_i^R - (1 + \sum_{j=1}^{n} \alpha_{ji}^P dP_j) D_i^P \big] > 0 \quad (2.D.8)$$

Superscripts R and P denote rich and poor respectively. D_R and D_P denote direct budget shares of rich and poor respectively.

Using the elasticity estimates and information from NSSO & input output table, I test if this inequality holds true when a tax is imposed on a particular fuel.

2.E A Note on Fuel Pricing in India

With the objective of moving towards market determined prices for petroleum products, the government of India abolished the Administered Price Mechanism (APM) in April,2002. However, the Indian government continues intervention in the petroleum sector by absorbing state owned oil company losses. Market determined prices are considered to be politically infeasible by the political forces.

Given that the government considers subsidization of cooking fuels to be an important social instrument in helping poorer households shift from biomass to modern fuel, the government in 2002 decided to continue providing subsidies for Liquid Petroleum Gas and Kerosene ex-ante in the budget. The Oil Marketing Companies (OMCs) were to adjust the retail selling prices of these products in line with international prices during this period. Subsidies were expected not to exceed 15% of the Gas-Import Parity Price and 33% of the kerosene-Import Parity Price. The government had even thought of abolishing all budget subsidies within 5 years from 2002. However, in compliance with Government directions, the OMCs did not adjust prices of kerosene distributed through the public distribution system and domestic LPG commensurately, resulting in losses on account of these two products.[18]. In October 2003, Government decided that the OMCs would make good about a third of the losses on these two products from the surpluses generated by them on petrol and diesel while the balance losses would be shared equally by the upstream companies (ONGC/OIL/GAIL) and the OMCs.

In late 2003, international oil prices started rising rapidly and this burden sharing arrangement collapsed. This had two impacts:

- The burden of subsidy on PDS kerosene and domestic LPG increased sharply - the burden of subsidies in 2005-06 was Rs.15, 000 crores [19] on account of PDS kerosene and Rs. 11,000 crores on account of domestic LPG. Tables 2.E.1 and 2.E.2 show how implicit and explicit subsidies on PDS kerosene and LPG changed during the period 2002-2006:

  Thus, since the abolition of APM, one witnesses a decline in the explicit component of

[18]In the oil sector, under-recoveries and losses are often used interchangeably. This is not correct as they are two distinct concepts. Refining of crude oil is a process industry where crude oil constitutes around 90% of the total cost. Since value added is relatively small, determination of individual product-wise prices becomes problematic. The oil marketing companies (OMCs) are currently sourcing their products from the refineries on import parity basis which then becomes their cost price. The difference between the cost price and the realized price represents the under-recoveries of the OMCs. The under-recoveries as computed above are different from the actual profits and losses of the oil companies as per their published results. The latter take into account other income streams like dividend income, pipeline income, inventory changes, and profits from freely priced products and refining margins in the case of integrated companies. (GoI, 2006)

[19]1 crore=10million

ITEM	PDS Kerosene (Rs. /Litre)			
	2002-03	2003-04	2004-05	2005-06
Subsidy from fiscal budget	2.45	1.65	0.82	0.82
"Under recoveries" to oil companies*	1.69	3.12	7.96	12.14
Total subsidy to consumer	4.14	4.77	8.78	12.96
	Domestic LPG (Rs./Cylinder)			
Subsidy from fiscal budget	67.75	45.18	22.58	22.58
"Under recoveries"to oil companies*	62.27	89.54	124.89	147.74
Total subsidy to consumer	130.02	134.72	147.47	170.32
*On the gross before adjusting amount shared by upstream companies				

Table 2.E.1: Subsidy on PDS Kerosene and Domestic LPG
Source: GoI (2006)

ITEM				
	2002-03	2003-04	2004-05	2005-06
Fiscal Budget	4496	6292*	2930	2900
Oil Companies "Under recovery"	5430	9274	17842	23704
Total	9926	15566	20772	26604
*includes arrears of 2002-03 of 2213 crores				

Table 2.E.2: Total Subsidy on Domestic LPG and PDS Kerosene (in Rs. Crores)
Source: GoI (2006)

subsidy (that is allotted for in the budget) and an increase in the implicit component. In 2004-05, the total subsidy on LPG and kerosene was Rs.20772 crores, where as the fiscal budget allotted for only Rs.2930 crores. Thus "Under Recoveries" constituted 85 percent of total combined subsidy on PDS kerosene and domestic LPG.

- The government started interfering in the pricing of petrol and diesel. It restricted the pass through of international prices to domestic consumers. As a result the margins available to OMCs during 2002-04 on petrol and diesel thinned and then rapidly turned negative. In 2003-04, oil companies made an under recovery of Rs. 2303 crores on petrol and diesel.

Thus, five years since the dismantling of APM, India has not made much headway towards market pricing of petroleum products and gas.

However, contrary to popular belief, the fuel sector is not a story of one way flow of subsidies. While on the one hand subsidies are in place, the same commodities are subjected to various taxes. Both the Central Government and the state government impose taxes which pull up retail prices. While on one hand Oil Public Sector Undertakings are advised not to revise prices in conformity with crude rates, the government imposes excise duties and a plethora on other taxes on these items. The result is that Indian retail prices for petroleum and diesel are the highest in South Asia. For cooking fuels, Budget subsidies are coupled with various central and state level taxes. The table below shows the component of taxes in retail prices:

PRODUCT	Central Taxes	State Taxes	Total Taxes
Petrol	38%	17%	55%
Diesel	23%	11%	44%
Domestic LPG	0%	11%	11%
PDS Kerosene	0%	4%	4%

Table 2.E.3: Component of Taxes in Retail Price
Source: GoI (2006)

However subsidies outweigh the taxes for cooking-lighting fuels [20]. The situation for transport fuels is not clear. Subsidies for transport fuels mainly take the form of under-recoveries and official statistics don't give any information on under-recoveries per unit of petrol or diesel. Rough calculations reveal that taxes outweigh implicit subsidies for transport fuels[20].
Thus we see that even after abolition of the administered price mechanism, there has been substantial government intervention in the fuel sector, especially the petroleum products sector [21]. In such an environment, it is important to know the distributional impact of additional taxes or removal of existing subsidies. This is especially important in an underdeveloped country like India, where the funds provided as fuel subsidies can be alternately used in socially productive investment in health and education, which can directly benefit the poor.

[20] Details already discussed in Appendix 2.A

[21] The pricing of coal was fully deregulated after the Colliery Control Order, 2000 was notified with effect from 1st January 2000 in suppression of the Colliery Control Order, 1945. Under the Colliery Control Order, 2000 the Central Government has no power to fix the prices of coal

3

Climate Policy and Innovation in the Absence of Commitment [1]

3.1 Introduction

Economic instruments for pollution control in general and climate policy in particular are considered superior to traditional regulation and subsidies because they are believed to induce adjustment on all appropriate margins in a least-cost way. Analyses of the virtues of these instruments, however, are typically made in a static context.

Avoiding dangerous climate change and ocean acidification involves a halt to, and possibly even a reversal of, the build-up of carbon dioxide in the atmosphere. It is, therefore, clear that energy technologies that replace those emitting carbon dioxide are a necessary part of any solution. This makes technological advance to reduce the cost of carbon-free energy an important target of climate policy.

In order to induce investment in research and development, incentive-based instruments such as emissions taxes and carbon cap and trade have to be expected to be in place *after* the new technology comes to market. This can be several years after the decision to invest in R & D is made. Policies announced or put in place today can be changed. To put it simply, there is a commitment problem. This commitment problem does not apply to policies put in place today that lower the cost of R & D, such as subsidies or complementary investments by

[1] This chapter is based on a paper co-authored with Prof. E. Somanathan, Planning Unit, Indian Statistical Institute, New Delhi.

public-sector entities. We compare the effects of an emissions tax, an emissions quota with tradeable permits, and R & D subsidies on a firm's incentive to conduct R & D in the absence of commitment by the government.

While there is a considerable literature on the role of emission-reducing R & D, Kneese and Schulze (1975), Marin (1978), Downing and White (1986), Milliman and Prince (1989), Jung, Krutilla, and Boyd (1996), Denicolo (1999), Fischer, Parry, and Pizer (2003), most of it concerns technologies that reduce the rate of emissions. This approach is suited to the study of end-of-pipe abatement technologies, or others where emissions rates can be reduced by changing the quality of fuel. It is of limited applicability in studying carbon dioxide emissions, the most significant contributor to climate change. Of greater significance in the climate context are technologies that replace carbon-based fuels with an entirely different source of energy, such as solar, wind, or nuclear energy. In recent years, Montgomery and Smith (2005) studied the commitment problem in climate policy in a framework where innovation leads to development of zero carbon technologies. They concluded that standard market-based environmental policy tools cannot create credible incentives for R & D. A crucial assumption in their paper was that the R & D sector is competitive. Thus their negative result is a consequence of the non-appropriability of the returns from R & D. In our work, we assume a monopolistic R & D sector so that the returns from R & D are appropriable. We obtain results that are less pessimistic than Montgomery and Smith (2005).

The paper whose framework most closely resembles our own is that of Denicolo (1999). Like us, Denicolo considers a monopolistic firm that decides how much to invest in R & D on the basis of its expectation about the level of an emissions tax or quota with tradeable permits. Denicolo assumes that the extent of emission reduction per unit of output is an increasing function of the amount invested in R & D but that the private marginal cost of producing a unit of output is unaffected by R & D. In contrast, we assume that R & D is used to reduce the marginal cost of zero-emission technologies. Our assumption is intended to model replacement technologies of the kind mentioned above, while his is better suited to modeling end-of-pipe abatement of a particular kind: one in which there is a sunk cost of abatement (R & D) but no variable cost. Denicolo shows that if the government sets the level of the emissions tax or aggregate quota to be optimal ex-post, that is, after the result of R & D is realized, then tax and quota policies are equivalent. They induce the same R & D. In contrast, we show that in our framework in which R & D affects the cost of a zero-emission technology, a tax can never induce R & D while a quota can do so.[2] Scotchmer (2009) uses a framework similar to that of Denicolo and obtains similar results.Kolstad (2010) develops a model without dynamic inconsistency. He models technological progress on the lines of Denicolo (1999) and shows that a single instrument in the form of a tax or an abatement quota can ensure social optimality.

In this chapter, we compare the effects of tax and tradeable quota policies in the absence of commitment, and the role of R & D subsidies.[3] In Section 2 we show that when the marginal cost of dirty (emission-producing) energy is constant, then an emissions tax is ineffective in inducing R & D, while a quota can be effective. The reason for this is that a fall in the marginal cost of the emission-free technology as a result of R & D means that a lower tax is sufficient to allow the new technology to compete. Since a higher-than-necessary tax results in a welfare loss by giving the owner of the new technology monopoly power, the government reduces the emissions tax in response to successful R & D. This destroys the incentive to do R & D.

When the policy instrument is an emissions quota, we show that the government will reduce the quota when the emission-free technology gets less expensive (as long as it remains more costly than the dirty alternative), because the cost of reducing emissions has fallen. This response induces R & D. But we also show that the introduction of a technology that is less costly than the dirty alternative is inhibited. This is because the government response in such a case is the opposite: It increases the quota since it is no longer needed to contain emissions

[2]This result holds only under the assumption (common to Denicolo (1999)) that the marginal cost of the dirty technology is constant.

[3]We do not model the international aspect of the problem. In any case, the results are relevant for jurisdictions with large energy markets such as China, the United States, and the European Union. In fact, one attractive feature of technological improvements is that they may make international agreement easier to reach.

and only enhances the monopoly power of the green firm. We show that any subsidy to R & D investment that actually induces R & D is welfare-reducing when the marginal cost of dirty energy is constant.

Since fossil fuels are subject to increasing marginal costs of production when harder to reach mineral deposits have to be extracted, it is more realistic to assume that the supply curve of dirty energy is upward-sloping. We make this assumption in Section 3 of the chapter. Now both tax and quota regimes can be effective in promoting R & D into emission-free technology but they are not equivalent. The results of Section 2 are reversed (for a sufficiently steep supply curve of dirty energy) and a tax generally induces more R & D than a quota. When the supply curve of dirty energy is sufficiently steep compared to the demand curve for energy, a subsidy to R & D can expand the range of parameter values under which R & D occurs and this can be welfare-improving.

Once we allow for the upward-sloping supply of dirty energy, then the owners of easily extractable fossil fuels have rents. The assumption that climate policy will be statically optimal ex-post is then questionable since fossil fuel rentiers will lobby to protect their rents. This will give rise to uncertainty about whether a climate policy will be adopted at all in the future. In Section 4, we assume that there is some probability that no climate policy will be adopted. We show that if this probability is sufficiently high, then the range of parameter values under which a welfare-improving subsidy to R & D exists is expanded.

3.2 The model with a constant marginal cost of dirty energy

3.2.1 Structure of the economy

There is a representative consumer who consumes two goods, energy (e) and the numeraire good (y). The consumer maximizes a quasi-linear utility function

$$U(e) + y = ae - \tfrac{b}{2}e^2 + y \tag{3.2.1}$$

subject to

$$Pe + y = Y, \tag{3.2.2}$$

where P is the price of energy and Y is the endowment with the consumer. Solving this problem gives the consumer's inverse demand function for energy

$$P = D^{-1}(e) = \begin{cases} a - be & \text{if} \quad e < \frac{a}{b} \\ 0 & \text{if} \quad e > \frac{a}{b} \end{cases} \tag{3.2.3}$$

So b is the slope of the marginal social *benefit* of energy.

Energy in the economy can be produced in two ways. There is a competitive industry that produces dirty energy e_d, with a pollutant being emitted as a by-product. This has a constant average and marginal cost of production of zero.[4] Energy can also be produced without any pollution emissions. The quantity of this green energy is denoted by e_g. The marginal cost of producing green energy depends on the research and development investment made by a monopolist in the period before production occurs. If I is investment measured in units of the numeraire good, then the marginal cost of green energy that will be realized next period is $g = g(I)$ given by

[4] We discuss the case of a positive marginal cost in Section 4.

$$g(I) = \begin{cases} \overline{g} - (\frac{I}{i})^{\frac{1}{2}} & \text{if } 0 \leq I < i\overline{g}^2 \\ 0 & \text{if } I \geq i\overline{g}^2 \quad \text{where} \quad i > 0. \end{cases} \tag{3.2.4}$$

Therefore,

$$g'(I) < 0, \quad g''(I) > 0, \quad g(0) = \overline{g} > 0 \tag{3.2.5}$$

Equation (3.2.4) can also be written as:

$$I : [0, \overline{g}] \to \mathbb{R}^+ \quad \text{where} \quad I(g) = i(\overline{g} - g)^2$$

$\frac{1}{i}$ measures the impact of investment on the marginal cost of green energy. The lower the value of i, the more sensitive the marginal cost of green energy is to R & D investment.

Emissions produce an externality that is not internalized by the consumer. We choose units so that one unit of dirty energy produces one unit of emissions and we suppose that the damage from emissions is linear so that e_d units of dirty energy result in an external damage of δe_d. Thus δ is the (constant) marginal damage of dirty energy.

The sequence of events in the model is as follows: The government inherits from the past the choice of policy instrument: tax or quota. It is assumed that it cannot change this. The government chooses a subsidy rate for the firm's investment in research and development. Then the green firm chooses its investment in R & D. In the next period, as a result of the green firm's R & D, its marginal cost of production g is realized. The government observes g and then chooses the level of the quota or tax (as the case may be) with the objective of maximizing social welfare. We assume that in the first period the government cannot credibly commit to the level of the quota or to the tax rate it will impose in the second period. However, it *is* committed to the kind of instrument it has inherited, whether that is a tax or a quota. The government is free to choose a non-binding quota or a zero tax. After observing the tax rate or the level of the quota, the green firm chooses its price and output. [5]

[5]Even with commitment, a single policy instrument will not be able to achieve the first best. The number of instruments required to achieve a vector of policy targets cannot be less than the number of elements in

In reality, we believe that the choice of quota or tax is made by governments on the basis of their usefulness in the current period. Governments are not looking half a decade, or even several decades ahead at the effects on the technologies that become available. Once this choice is made, an institutional infrastructure is locked in around it, so it is not easily reversible. On the other hand, the effective level of the tax or quota can be altered by future legislatures or governments that react to the then prevailing conditions. This is the motivation for our assumptions above. Since we are interested in the effects of instruments on the incentive to innovate, we do not model production and emissions in the current period.

We assume that in the absence of a green firm, it is socially optimal to produce a positive level of dirty energy, and that the initial marginal cost of the green firm is below the marginal social value of energy at $e = 0$. That is,

Assumption 3.2.1 $a \geq max(\delta, \overline{g}) \geq 0$

Now if $g = 0$, then the green firm's monopoly price is $\frac{a}{2}$. For positive g the monopoly price will be $\frac{a+g}{2}$. (This is easily checked.)

The green firm's profit net of investment in R & D is denoted by

$$\Pi = \pi - I$$

where π denotes gross profit in the last stage of the game. Similarly, social welfare net of investment in R & D is denoted by

$$W = w - I$$

where w is the gross social welfare that the government maximizes in the second stage of the game:

the vector. Since we have two targets: the level of abatement, given a marginal cost of abatement and the marginal cost of abatement itself, a single instrument is unable to achieve it (Tinbergen, 1964).
In Kolstad (2010), optimality is achieved as he assumes that policy targets abatement rather the level of emissions, thus restricting the number of margins along which adjustment can take place.

$$w = ae - \frac{b}{2}e^2 + Y - ge_g + \delta e_d \tag{3.2.6}$$

3.2.2 The Tax Regime

PROPOSITION 1 *There will be no investment in research and development under the tax regime.*

Proof:

Suppose the firm chooses $g > \delta$ (which can happen only if $\overline{g} > \delta$) in the first stage. Then the social marginal cost of green energy is greater than that of dirty energy. Thus the optimal tax is δ, the difference between the social and private marginal costs of energy production. The green firm will not produce and so will incur a net loss with $\pi = -I(g) \leq 0$, where equality holds only when $g = \overline{g}$.

If $g \leq \delta$, then the optimal tax is infinitesimally greater than g. This is just sufficient to drive the dirty firms out of the market, but not enough to allow the green firm to exercise its monopoly power to restrict output. Now the green firm can only charge the tax, which is just infinitesimally greater than g. Thus the green firm incurs a loss of $-I(g) \leq 0$.

Therefore, the green firm must set $I = 0$ if it is to avoid a loss.

■

The optimal tax falls with g, wiping out the incentive to do R & D.

3.2.3 The Quota Regime

The model is a sequential game between the government and the green firm with three stages,

1. The green firm choosing investment.

2. The government choosing an emissions quota q.

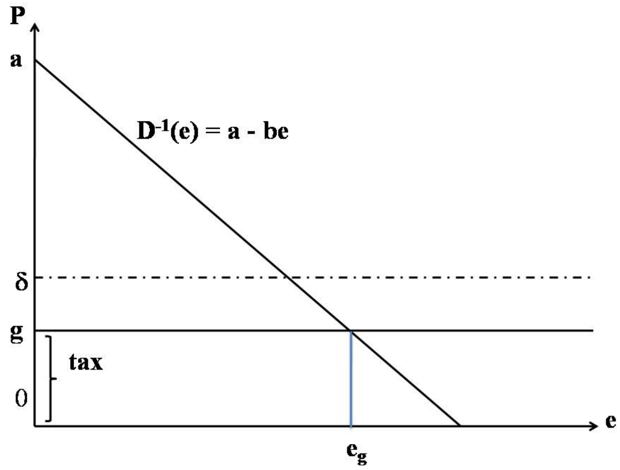

Figure 3.2.1: Tax Regime with $g < \delta$

3. The green firm choosing its price and output.

We use backward induction to solve it.

3.2.3.1 Response of firms given that investment has been made and a quota chosen by government.

Suppose $q \geq D(g)$ for some $g \geq 0$. Then the price of tradeable emissions permits will be $D^{-1}(q)$ and the dirty sector can supply energy at a price less than the green firm's cost. Thus the green energy firm will not produce. The price of energy will be $D^{-1}(q)$ and energy produced will be equal to the level of quota.

Now suppose $q < D(g)$ for $g \geq 0$. The green firm faces a residual demand curve of $D(P) - q$ for P in the relevant range $D^{-1}(q) \geq P \geq 0$. It acts as a monopolist in this market and chooses e_g to maximize

The profit function of the R&D firm is :

$$\begin{aligned} \pi &= e_g[D^{-1}(e_g + q) - g] \\ &= e_g[a - b(q + e_g) - g]. \end{aligned}$$

π is concave in e_g and there is no corner solution. The monopoly price is the average of

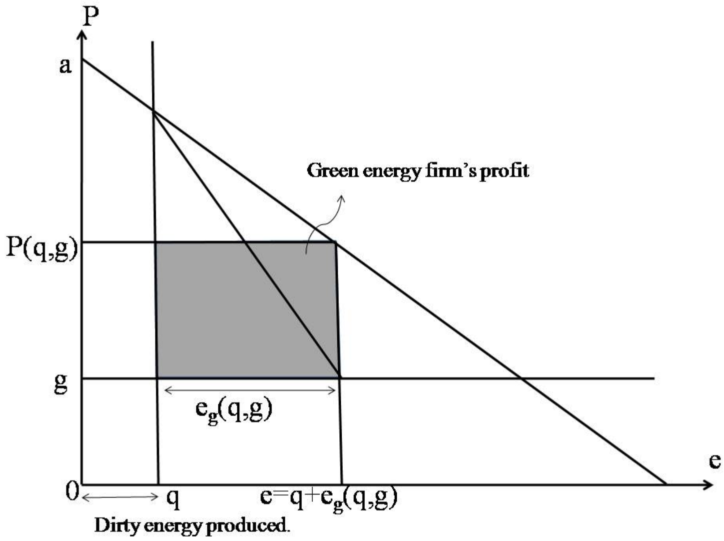

Figure 3.2.2: Quota Regime: $q < D(g)$

marginal cost and the highest point of the residual demand curve $D^{-1}(q)$. Thus the output of clean energy and total energy, the price of energy and the profit of the green firm are respectively:

$$\begin{aligned} e_g(g,q) &= \frac{1}{2}[D(g) - q] \\ &= \frac{a - bq - g}{2b} \end{aligned} \tag{3.2.7}$$

$$\begin{aligned} e(g,q) &= \frac{1}{2}[D(g) + q] \\ &= \frac{a + bq - g}{2b} \end{aligned} \tag{3.2.8}$$

$$\begin{aligned} P(g,q) &= \frac{1}{2}(D^{-1}(q) + g) \\ &= \frac{a - bq + g}{2} \end{aligned} \tag{3.2.9}$$

$$\begin{aligned}\pi(g,q) &= \frac{1}{4}[D(g)-q][D^{-1}(q)-g] \\ &= \frac{(a-bq-g)^2}{4b}\end{aligned} \quad (3.2.10)$$

3.2.3.2 Optimal selection of q by the government, after observing the green firm's choice of g and taking the green firm's reaction function as a constraint in its welfare-maximizing exercise.

In this section we make the assumption that $\delta < \overline{g}$. If $\overline{g} < \delta$, there would be no emissions problem, only a problem of making emission control less expensive.

Assumption 3.2.2 $\delta < \overline{g}$

If $g > \delta$, the social marginal cost of green energy is greater than that of dirty energy, and it would be inefficient to allow the green firm to operate. So the optimal $q \geq D(g)$. Optimality is attained at $q = D(\delta)$ where the marginal social cost of dirty energy equals the marginal social benefit from energy consumption.

Now consider the case $g < \delta$. Now the marginal social cost of green energy is lower than that of dirty energy. While a stricter quota brings a welfare gain from reduced emissions, it inflicts a welfare loss from lower consumption of energy. The government chooses the quota taking this trade off into account.

Starting with $q = D(\delta)$, note that the marginal social benefit of tightening the quota is

$$\begin{aligned}&\delta - g - \frac{\partial e}{\partial q}(P(q,g)-g) \\ &= \delta - g - \frac{1}{2}[\frac{1}{2}(D^{-1}(q)-g)].\end{aligned}$$

$\delta - g$ (= IJ in Figure 3.2.3) is the marginal reduction in the social cost of energy as dirty energy is replaced by clean energy while $\frac{1}{2}(D^{-1}(q)-g)$ (= KL in Figure 3.2.3) is the marginal loss of social surplus when energy consumption falls in response to the decrease in q. When

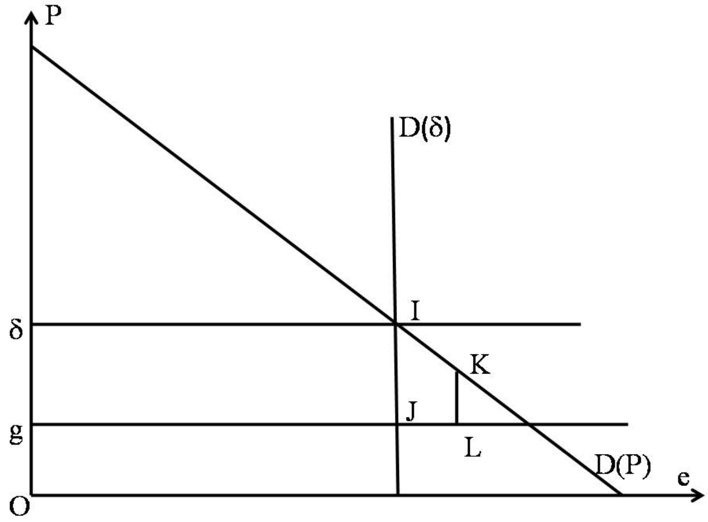

Figure 3.2.3: Quota Regime: Sub-optimality of $q = D(\delta)$ when $g^0 < g < \delta$

$q = D(\delta)$, the expression above equals $\frac{3}{4}(\delta - g) > 0$. Thus the optimal $q < D(\delta)$.

In fact, note that for any q, if $e(q, g) > D(\delta)$, then $P(q, g) < \delta$, so

$$\delta - g > \frac{1}{2}(P(q, g) - g). \tag{3.2.11}$$

Thus, *total* energy consumption must fall when g falls below δ. As will be seen shortly, this fact has important implications for the welfare effects of an R & D subsidy.

Differentiating w with respect to q in 3.2.6 and using 3.2.7 and 3.2.8, we find that at the optimal quota,

$$\delta - g = \frac{1}{4}(D^{-1}(q) - g). \tag{3.2.12}$$

It is clear from this that if g falls, then q must also fall to restore equality. Thus, in contrast to the tax regime, a fall in g induces a tightening of the emissions quota, thus reinforcing the incentive for the green firm to conduct R & D. Solving equation 3.2.12 for q, we find that the optimal quota is given by

$$q(g) = \begin{cases} D(\delta), & \text{if} \quad g \geq \delta \\ \max \frac{a+3g-4\delta}{b}, 0 & \text{if} \quad g < \delta \end{cases} \tag{3.2.13}$$

From now on, we ignore corner solutions in q for the sake of simplicity. In other words, we assume that the externality from emissions is not high enough to justify setting a zero quota. It follows from 3.2.13 that the required assumption is

ASSUMPTION 3.2.3 *$a > 4\delta$.*

3.2.3.3 Optimal choice of investment (and marginal cost) by the green firm given the reaction function of the government.

The green firm's net profit function is

$$\begin{aligned} \Pi(g) &= \pi(g, q(g)) - I(g) \\ &= \frac{4}{b}(\delta - g)^2 - i(g - \overline{g})^2 \qquad \text{(using (3.2.10) and (3.2.13))}, \\ &< 0 \qquad \text{at } g = \delta. \end{aligned}$$

Now

$$\begin{aligned} \Pi'(g) &= -\frac{8}{b}(\delta - g) - 2i(g - \overline{g}) \\ &> 0 \qquad \text{at } g = \delta. \end{aligned}$$

Unless the positive slope of Π at $g = \delta$ is reversed at a lower value of g, investment in R & D is ruled out. Now

$$\Pi''(g) = \frac{8}{b} - 2i.$$

It follows immediately that R & D can take place only if Π is convex and, therefore, if and only if $\Pi > 0$ at $g = 0$. This argument is summarized in

PROPOSITION 2 *The quota regime induces R & D with $g = 0$ provided the marginal cost of green energy is sufficiently sensitive to R & D investment, that is, if (and only if) $i < \frac{4\delta^2}{b\overline{g}^2}$.*

This is illustrated in the figure below.

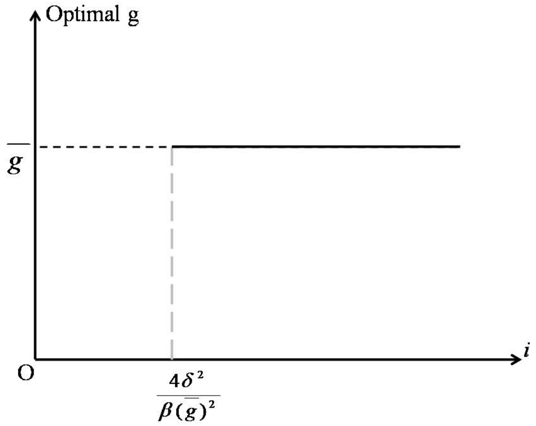

Figure 3.2.4: Optimal Choice of g in the quota regime.

3.2.4 Welfare Analysis

We now compare social welfare under the tax and quota regimes. Under the tax regime, since no R & D is induced and the green firm does not operate, welfare is simply the utility of energy consumption less the total social damage from dirty energy consumption. (We can ignore the term Y in 3.2.6 since it is constant.) This is consumer surplus given by the area of $\triangle a\delta G$ in Figure 3.2.5.

For values of i greater than $\frac{4\delta^2}{b\overline{g}^2}$, there is no investment in the quota regime either, the quota is set to internalize the externality, and energy consumption and welfare are identical to what would prevail under the tax regime.

If $i < \frac{4\delta^2}{b\overline{g}^2}$, R & D is induced and the marginal cost of green energy falls to 0. Social welfare w (without deducting investment in R & D) is now[6]

the area of quadrilateral $aBE\delta) +$ the area of quadrilateral $BDIH$.

Thus, *gross* welfare under the quota regime exceeds welfare under the tax regime by

[6]In drawing the figure in this way, we are making use of the remark made in Section 2.3.2 that total energy consumption is less than $D(\delta)$.

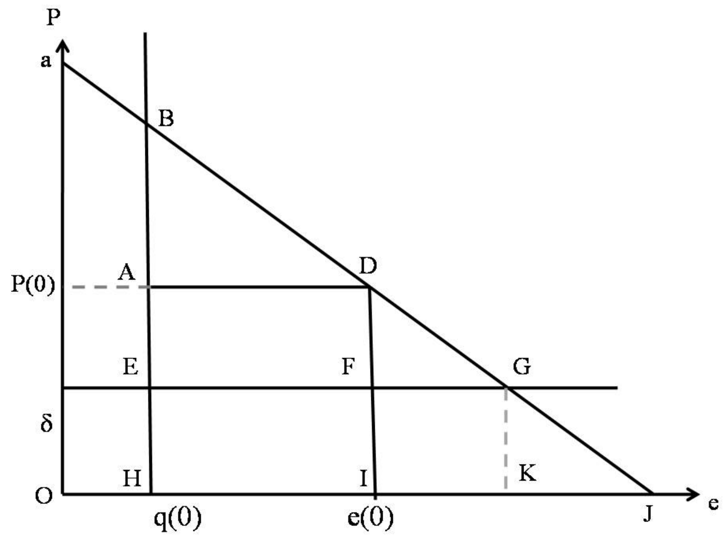

Figure 3.2.5: Welfare Analysis of Tax and Quota Regimes

$$\triangle w = \text{the area of the rectangle } EFIH - \text{the area of } \triangle DFG. \qquad (3.2.14)$$

Using 3.2.7 and 3.2.13,

$$\text{the area of rectangle } EFIH = \frac{2\delta^2}{b}. \qquad (3.2.15)$$

Using 3.2.8, 3.2.9, and 3.2.13,

$$\text{the area of } \triangle DFG = \frac{\delta^2}{2b}. \qquad (3.2.16)$$

Therefore,

$$\triangle w = \frac{3\delta^2}{2b}. \qquad (3.2.17)$$

Hence, a quota regime will offer higher *net* welfare than a tax regime if $\triangle w > i\overline{g}^2$ that is, if $i < \frac{3}{2}\frac{\delta^2}{b\overline{g}^2}$. (If this condition holds, then the hypothesis of Proposition 2 will be satisfied and R & D investment will occur.) This argument is summarized as

Proposition 3 *A quota regime that induces R & D results in higher welfare than a tax regime* *(that never induces R & D) provided the marginal cost of green energy is sufficiently sensitive to R & D investment, that is, if $i < \frac{3}{2}\frac{\delta^2}{b\overline{g}^2}$. If $\frac{3}{2}\frac{\delta^2}{b\overline{g}^2} < i < \frac{4\delta^2}{b\overline{g}^2}$, then the R & D induced by the quota regime is socially too expensive.*

3.2.5 The Role of an R & D Subsidy

Proposition 4 *In a tax regime, an R & D subsidy is ineffective (has no impact on R & D). Under a quota regime, an R & D subsidy is either ineffective, or, if effective, reduces welfare.*

Proof: When the subsidy is s, the amount the green firm has to spend on R & D in order to achieve a marginal cost g becomes $(1-s)i(g-\overline{g})^2$. Thus, a subsidy reduces the effective i for the green firm. It can have no effect in a tax regime (as long as $s < 1$ which we assume), since any expenditure at all is sufficient to deter the firm from conducting R & D. In a quota regime, it is clear from Proposition 2 that it can have an effect only if it moves the effective i for the firm below the threshold $\frac{3}{2}\frac{\delta^2}{b\overline{g}^2}$. At this threshold value of i, the firm is indifferent between conducting R & D and not doing so. That is $\Pi(0) = \Pi(\overline{g}) = 0$. Therefore, its gross profit if it conducts R & D, $\pi(0)$ must equal $i\overline{g}^2$, the social cost of R & D at the threshold level of i.

Now welfare will be raised by inducing the firm to conduct R & D if and only if $w(0) - w(\overline{g}) > i\overline{g}^2$, that is, if and only if

$$w(0) - w(\overline{g}) > \pi(0).$$

$\pi(0)$ is equal to the area of the rectangle $ADIH$ in Figure 3.2.5. But this is greater than $w(0) - w(\overline{g})$ by 3.2.14. Thus in a quota regime, if a subsidy is effective, it must reduce welfare. ■

3.3 The model with increasing marginal cost of dirty energy

Since fossil fuels have heterogeneous extraction costs that depend on the location and quality of deposits, they can be expected to have an increasing marginal cost of extraction. Accordingly we now assume the supply curve of dirty energy has a positive slope. We show that it is possible for the tax regime to induce R & D, and that a welfare improving R & D subsidy is possible under both tax and quota regimes.

3.3.1 Structure of the model

We assume that

$$\text{the marginal cost of producing } e_d = ce_d \tag{3.3.1}$$

The supply curve of dirty energy implied by equation (3.3.1) can also be written as:

$$S_d(P) = \frac{P}{c} \tag{3.3.2}$$

Thus, c denotes the slope of the dirty technology's marginal *c*ost. Recall that the marginal benefit of energy is $a - be$ while the marginal cost of dirty energy when there is an emissions tax of t is $t + ce_d$.

Let

$$P_d^*(t) = \frac{ac + bt}{b + c} \tag{3.3.3}$$

denote the equilibrium price of dirty energy when there is no green energy produced and there is an emissions tax of t.

We assume that the initial marginal cost of the green technology $\overline{g}$ is too high for it to be socially optimal to have any production of green energy. (Later we show that the alternative assumption leads to qualitatively similar results).

Assumption 3.3.1

$$P_d^*(t = \delta) < \overline{g}$$

The equilibrium quantity of dirty energy when there is no green sector and there is an emissions tax of t is

$$e_d^*(t) \equiv S_d(P_d^*(t) - t) = \frac{a - t}{b + c}. \tag{3.3.4}$$

The model under these assumptions is summarized in Figure 3.3.1.

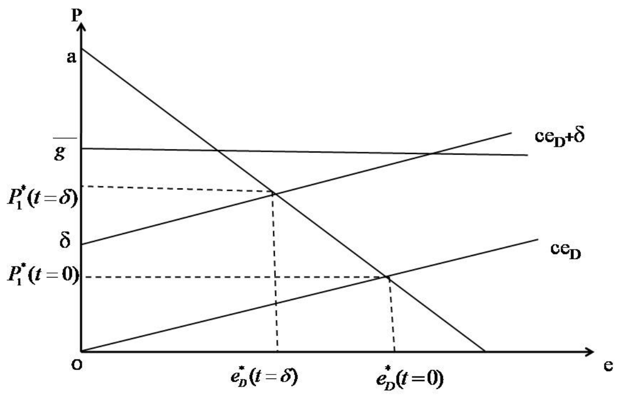

Figure 3.3.1: Diagrammatic representation of Assumptions 1 to 4

3.3.2 Quota Regime

As before, we solve the game by backward induction.

3.3.2.1 Response of firms given that R & D investment has been made and a quota chosen by government

If $g > P_d^*(t = \delta)$, it is clear that the optimal quota is $e_d^*(t = \delta)$ and the green firm is shut out of the market.

Now consider the case $P_d^*(t = 0) \leq g \leq P_d^*(t = \delta)$. As in Section 3.2, the green firm chooses its output to maximize its profit given the residual demand curve for energy after

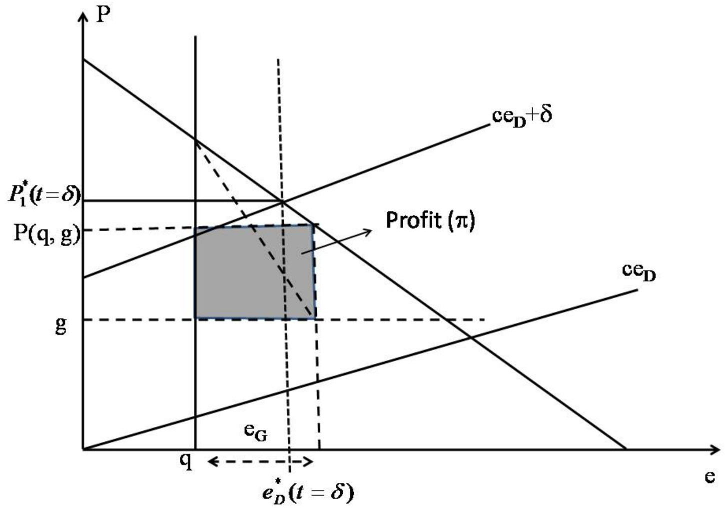

Figure 3.3.2: Choice of green energy output when $P_d^*(t=0) \leq g \leq P_d^*(t=\delta)$

the dirty sector has produced q.[7] Thus, the green firm's optimization problem is identical to that in Section 3.2. So optimal green energy production, total energy production, the price of energy, and the gross profit of the green firm are given by (3.2.7), (3.2.8), (3.2.9) and (3.2.10) respectively. (Refer to figure 3.3.2).

Next, consider the case $g < P_d^*(t=0)$. It is straightforward to show that in the absence of government intervention, profit maximization by the green firm would lead to an energy price $P = \frac{1}{2}[P_d^*(t=0)+g]$ and dirty energy production $e_d = \frac{1}{2c}[P_d^*(t=0)+g]$. To avoid a proliferation of cases, we assume below that the marginal damage δ from dirty energy is high enough that the government never finds it optimal to set a non-binding quota $q > e_d = \frac{1}{2c}[P_d^*(t=0)+g]$. Hence, in this case also, optimal green energy production, total energy production, the price of energy, and the gross profit of the green firm are given by (3.2.7), (3.2.8), (3.2.9) and (3.2.10) respectively.

[7] It is clear that the quota must be binding on the dirty sector, since $g \geq P_d^*(t=0)$ and it cannot be optimal for the government to set $q \geq D(g)$.

3.3.2.2 The government's choice of quota, after observing the green firm's choice of g and taking the green firm's reaction function as given.

We have already noted that when $g > P_d^*(t = \delta)$, then the optimal quota is $e_d^*(t = \delta)$. When $0 \leq g \leq P_d^*(t = \delta)$, the gross welfare function is

$$w(q, g) = a(\frac{a + bq - g}{2b}) - \frac{b}{2}(\frac{a + bq - g}{2b})^2 - \delta q - \frac{\delta q^2}{2} - g(\frac{a - bq - g}{2b}) \tag{3.3.5}$$

The marginal social benefit from tightening the quota is, as in Section 3.2, the reduction in social cost when dirty energy is replaced by green energy, while the marginal welfare loss arises from the reduction in net welfare from energy consumption. So the optimal quota satisfies

$$cq + \delta - g = \frac{1}{2}[\frac{a - bq - g}{2}] \tag{3.3.6}$$

provided it is not optimal to set a zero quota, which we assume. The required assumption, as in Section 3.2, is

Assumption 3.3.2 $a - 4\delta > 0$

For $g < P_d^*(t = 0)$, we make the following assumption which ensures that it is optimal for the government to set a quota that is binding for the dirty sector[8]:

Assumption 3.3.3 $\frac{b-2c}{2(b+c)}a - 4\delta < 0$

Given assumption 3.3.2 and 3.3.3, it follows from 3.3.6 that the government's reaction function is:

$$q(g) = \begin{cases} e_d^*(t = \delta) & \text{if} \quad g > P_d^*(t = \delta) \\ \frac{a+3g-4\delta}{b+4c} & \text{if} \quad g \leq P_d^*(t = \delta) \end{cases} \tag{3.3.7}$$

As in Section 3.2 the optimal quota falls when g falls.

There is an important respect in which this model differs from the model with a constant marginal cost of dirty energy. In the flat supply curve case, it was seen that for every $g < \delta$,

[8] This is proved in the Appendix 3.A.

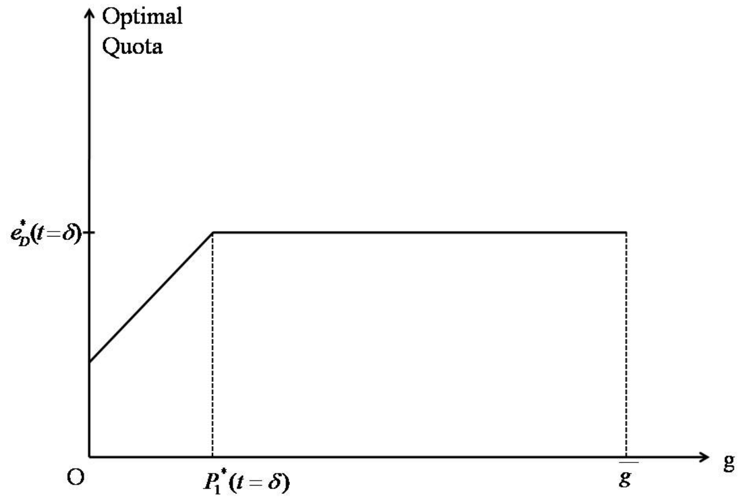

Figure 3.3.3: Government's reaction Function

the optimal choice of q was such that $e(g,q) < D(\delta)$. To be precise, $e(g,q(g)$ was a increasing function of g that is, $\frac{de}{dg} > 0$. However, with increasing marginal cost,

$$\begin{aligned}\frac{de}{dg} &= \frac{\partial e}{\partial g} + \frac{\partial e}{\partial q}.\frac{dq}{dg} \\ &= -\frac{1}{2b} + \frac{1}{2}\frac{3}{(b+4c)} \\ &= \frac{(b-2c)}{b(b+4c)}\end{aligned}$$

Thus, if $c > \frac{b}{2}$, then energy consumption rises as g falls. This has implications for welfare analysis and the role of an R & D subsidy.

3.3.2.3 Optimal choice of investment (and marginal cost) by green firm subject to the reaction function of government and it's own reaction function in period 2

As before, the firm never chooses $g \in [P_d^*(t=\delta), \overline{g})$. This is because while such cost reduction from $\overline{g}$ is costly, it does not allow the firm to operate in the market in the second period. In the range$[0, P_d^*(t=\delta))$, the net profit function is (obtained by substituting the government's

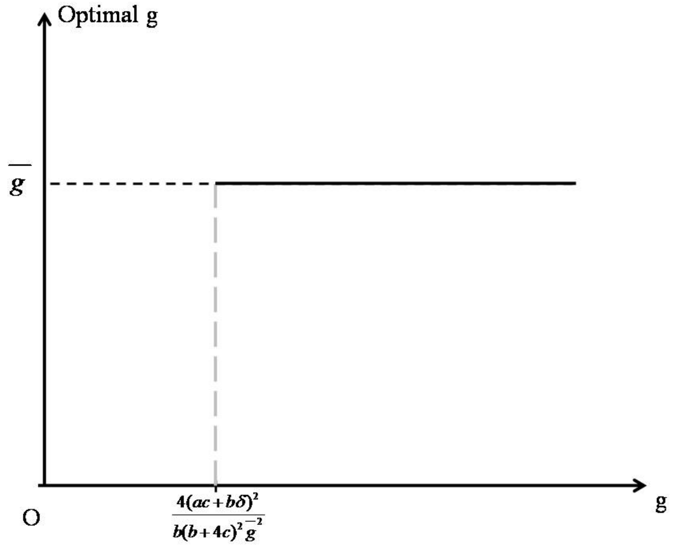

Figure 3.3.4: Optimal Choice of Marginal Cost

reaction function into the profit function (3.2.10) and subtracting the investment cost):

$$\begin{aligned}\Pi(g) &= \frac{4}{b(b+4c)^2}[ac+b\delta-(b+c)g]^2 - i(\overline{g}-g)^2 \\ &= \frac{4(b+c)^2}{b(b+4c)^2}[P_d^*(t=\delta)-g]^2 - i(\overline{g}-g)^2 \qquad (3.3.8)\end{aligned}$$

As before, the green firm's maximization problem has a corner solution (proof in the Appendix 3.B):

$$g = \begin{cases} 0, & \text{if} \quad i \leq \frac{4(ac+b\delta)^2}{b(b+4c)^2\overline{g}^2} \\ \overline{g}, & \text{if} \quad i \geq \frac{4(ac+b\delta)^2}{b(b+4c)^2\overline{g}^2}. \end{cases} \qquad (3.3.9)$$

This is depicted in Figure 3.3.4.

3.3.2.4 The Role of an R & D Subsidy

We remarked above that total energy output will be greater when there is a green firm than in its absence if and only if the marginal cost of dirty energy is sufficiently steep relative to the marginal benefit of energy, that is, $c > \frac{b}{2}$. If this is not the case, then for i below the threshold, $g = 0$ and the quota, energy output, and the energy price will be as depicted in

Figure 3.3.5.

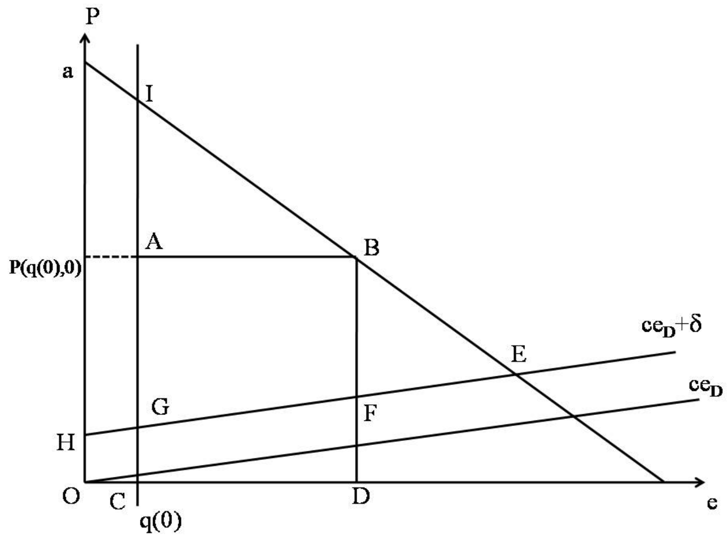

Figure 3.3.5: Case A: Role of Subsidy

By an argument similar to the one made in 3.2.5 with reference to Figure 3.2.5, we can conclude that an R & D subsidy would be welfare-reducing if it had any effect.

On the other hand, if $c > \frac{b}{2}$, then for i below the threshold, the situation would be as depicted in Figure 3.3.6.

$\pi(0)$ is given by the area of the rectangle AFED. Gross welfare when there is R & D and $g = 0$ is

$$w(0) = aKBJ + KFED.$$

If there is no R & D, then

$$w(\overline{g}) = \triangle aIJ.$$

So the increase in welfare from conducting R & D minus the increase in profits from conducting R & D is

$$\{w(0) - w(\overline{g})\} - \pi(0) = \triangle IFL - \triangle ALB.$$

Now $\triangle LIF > \triangle ALB$ if and only if $c > \frac{5}{4}b$ (proof in the Appendix 3.C). At the threshold value of i, the increase in profit from R & D is zero. Thus, if $c < \frac{5}{4}b$, there can be no welfare

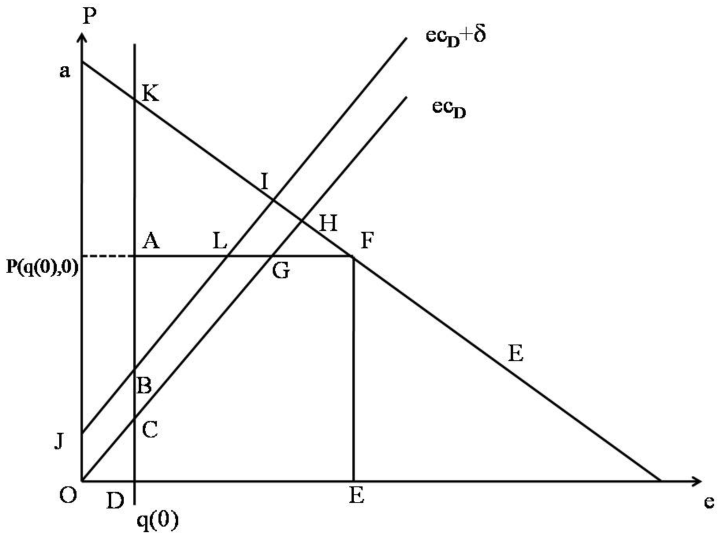

Figure 3.3.6: Case B: Role of Subsidy

improving subsidy. This argument has been summarized in proposition 5

PROPOSITION 5 *If* $c < \frac{5}{4}b$, *then there can be no welfare-improving subsidy to R & D in the quota regime. If* $c > \frac{5}{4}b$, *then an R & D subsidy can improve investment and welfare if the marginal cost of green energy is sufficiently sensitive to R & D, that is for* $i \in [\frac{4(ac+b\delta)^2}{b(b+4c)^2\overline{g}^2}, \frac{3(ac+b\delta)^2}{2b(b+c)(b+4c)\overline{g}^2}]$.

3.3.2.5 Relaxing assumption 3.3.1

Suppose we relax assumption 3.3.1. We allow the initial marginal cost of green technology to be too high for it to be introduced in the absence of government policy intervention, but low enough for it to be socially optimal to have some green production of energy. The results of this changed situation can be summarized in:

PROPOSITION 6 *Let* $P_d^*(t = 0) \leq g \leq P_d^*(t = \delta)$. *Then with all other assumptions of section 3.3 remaining unchanged, the quota regime induces the maximum possible R & D with* $g = 0$ *provided that the marginal cost of green energy is sufficiently sensitive to R & D investment, that is, if (and only if)* $i \leq \frac{4(b+c)(ac+b\delta)}{b(b+4c)^2\overline{g}}$. *For values of* i *greater than* $\frac{4(b+c)(ac+b\delta)}{b(b+4c)^2\overline{g}}$, *the optimal choice of* g *by the green firm increases smoothly (at a decreasing rate) with* i. *The optimal* *choice of* g *is strictly less than* $\overline{g}$ *for all finite values of* g.

If $c < \frac{5}{4}b$, *then there can be no welfare-improving subsidy to R & D in the quota regime. If* $c > \frac{5}{4}b$, *then an R & D subsidy can improve investment and welfare if* $i \geq \frac{4(b+c)(ac+b\delta)}{b(b+4c)^2\overline{g}}$.

Proof: In Appendix 3.D. ■

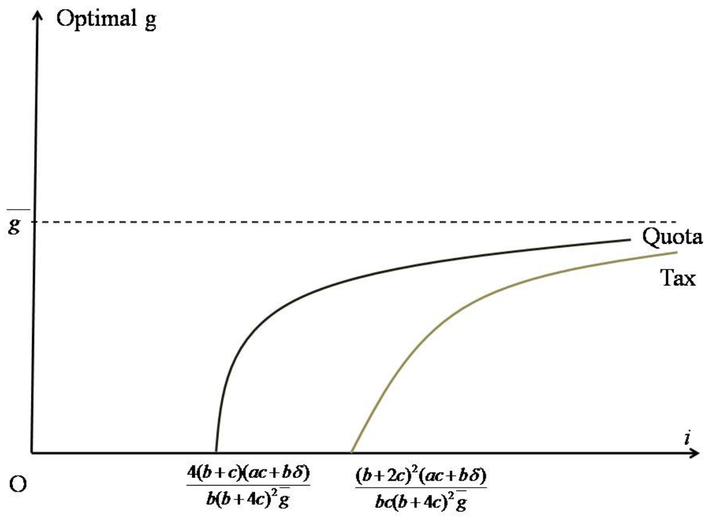

Figure 3.3.7: Optimal Choice of g when $P_d^*(t=0) \leq g \leq P_d^*(t=\delta)$

3.3.3 Tax Regime

As before, we solve the game by backward induction:

3.3.3.1 Response of firms given that investment has been made and a tax chosen by government.

In the last stage, the firm chooses its price P to maximize its profit function

$$\pi(g,t) = \begin{cases} \pi^{+} = (P-g)D(P), & \text{if} \quad P \in [g,t) \\ \pi^{++} = (P-g)\left[D(P) - S_1(P-t)\right], & \text{if} \quad P \in [t, P_d^*(t)] \end{cases}$$

Suppose $g > P_d^*(t = \delta)$ so that the marginal cost of the green firm is greater than the marginal social cost of dirty energy at $e_d^*(t = \delta)$. It is clear that the optimal tax level is δ and the green firm is shut out of the market. The price of energy will be $P_d^*(t = \delta)$.

Now consider the case $g \in (P_d^*(t = 0), P_d^*(t = \delta)]$. In this case, the price reaction function is as follows:

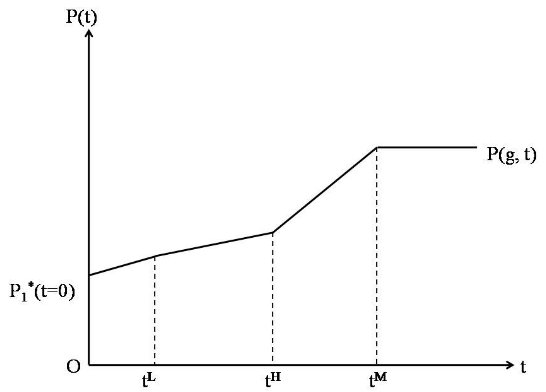

Figure 3.3.8: Price as a function of tax, for a particular marginal cost above $P_d^*(t)$

The government never chooses a tax lower than $t^L = \frac{(b+c)g-ac}{b}$, the highest tax level at which the green firm does not find it optimal to operate in the energy market. At the tax level t^L, the green firm's marginal cost is just equal to the post-tax price attained in its absence i.e. $P_d^*(t = t^L)$. Total energy produced is $e_d^*(t = t^L)$. For tax levels less than t^L, energy consumption (the whole of which is dirty energy) rises. However $e_d^*(t = t^L) > e_d^*(t = \delta)$ where $e_d^*(t = \delta)$ is the level of dirty energy produced at which the marginal social cost equals marginal social benefit. Thus increased production of dirty energy starting from a level greater than $e_d^*(t = \delta)$, ensures that the addition social costs of increased production outweigh the addition gains from increased production. Thus tax levels less than t^L are never optimal.

Suppose the government chooses a tax higher than t^L but lower than t^H where t^H refers to the lowest possible tax level at which the green firm's profit maximizing level of price is such that the dirty firms are driven out of the market. This is denoted by $t^{\#}$ in Figure 3.3.9. Now the green firm has a role to play as the post-tax price attained in absence of the green

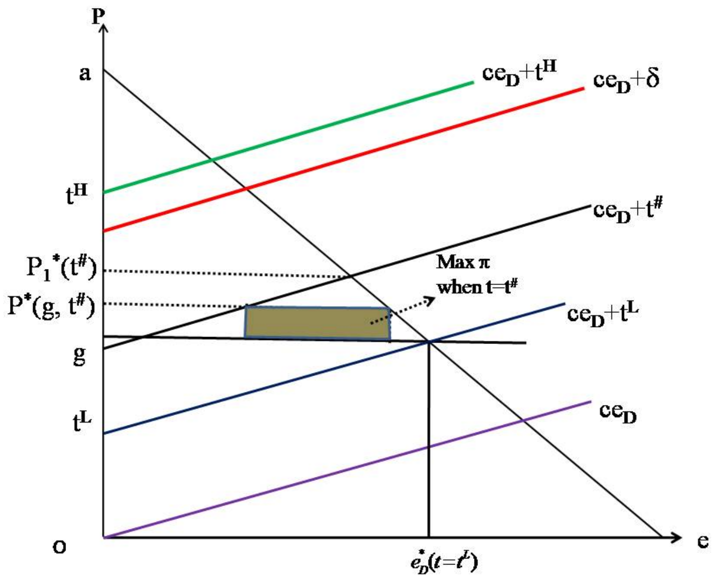

Figure 3.3.9: Diagram explaining the choice of prices under a tax regime

firm is higher than g. To drive out the dirty sector completely, the green firm has to set the price marginally less than t. Since the tax is not very high, by choosing a price marginally less than t, the green firm enjoys the entire market (which is quite high given the low price) but the per unit margin is negative or positive but not very high. Thus the overall gain from driving out the dirty firms is either negative or positive but low. The firm does better by choosing a higher price optimally that reduces the demand it serves (and market share) but increases the per-unit gains. This optimal price is P^*, which is the equally weighted average of g and $P_d^*(t)$. Profit is shown by the rectangle shaded in grey in Figure 3.3.9. As the tax moves higher towards t^H, the price set by the firm rises and the demand served by the dirty sector falls. This continues till t^H, the tax level at which the optimal price P^* reaches a level at which the dirty industry is driven out of the market.

Suppose a tax greater than t^H but less than t^M is set, where t^M is the lowest possible tax level at which the green firm can choose it's monopoly price. In this situation the green firm chooses $P = t$. By doing so it reduces demand but enhances the profit margin, but profit still increases as price is still below monopoly price. Once the tax level reaches t^M- a level that is high enough to ensure that even the choice of monopoly price can drive the dirty firms out, further increase in tax has no impact on price. The price stays unchanged at $P^M(g)$ as the firm can never earn more than what it does under monopoly.

However it should be noted that the government never raises the tax above t^H. Once the tax reaches t^H, the dirty sector is driven out. If the tax is increased further, the resultant rise in price reduces energy consumption but no gain is achieved from reduction in emissions as production of dirty energy has already reached zero. Thus if $g \in [P_d^*(t=0), P_d^*(t=\delta))$, the relevant range from which the government chooses the tax is $[t^L, t^H]$.

Now suppose $g < P_d^*(t=0)$. Then $t^L < 0$. We assume that zero is the minimum tax that can be set [9]. Taxes higher than t^H are ruled out for reasons discussed earlier. The relevant range from which the government chooses a tax is $[0, t^H]$ for this case.

Summarizing the results obtained in this section, we can say that for any $g \geq P_d^*(t=\delta)$, $P(g, t(g)) = P_d^*(t=\delta)$ and energy consumption is as follows: $e_d = e_d^*(t=\delta)$ and $e_g = 0$.

For $g \in [0, P_d^*(t=\delta))$,

$$P(g, t(g)) = \frac{1}{2}[g + P_d^*(t) \tag{3.3.10}$$

$$e(g, t(g)) = \frac{1}{2}[e_d^*(t) + D(g)] \tag{3.3.11}$$

$$e_d(g, t(g)) = \frac{1}{2}[e_d^*(t) + S_1(g-t)] \tag{3.3.12}$$

$$e_g(g, t(g)) = \frac{1}{2}[D(g) - S_1(g-t)] \tag{3.3.13}$$

[9]Unlike the situation where $g > P_d^*(t=0)$, a subsidy to the dirty sector might be welfare improving as that reduces the loss arising out of the monopoly power of the green firm. However, we assume that once the government decides on as tax as its instrument, it sticks to that in future and a non-negative tax is then the only option available to the government.

$$\pi(g, t(g)) = \frac{b+c}{4bc}[P_d^*(t) - g]^2 \tag{3.3.14}$$

where $S_1(P)$ denotes the supply curve of the dirty sector in absence of tax.

3.3.3.2 Optimal selection of t by government, which observes green firm's choice of g and takes the green firm's reaction function as given.

It has already been argued that when $g > P_d^*(t = \delta)$, the optimal tax is equal to δ. When $g \leq P_d^*(t = \delta)$, the government chooses a tax from the interval $(\min\{0, t^L\}, t^H]$ so as to maximize welfare.

The corner solution at t^L is ruled out as an infinitesimally higher tax ensures first-order benefits from reduced emissions but the welfare loss from the fall in energy consumption is second-order. The corner solution at t^H is attained only when $g \leq g^H$ where

$$g^H = \frac{\delta(b+2c)^2 - ac^2}{(b+c)(b+3c)}$$

g^H is the maximum cost level at which the optimal tax is such that green firm's optimal choice of price can drive out the dirty sector [10]. If $g > g^H$, we have an interior solution at a level of tax that satisfies:

$$(a - be)\frac{\partial e}{\partial t} = (\delta + ce_d)\frac{\partial e_d}{\partial t} + g\frac{\partial e_g}{\partial t} \tag{3.3.15}$$

where

$$\frac{\partial e_d}{\partial t} = -(\frac{1}{2(b+c)} + \frac{1}{2c})$$

$$\frac{\partial e_g}{\partial t} = \frac{1}{2c}$$

$$\frac{\partial e_d}{\partial t} + \frac{\partial e_g}{\partial t} = \frac{\partial e}{\partial t}$$

where the marginal social benefit from higher tax (reduction in social cost when dirty energy is replaced by green energy) is equal to the marginal welfare loss (reduction in net

[10] Note that $g^H < \delta$.

welfare due to reduced energy consumption) [11].

The intuition behind this non- monotonic shape of the tax curve (t as a function of g) is the following: $g > g^H$ implies that the difference between the MSC of dirty and green energy is not very large.Thus it is not optimal for the government to choose a high tax like $t^H(g)$ that will allow the green firm to drive out the dirty sector. Instead a lower tax is chosen, which allows both the sectors to survive. When g falls substantially i.e. $g < g^H$, the difference in the MSC of two firms becomes large to allow the choice of $t^H(g)$. [12]

Now for $g < g^H$, a reduction in marginal cost leads to a reduction in optimal tax. Thus the optimal choice of policy has a dampening effect on the profitability of the green energy firm. The situation is similar to the earlier model where the supply curve of dirty sector was flat. Since the objective of this model is to explore situations different from the earlier model, we rule out $g < g^H$ by making the following assumption [13]:

Assumption 3.3.4 $g^H \leq 0$ *that is* $\delta(b+2c)^2 < ac^2$

Given assumption 3.3.4, we can solve equation 3.3.15 to get the government's reaction function:

$$t(g) = \begin{cases} \frac{ac-(b+c)g+2\delta(b+2c)}{b+4c}, & \text{if} \quad g \in [0, P_d^*(t=\delta)] \\ \delta, & \text{if} \quad g > P_d^*(t=\delta) \end{cases} \tag{3.3.16}$$

3.3.3.3 Optimal choice of investment (and marginal cost) by the green firm subject to the reaction function of the government and it's own reaction function in period 2.

As before, the firm never chooses $g \in [P_d^*(t=\delta), \overline{g})$ as such investments do not allow firms to operate in the market in the second period. In the range $[0, P_d^*(g))$, the net profit function is (obtained by sequentially substituting the firm's second period reaction function and the

[11] Proved in Appendix 3.E.

[12] Technical details are discussed in Appendix 3.E.

[13] This assumption ensures that the slope of the supply curve is strictly positive. Thus we get results that are qualitatively different from Section 3.2.2. Unlike in Section 3.2.2, the tax ensures R & D for low values of i.

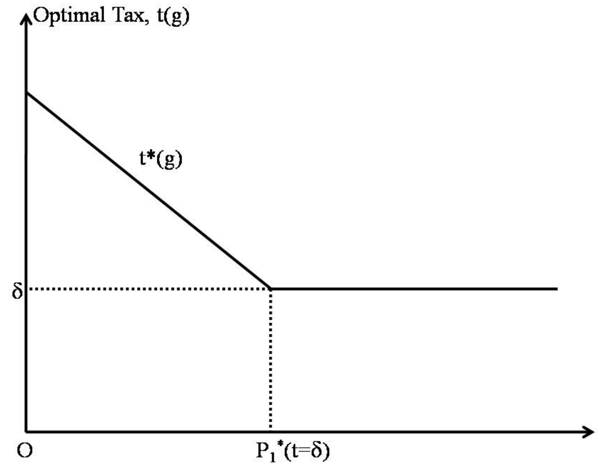

Figure 3.3.10: Government's reaction function: Tax as function of green firm's marginal cost

government's reaction function into the profit function 3.3.14 and subtracting investment cost):

$$\begin{aligned} \Pi(g) &= \frac{b+c}{4bc}[\frac{ac+bt}{b+c} - g]^2 - i(\overline{g}-g)^2 \\ \text{where,} \quad t &= \frac{ac-(b+c)g+2\delta(b+2c)}{b+4c} \end{aligned} \tag{3.3.17}$$

Unlike section 3.2.2, the green firm's maximization problem can have solutions at either of the two corners: 0 or $\overline{g}$

$$g = \begin{cases} 0, & \text{if} \quad i \leq \frac{(b+2c)^2(ac+b\delta)^2}{bc\overline{g}^2(b+c)(b+4c)^2} \\ \overline{g}, & \text{if} \quad i \geq \frac{(b+2c)^2(ac+b\delta)^2}{bc\overline{g}^2(b+c)(b+4c)^2} \end{cases} \tag{3.3.18}$$

Comparison between the optimal cost curves under the two regimes leads to the following propositions:

PROPOSITION 7 *For $i \in (\frac{4(ac+b\delta)^2}{b(b+4c)^2\overline{g}^2}, \frac{(b+2c)^2(ac+b\delta)^2}{bc\overline{g}^2(b+c)(b+4c)^2})$, a tax regime induces R & D while a quota regime does not. For all other values of i, the two instruments are equivalent.*

This is depicted in Figure 3.3.11. Proof of the above proposition (Proposition 7) discussed in Appendix 3.F.

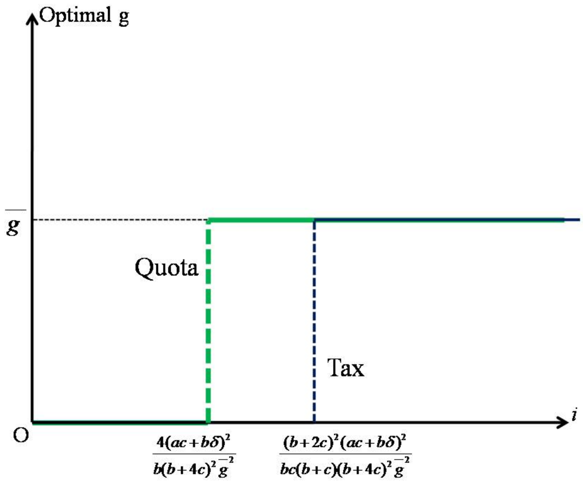

Figure 3.3.11: Optimal Cost as a function of i in both tax and quota regimes

3.3.3.4 The role of an R & D subsidy

We know that at $i = \frac{(b+2c)^2(ac+b\delta)^2}{bc\overline{g}^2(b+c)(b+4c)^2}$,

$$\Pi(\overline{g}) = \Pi(0)$$

$$\text{i.e.} \quad \pi(0) = i.\overline{g}^2$$

By substituting $g = 0$ in the optimal tax and price function, we get

$$t^*(0) = \frac{ac + 2\delta(b + 2c)}{(b + 4c)} > \delta$$

$$\begin{aligned} P(t^*(0), 0) &= \frac{(ac + b\delta)(b + 2c)}{(b + c)(b + 4c)} \\ &= \frac{(b + 2c)}{(b + 4c)} P_d^*(t = \delta) \\ &< P_d^*(t = \delta) \end{aligned}$$

This situation is depicted in Figure 3.3.12. $\pi(0)$ is given by the rectangle $EGLK$. Gross

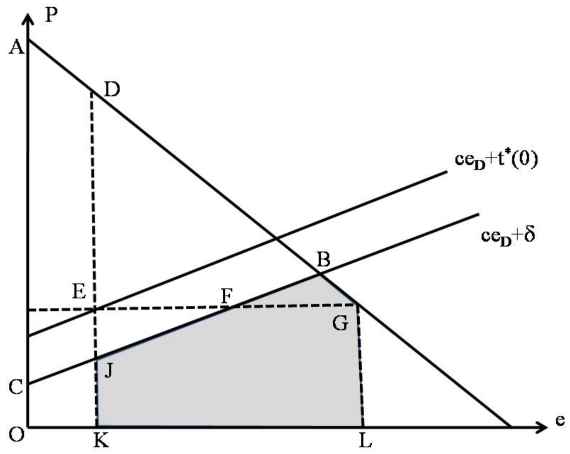

Figure 3.3.12: Diagram Explaining the role of subsidy

welfare when there is R & D and $g = 0$ is

$$w(0) = ADJC + DKLG$$

If there is no R& D, $w(\overline{g}) = \triangle ABC$. Therefore,

$$w(0) - w(\overline{g}) = JKLGB \quad \text{(Shaded in Grey)}$$

So the increase in welfare from conducting R & D minus the increase in profits from conducting R& D is

$$\{w(0) - w(\overline{g})\} - \pi(0) = \triangle FGB - \triangle EFJ$$

Now $\triangle FGB > \triangle EFJ$ if and only if $4c^2 - bc - b^2 > 0$ i.e $c > \frac{1+\sqrt{17}}{8}b$. At the threshold value of i, the increase in profit from R & D is zero. Thus if $c < \frac{1+\sqrt{17}}{8}b$, there can be no welfare improving subsidy. Also note that $i = \frac{(b+3c)(ac+b\delta)^2}{2bc\overline{g}^2(b+c)(b+4c)}$ is the maximum level of i from which a subsidy can reduce g from $\overline{g}$ to 0 and yet increase welfare [14]. Thus we can summarize the results of this subsection in

Proposition 8 *If $c < \frac{1+\sqrt{17}}{8}b$, then a welfare-improving subsidy to R & D does not exist in the tax regime. If $c > \frac{1+\sqrt{17}}{8}b$, then an R & D subsidy can improve investment and welfare if*

[14]Proof in Appendix 3.G.

$i \in [\frac{(b+2c)^2(ac+b\delta)^2}{bc\overline{g}^2(b+c)(b+4c)^2}, \frac{(b+3c)(ac+b\delta)^2}{2bc\overline{g}^2(b+c)(b+4c)}]$

3.3.3.5 Relaxing assumption 3.3.1

Suppose we relax Assumption 3.3.1. We allow the initial marginal cost of the green technology ($\overline{g}$) to be too high for it to be introduced in the absence of government policy intervention, but low enough for it to be socially optimal to have some green production of energy. The results of this changed situation can be summarized in:

PROPOSITION 9 *Let $P_d^*(t=0) \leq \overline{g} \leq P_d^*(t=\delta)$. Then with all other assumptions of Section 3.3 remaining unchanged, the tax regime induces the maximum possible R & D with $g = 0$ provided that the marginal cost of green energy is sufficiently sensitive to R & D investment, that is, if (and only if) $i \leq \frac{(b+2c)^2(ac+b\delta)}{bc\overline{g}(b+4c)^2}$. For values of i greater than $\frac{(b+2c)^2(ac+b\delta)}{bc\overline{g}(b+4c)^2}$, the optimal choice of g by the green firm increases smoothly (at a decreasing rate) with i. The optimal choice of g is strictly less than $\overline{g}$ for all values of g.*
For $i > \frac{4(b+c)(ac+b\delta)}{b(b+4c)^2\overline{g}}$, the tax regime induces more investment in R & D compared to the quota regime (Figure 3.3.7).
If $c < \frac{1+\sqrt{17}}{8}b$, then there can be no welfare-improving subsidy to R & D in the tax regime. If $c > \frac{1+\sqrt{17}}{8}b$, then an R & D subsidy can improve investment and welfare if $i \geq \frac{(b+2c)^2(ac+b\delta)^2}{bc\overline{g}^2(b+c)(b+4c)^2}$.

Proof: Proof discussed in Appendix 3.H. ■

Thus, we see that the change in assumption $\overline{g} > P_d^*(t=\delta)$ does not change any of the earlier results qualitatively. A tax continues to induce more R & D than a quota. The only change is in the shape of the optimal g curve.

3.3.4 Welfare Comparisons between the two regimes

PROPOSITION 10 *When $c > \frac{1+\sqrt{17}}{8}$, the tax regime leads to higher welfare for all values of i for which it ensures $g = 0$. When $c < \frac{1+\sqrt{17}}{8}$, tax regime ensures higher welfare for $i < \frac{(b+3c)(ac+b\delta)^2}{2bc\overline{g}^2(b+c)(b+4c)}$, quota regime lead to higher welfare for $i \in (\frac{(b+3c)(ac+b\delta)^2}{2bc\overline{g}^2(b+c)(b+4c)}, \frac{(b+2c)^2(ac+b\delta)^2}{bc\overline{g}^2(b+c)(b+4c)^2})$ and both regimes ensure equal welfare for $i > \frac{(b+2c)^2(ac+b\delta)^2}{bc\overline{g}^2(b+c)(b+4c)^2}$.*

Proof: Proof discussed in Appendix 3.I. ■

3.4 Introducing Uncertainty

Until now we have assumed that a social planner (government) is a social welfare maximizer. In addition to that, it is assumed that the social planner of the current period and the green energy firm believe with certainty that the social planner will act as a social welfare maximizer even after R & D investment has been made. While such an assumption is quite weak when the supply curve of dirty energy is flat, it becomes stringent when we assume a positively sloped supply curve. When the supply curve is flat, the dirty firms never earn rents irrespective of the stringency of the climate policy adopted by the government. In such a situation, welfare maximization seems to be the only rational objective of a government. However a positively sloped supply means that dirty sector rents could be negatively related to the stringency of climate policy. Political economy models suggest that governments will attach some weight to firm rents while choosing policy. The weight that a future government assigns to firm rents is a parameter in its objective function. The current government and the green firm do not know the value of this parameter with certainty.

For simplicity, we assume a binary distribution parameter values. Let us assume that with probability p, the government in the second period acts as a benevolent social welfare maximizer and with probability $(1 - p)$ it only cares about firm rents. Thus, we can say that in period 2, the government chooses the welfare maximizing optimal policy with probability p and with probability $1-p$ it chooses the business as usual policy, i.e. there is no climate policy.

Introduction of uncertainty in this way changes only the green firm's optimal investment problem. There is no change in the government's ex-post choice problem and the green firm's optimal output decision. We assume that all other assumptions of section 3.3 remain unchanged.

In period 1, the firm chooses g so as to maximize the expected profit:

$$\begin{aligned} E[\Pi(g)] &= p[\pi(g) - I(g)] + (1-p)[\pi^n(g) - I(g)] \\ &= p.\pi(g) + (1-p).\pi^n(g) - I(g) \end{aligned} \quad (3.4.1)$$

where π is the profit under optimal climate policy, π^n is the profit with no climate policy and E denotes the expectation operator.

In a situation of no climate policy, a green firm with a marginal cost above $P_d^*(0)$ is shut out of the market (and hence the gross profit of the firm is zero). If $g < P_d^*(0)$, the green firm maximizes profit by choosing a price equal to the equally weighted average of g and $P_d^*(0)$. So when $g \leq P_d^*(0)$, the price, output and profit are as follows:

$$\begin{aligned} P^n(g) &= \frac{1}{2}\big[g + P_d^*(0)\big] \\ &= \frac{1}{2}\big[\frac{ac}{b+c} + g\big] \\ e_g^n(g) &= \frac{1}{2}\big[D(g) - S_1(g)\big] \\ &= \frac{(b+c)}{2bc}\big[\frac{ac}{b+c} - g\big] \\ \pi^n(g) &= \big[P(g) - g\big]e_g(g) \\ &= \frac{(b+c)}{4bc}\big[\frac{ac}{b+c} - g\big]^2 \end{aligned}$$

Substituting for $\pi(g)$ and $\pi^n(g)$ is equation 3.4.1, we get the expected net profit function:

$$E[\Pi(g)] = \begin{cases} p.\big[\frac{4(b+c)^2}{b(b+4c)^2}\big[P_d^*(\delta) - g\big]^2\big] + (1-p).\big[\frac{(b+c)}{4bc}\big[P_d^*(0) - g\big]^2\big] - i(\overline{g} - g)^2, \\ \quad \text{if} \quad g \in [0, P_d^*(0)) \\ \\ p.\big[\frac{4(b+c)^2}{b(b+4c)^2}\big[P_d^*(\delta) - g\big]^2\big] - i(\overline{g} - g)^2, \\ \quad \text{if} \quad g \in [P_d^*(0), P_d^*(\delta)) \\ \\ -i(\overline{g} - g)^2, \\ \quad \text{if} \quad g \in [P_d^*(\delta), \overline{g}] \end{cases}$$

The green firm's maximization problem has a corner solution (proof in Appendix 3.J):

$$g = \begin{cases} 0, & \text{if} \quad i < \frac{1}{\overline{g}^2}\big[\frac{4p(ac+b\delta)^2}{b(b+4c)^2} + \frac{(1-p)a^2c^2}{4bc(b+c)}\big] \\ \overline{g}, & \text{otherwise} \end{cases} \tag{3.4.2}$$

We observe that as in the case with certainty, g is a step function of i. Only the threshold at which the firm shifts from 0 to $\overline{g}$ has shifted down. The lower the value of p , lower is the cut-off at which this shift happens.

Now we study the role of an R & D subsidy in a situation with uncertainty. Here we consider the case where $c < \frac{5}{4}b$. This was the case in which a subsidy was always welfare reducing in an environment of certainty. The intent is to show that uncertainty can reverse this result.

At $i = \frac{1}{\overline{g}^2}\big[\frac{4p(ac+b\delta)^2}{b(b+4c)^2} + \frac{(1-p)a^2c^2}{4bc(b+c)}\big]$,

$$E[\Pi(0)] > E[\Pi(\overline{g})]$$

$$\text{or,} \quad p.\pi(0) + (1-p)\pi^n(0) - i\overline{g}^2 = 0$$
$$\text{or,} \quad p.\pi(0) + (1-p)\pi^n(0) = i\overline{g}^2$$

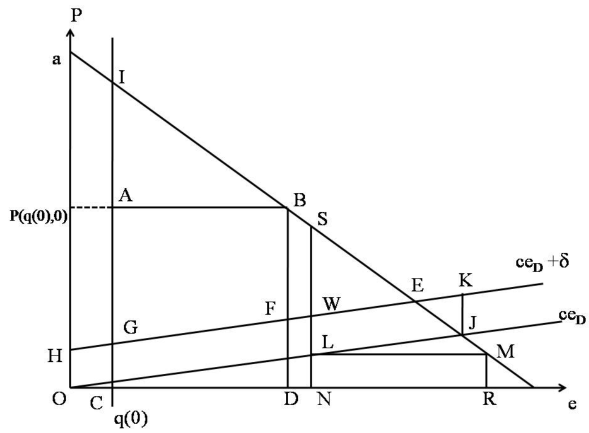

Figure 3.4.1: Subsidy analysis in quota regime with uncertainty

Now $E[\pi(0)]$ is given by the sum of p times the area of $ABCD$ and $(1-p)$ times the area of $LNRM$. An R & D subsidy can be welfare improving only if at $i = \frac{1}{\overline{g}^2}[\frac{4p(ac+b\delta)^2}{b(b+4c)^2} + \frac{(1-p)a^2c^2}{4bc(b+c)}]$

$$\Omega(p) = p[w(0) - w(\overline{g})] + (1-p)[w^n(0) - w^n(\overline{g})] - i\overline{g}^2 > 0$$

where $w^n(g)$ denotes gross welfare as a function of g when there is no policy.

For $p = 1$,which is the case with no uncertainty, we know from the earlier section that $\Omega(p) = w(0) - w(\overline{g}) - i\overline{g}^2 < 0$. For $p = 0$, which is the situation with no climate policy, we know from Figure 3.4.1,

$$\begin{aligned}
p[w(0) - w(\overline{g})] + (1-p)[w^n(0) - w^n(\overline{g})] &= w^n(0) - w^n(\overline{g}) \\
&= [aSWH + SMRN] - [\triangle aEH - \triangle EKJ] \\
&= WEMRN + \triangle EKJ \\
&> LMRN \\
&> \pi^n(0) \\
&= i.\overline{g}^2 \quad \text{where} \quad i = \frac{1}{\overline{g}^2}[\frac{4p(ac+b\delta)^2}{b(b+4c)^2} + \frac{(1-p)a^2c^2}{4bc(b+c)}]
\end{aligned}$$

This implies that $\Omega(0) > 0$. Since $\Omega(p)$ is a linear function of p, $\exists\ \hat{p} \in (0,1)$ such that $\Omega(p)$ is positive below $\hat{p}$ and negative thereafter. Using exactly similar reasoning, it can be shown that introduction of uncertainty expands the parameter space that supports welfare enhancing subsidy. The discussion in this section can be summarized in form of the following proposition:

PROPOSITION 11 *Suppose the parameters b and c are such that there can be no welfare-improving subsidy in the absence of uncertainty in a quota regime. If p is the probability of having an ex-post optimal climate policy, there exists $\hat{p} \in (0,1)$ such that for $p < \hat{p}$, an R & D subsidy is welfare-improving for values of $i > \frac{1}{\overline{g}^2}[\frac{4p(ac+b\delta)^2}{b(b+4c)^2} + \frac{(1-p)a^2c^2}{4bc(b+c)}]$. Similarly, the introduction of uncertainty expands the parameter space that supports a welfare-enhancing subsidy in a tax regime.*

3.5 Conclusion

Technological innovation in the energy sector is clearly of central importance in any strategy to avoid too much climatic change. In this respect, the climate problem is distinct from many environmental problems in that it is probably more feasible to replace existing technologies entirely rather than find better ways to abate pollution using existing technologies. Accordingly, we have departed from most of the literature on innovation in environmental economics and modeled the incentive to conduct R & D to lower the cost of such replacements. We have done this in a context in which the government is unable to commit to the future level of any policy instrument (although it is committed to the choice of instrument), an assumption that is necessary, given the fairly long delays to be expected between the decision to conduct R & D and the arrival of the resulting technology in the market. An important finding is that when the marginal cost curve of the existing dirty technology is flat, then an emissions tax is ineffective in inducing R & D, but an emissions quota with tradeable permits can be effective (Propositions 1 and 2). In this case, under our maintained assumption of the perfect appropriability of the fruits of R & D, an R & D subsidy was shown to be ineffective or welfare-reducing if effective (Proposition 4).

We noted that since existing carbon-emitting technologies are based on mineral deposits with heterogeneous extraction costs, there can be no doubt that the marginal cost of dirty energy is increasing in output, although we may not know how steeply. If the marginal cost curve of dirty energy is increasing sufficiently steeply, the results mentioned above are reversed. We have shown in Section 3 that both the emissions tax and the emissions quota can induce R & D and that an R & D subsidy can be a welfare-improving policy in conjunction with either an emissions tax or an emissions quota. Whether the tax or the quota regime gives rise to higher welfare under these circumstances depends on the sensitivity of the marginal cost of green energy to R & D investment.

Since increasing marginal extraction costs give rise to rents, it is to be expected that rentiers will lobby to protect their rents. This introduces uncertainty about whether there will be any climate policy when the results of R & D are realized. It was shown in Section 4 that in the presence of such uncertainty, a subsidy to R & D, because it takes effect in the present rather than the future, becomes a more attractive policy instrument.

What do these results imply for the choice of instruments in climate policy making? The likelihood that the marginal cost of dirty energy is increasing, together with the undoubted presence of uncertainty about whether there will be a meaningful climate policy in the future lead us to emphasize the results in Sections 3 and 4. Notice also that we did not model the possibility that the marginal cost of the green technology can fall *below* that of the dirty technology. In an earlier version of the paper we showed that in this case an R & D subsidy is welfare-improving if the effectiveness of R & D investment $1/i$ is in an intermediate range. These considerations, together with the public good aspects of research and development that were not modeled in this paper, suggest that R & D subsidies should form part of the policy mix.[15].

What about the choice between an emissions tax and a quota? Either could lead to greater welfare (assuming a sufficiently steep supply curve of dirty energy) depending on parameter values (Proposition 10). However, Propositions 7 and 9 tell us that a tax regime leads to a lower marginal cost of green energy than a quota regime, unless i is small enough, in which case both induce the maximum possible R & D. If we believe that the public good aspects of R & D are sufficiently important, then these propositions make the emissions tax seem more attractive than the emissions quota with tradeable permits.

[15](Acemoglu, Aghion, Bursztyn, and Hemous, 2010) explore the implications of positive externalities in R & D in a dynamic setting

Appendices for Chapter 3

3.A Appendix for section 3.3.2.2: Derivation of the government's reaction function

Differentiating Equation 3.3.5 with respect to q, we get

$$\frac{\partial w}{\partial q} = \frac{a}{4} - \frac{bq}{4} + \frac{3g}{4} - \delta - cq \tag{3.A.1}$$

$$\left.\frac{\partial w}{\partial q}\right|_{q=0} = \frac{a}{4} + \frac{3g}{4} - \delta \tag{3.A.2}$$

To rule out corner solution at $q = 0$: $a+3g-4\delta > 0 \quad \forall g \geq 0 \Rightarrow a-4\delta \geq 0$. This is Assumption 3.3.2. For $P_d^*(t = \delta) \geq g \geq P_d^*(t = 0)$, the upper bound on the quota is $e_d^*(t = \delta)$.

$$\begin{aligned}\left.\frac{dW}{dq}\right|_{e_d^*(t=\delta)} &= \frac{a}{4} - \frac{b}{4}\frac{a-\delta}{b+c} + \frac{3}{4}g - \delta - c\frac{a-\delta}{b+c} \\ &= \frac{3}{4}[g - P_d^*(t=\delta)] < 0\end{aligned}$$

For $g < P_d^*(t = 0)$, the upper bound on the quota is the emission level achieved in the absence of a climate policy that is $q^F(g)$.

$$\begin{aligned}\left.\frac{dW}{dq}\right|_{q^F(g)} &= \frac{a}{4} + \frac{3g}{4} - \delta - (\frac{b}{4} + c)\frac{1}{2c}[\frac{ac}{b+c} + g] \\ &= (\frac{a}{4} - \delta - \frac{a(b+4c)}{8(b+c)} - \frac{g}{8c}(b-2c)\end{aligned}$$

If $b > 2c$, $\left.\frac{dW}{dq}\right|_{q^F(g)}$ is decreasing in g. To ensure that the quota is below $q^F(g)$ for all values of g, we need $\left.\frac{dW}{dq}\right|_{q^F(g)}$ evaluated at $g = 0$ to be negative, that is, $\frac{b-2c}{2(b+c)}a - 4\delta < 0$. This is Assumption 3.3.3.

If $b < 2c$, $\left.\frac{dW}{dq}\right|_{q^F(g)}$ is increasing in g. To ensure that the quota is below $q^F(g)$ for all values of g, we need $\left.\frac{dW}{dq}\right|_{q^F(g)}$ evaluated at $g = P_d^*(t = 0)$ to be negative , which is always true. Note that when $b < 2c$, the inequality in Assumption 3.3.3 is satisfied.

3.B Appendix for section 3.3.2.3: The green firm's choice of g has a corner solution in the quota regime

Differentiating Equation 3.3.8 with respect to g,

$$\frac{d\Pi}{dg} = -\frac{8(b+c)}{b(b+4c)^2}[P_1^*(\delta) - g] + 2i(\overline{g} - g)$$

$$\frac{d\Pi}{dg}\Big|_{P_1^*(\delta)} = 2i(\overline{g} - P_1^*(\delta)) > 0 \tag{3.B.1}$$

Now suppose the net profit curve is concave in the range $[0, P_1^*(\delta))$. Given inequality (3.B.1), $P_1^*(\delta)$ maximizes net profit in this range. We know that net profit is negative at $P_1^*(\delta)$. Thus $\overline{g}$ is the global optimum when the profit function (3.3.8) is concave.

If the net profit curve is convex in the range $[0, P_1^*(\delta))$, there are two candidates for optimum in the range $[0, P_1^*(\delta))$: 0 and $P_1^*(\delta)$. We know that net profit is negative at $P_1^*(\delta)$. Thus $\overline{g}$ and 0 are the two candidates for global optimum.

We know that net profit is zero when $g = \overline{g}$. The net profit at $g = 0$ is as follows:

$$\Pi(0) = \frac{4(ac+b\delta)^2}{b(b+4c)^2} - i\overline{g}^2$$

The firm chooses $g = 0$ if $\Pi(0) \geq 0$ and $\overline{g}$ otherwise.

$$i = \frac{4(ac+b\delta)^2}{b(b+4c)^2\overline{g}^2}$$

is the level of i at which the firm is indifferent between choosing 0 and $\overline{g}$. Below this threshold, the firm chooses 0 and $\overline{g}$ otherwise.

3.C Appendix for section 3.3.2.4: Derivation of conditions for a welfare improving subsidy in the quota regime

Here we show that $\triangle LIF > \triangle ALB$ (in Figure 3.3.6) implies $c > \frac{5}{4}b$. Note

$$P(q(g), g) = \frac{2(ac + b\delta) - (b - 2c)g}{b + 4c}$$

Consider Figure 3.3.6. This figure corresponds to the situation where $b < 2c$.

$$\begin{aligned} MSC_1(q(0)) &= c.\{\frac{a - 4\delta}{b + 4c}\} + \delta \\ &= \frac{ac + b\delta}{b + 4c} \\ &= \frac{1}{2}P(q(0), 0) \end{aligned}$$

where $MSC_1(q(0))$ is the marginal social cost of producing $q(0)$ of energy, using the dirty technology.

$$P_d^*(\delta) - P(q(0), 0) = \frac{(2c - b)(ac + b\delta)}{(b + c)(b + 4c)} > 0$$

$$\begin{aligned} \text{Area of } \triangle ALB &= \frac{1}{2}AL.AB \\ &= \frac{1}{2}[P(q(0), 0) - MSC_1(q(0))].[S_1(P(q(0), 0) - \delta) - q(0)] \\ &= \frac{1}{2c}(\frac{ac + b\delta}{b + 4\delta})^2 \end{aligned}$$

$$\begin{aligned} \text{Area of} \triangle IFL &= \frac{1}{2}FL.[\text{Perpendicular distance from vertex I}] \\ &= \frac{1}{2}[D(P(q(0), 0)) - S_1(P(q(0), 0) - \delta)].[P_d^*(\delta) - P(q(0), 0)] \\ &= \frac{(ac + b\delta)^2(2c - b)^2}{2bc(b + c)(b + 4c)^2} \end{aligned}$$

Therefore, $\triangle LIF > \triangle ALB$ if $b < \frac{4}{5}c$. Thus if $c < \frac{5}{4}b$, there can be no welfare-improving subsidy.

If $c > \frac{5}{4}b$, then

$$\{w(0) - w(\overline{g})\} - \pi(0) > 0$$

$$\text{or,} \quad w(0) - i.\overline{g}^2 > w(\overline{g}) \quad \text{where} \quad i = \frac{4(ac+b\delta)^2}{b(b+4c)^2\overline{g}^2}$$

Thus at the right hand neighborhood of $\frac{4(ac+b\delta)^2}{b(b+4c)^2\overline{g}^2}$, even an infinitesimal subsidy can increase both welfare and investment. Now,

$$\begin{aligned} w(0) - w(\overline{g}) &= BDEF \\ &= AFED + \triangle IFL - \triangle ALB \\ &= \frac{3(ac+b\delta)^2}{2b(b+c)(b+4c)} \end{aligned}$$

Thus $\frac{3(ac+b\delta)^2}{2b(b+c)(b+4c)\overline{g}^2}$ is the highest level of i from which a subsidy that ensures $g = 0$ is welfare improving.

3.D Appendix for section 3.3.2.5: Proof of Proposition 6

The firm chooses $g \in [0, \overline{g}]$ to maximize net profit which is given by Equation (3.3.8).

$$\text{FOC:} \quad \frac{d\Pi}{dg} = -\frac{8(b+c)}{b(b+4c)^2}[P_d^*(\delta) - g] + 2i(\overline{g} - g)$$

$$\text{SOC:} \quad \frac{d^2\Pi}{dg^2} = \frac{8(b+c)^2}{b(b+4c)^2} - 2i$$

From the FOC, it is evident that the net profit curve is negatively sloped at $g = \overline{g}$ and hence $\overline{g}$ can never be optimum. The net profit curve is convex that is $\frac{d^2\Pi}{dg^2} > 0$ for

$$i < \frac{4(b+c)^2}{b(b+4c)^2}$$

while the net profit curve is negatively sloped at $g = 0$ that is $\left.\frac{d\Pi}{dg}\right|_{g=0}$ if

$$i < \frac{4(b+c)(ac+b\delta)}{b(b+4c)^2\overline{g}}$$

Equating the FOC to 0, we get the interior solution as

$$g = \frac{bi\overline{g}(b+4c)^2 - 4(b+c)(ac+b\delta)}{bi(b+4c)^2 - 4(b+c)^2}$$

Thus the optimal choice of g is given by:

$$g = \begin{cases} 0, & \text{if} \quad i \leq \frac{4(b+c)(ac+b\delta)}{b(b+4c)^2\overline{g}} \\ \frac{bi\overline{g}(b+4c)^2 - 4(b+c)(ac+b\delta)}{bi(b+4c)^2 - 4(b+c)^2}, & \text{if} \quad i \geq \frac{4(b+c)(ac+b\delta)}{b(b+4c)^2\overline{g}} \end{cases} \tag{3.D.1}$$

If s is the rate of subsidy on investment, the net profit function is:

$$\begin{aligned} \Pi(g) &= \frac{4}{b(b+4c)^2}[ac + b\delta - (b+c)g]^2 - i(1-s)(\overline{g} - g)^2 \\ &= \frac{4(b+c)^2}{b(b+4c)^2}[P_d^*(\delta) - g]^2 - (1-s)i(\overline{g} - g)^2 \end{aligned} \tag{3.D.2}$$

$$\text{FOC:} \quad \frac{d\Pi}{dg} = 0$$

$$\text{or,} \quad -\frac{8(b+c)}{b(b+4c)^2}[P_d^*(\delta) - g] + 2(1-s)i(\overline{g} - g) = 0 \tag{3.D.3}$$

Initially $s = 0$ and we assume that the optimum g is greater than zero [16]. Differentiating (3.D.3), with respect to s, we get:

$$\frac{\partial g}{\partial s} = \frac{2bi(b+4c)^2(\overline{g} - g)}{8(b+c)^2 - 2bi(1-s)(b+4c)^2} < 0 \tag{3.D.4}$$

as

$$\frac{\partial^2 \Pi}{dg^2} = \frac{8(b+c)^2}{b(b+4c)^2} - 2i(1-s) < 0$$

[16] If initial g is zero, then a subsidy is ineffective as marginal cost is already at it's lowest possible level

Now, social welfare as a function of $g(s)$ is as follows:

$$w(g(s)) = Y + a.e - \frac{b}{2}e^2 - \frac{c}{2}e_d^2 - \delta e_d - g e_g \tag{3.D.5}$$

where:

$$\begin{aligned} e_d &= q \\ e_g &= \frac{a - bq - g}{2b} \\ e &= e_d + e_g \\ q &= \frac{a + 3g - 4\delta}{b + 4c} \end{aligned}$$

$$\frac{dW}{dg} = \frac{3[(b+c)g - (ac + b\delta)]}{b(b+4c)} + 2i(\overline{g} - g)$$

Substituting from equation (3.D.3),

$$\begin{aligned} \frac{dW}{dg}\Big|_{s=0} &= \frac{[(b+c)g - (ac + b\delta)]}{b(b+4c)}\Big[\frac{8(b+c)}{b+4c} - 3\Big] \\ &= \frac{[(b+c)g - (ac + b\delta)]}{b(b+4c)^2}\Big[5b - 4c\Big] \end{aligned}$$

A marginal subsidy is welfare improving if $c > \frac{5}{4}b$ and welfare reducing if $c < \frac{5}{4}b$
Now holding i constant at a particular level greater than $\frac{4(b+c)(ac+b\delta)}{b(b+4c)^2\overline{g}}$, $W(g,i)$ is a smooth and continuous function of g. Now,

$$\begin{aligned} \frac{dW}{dg}\Big|_{g=\overline{g}} &= \frac{3((b+c)g - (ac + b\delta))}{b(b+4c)} < 0 \quad \text{as} \quad \overline{g} < P_d^*(\delta) \\ \frac{d^2W}{dg^2} &= \frac{3(b+c)}{b(b+4c)} - 2i \end{aligned}$$

$W(h,i)$ is globally concave or convex depending on the value of i and is negatively sloped at $\overline{g}$. If a marginal subsidy is welfare reducing, it means that $W(g,i)$ curve is positively sloped in the neighborhood of the no-subsidy equilibrium value of g. Given the above two observations, the curve should be positively sloped for all values of g to the left of no-subsidy equilibrium value of g. Thus if a marginal subsidy is welfare reducing, so is a subsidy of higher magnitude.

3.E Appendix for section 3.3.3.2: Derivation of Government's Reaction Function under Tax Regime

Expanding Equation 3.3.15, we get:

$$\frac{\partial w}{\partial t} = \frac{ac + 2\delta(b+2c) - (b+c)g - (b+4d)t}{4c(b+c)} \tag{3.E.1}$$

$$\left.\frac{\partial w}{\partial t}\right|_{t_L} = \frac{(2b+c)(ac+b\delta-(b+c)g)}{2bc(b+c)} > 0 \quad \text{as} \quad g < P_d^*(\delta)$$

$$\left.\frac{\partial w}{\partial t}\right|_{0} = \frac{ac + 2\delta(b+2c) - (b+c)g}{4c(b+c)} > 0 \quad \text{as} \quad g < P_d^*(\delta) + \frac{(b+4c)\delta}{b+c}$$

Thus corner solutions at $\min\{0, t^L\}$ is ruled out.

$$\left.\frac{\partial w}{\partial t}\right|_{t^H} = \frac{\delta(b+2c)^2 - ac^2 - (b+c)(b+3c)g}{2c(b+c)(b+2c)}$$

The corner solution at t^H is attained only when $\left.\frac{\partial w}{\partial t}\right|_{t^H} > 0$ that is $g < g^H = \frac{\delta(b+2c)^2 - ac^2}{(b+c)(b+3c)}$.

If $g > g^H$, we solve the first order condition, by equating 3.E.1 to zero, to get an interior solution at $t^*(g)$ where

$$t^* = \frac{ac - (b+c)g + 2\delta(b+2c)}{b+4c}$$

3.F Appendix for section 3.3.3.3: Proof of Proposition 7

Differentiating Equation 3.3.17 with respect to g,

$$\frac{d\Pi(g)}{dg} = \frac{(b+c)}{2bc}[\frac{ac+bt}{b+c} - g][\frac{b}{b+c}\frac{dt(g)}{dg} - 1] + 2i(\overline{g} - g) \tag{3.F.1}$$

$$\text{where} \quad \frac{dt(g)}{dg} = -\frac{b+c}{b+4c}$$

Substituting, we get:

$$\frac{d\Pi(g)}{dg} = -\frac{2(b+c)(b+2c)^2}{bc(b+4c)^2}[P_d^*(t=\delta) - g] + 2i(\overline{g} - g) \tag{3.F.2}$$

$$\frac{d^2\Pi(g)}{dg^2} = \frac{2(b+c)(b+2c)^2}{bc(b+4c)^2} - 2i \tag{3.F.3}$$

Note that:

$$\left.\frac{d\Pi(g)}{dg}\right|_{g=P_d^*(t=\delta)} > 0 \tag{3.F.4}$$

If the net profit curve is concave, inequality (3.F.4) ensures that in the range $[0, P_d^*(g)]$, $g = P_d^*(g)$ gives the lowest net loss. Thus the only choice of g that can give non-negative net profits is $\overline{g}$. Thus $\overline{g}$ is the global optimum.

If the net profit curve is convex, then in the range $[0, P_d^*(g)]$, there are two candidates for optimum: 0 and $P_d^*(g)$. We know that at $g = P_d^*(g)$, net profit is negative. Thus we are left with just two candidates for global optimum : 0 and $\overline{g}$.

$\overline{g}$ is the optimal choice if i is greater than the level of i at which:

$$\begin{aligned} \Pi(0) &= 0 \\ \text{or,} \quad i &= \frac{(b+2c)^2(ac+b\delta)^2}{bc\overline{g}^2(b+c)(b+4c)^2} \end{aligned} \tag{3.F.5}$$

The green firm's maximization problem can have solutions at either of the two corners: 0

or $\overline{g}$. The optimal cost function is :

$$g = \begin{cases} 0, & \text{if} \quad i \leq \frac{(b+2c)^2(ac+b\delta)^2}{bc\overline{g}^2(b+c)(b+4c)^2} \\ \overline{g}, & \text{if} \quad i \geq \frac{(b+2c)^2(ac+b\delta)^2}{bc\overline{g}^2(b+c)(b+4c)^2}. \end{cases} \tag{3.F.6}$$

Let i^T and i^Q be the threshold levels at which the optimal cost curves in tax and quota regime jump from $g = 0$ to $g = \overline{g}$.

$$i^T = \frac{(b+2c)^2(ac+b\delta)^2}{bc\overline{g}^2(b+c)(b+4c)^2}$$

$$i^Q = \frac{4(ac+b\delta)^2}{b(b+4c)^2\overline{g}^2}$$

$$\text{Thus,} \frac{i^T}{i^Q} = \frac{(b+2c)^2}{4c(b+c)} > 1$$

Thus, the optimal cost curves have the shape given in Figure 3.3.11.

3.G Appendix for section 3.3.3.4: Derivation of conditions for a welfare improving subsidy in tax regime

We show that for $\triangle FGB > \triangle EFJ$ (in Figure 3.3.12) , we need $4c^2 - bc - b^2 > 0$. Consider Figure 3.3.12.

$$\begin{aligned} \triangle EFJ &= \frac{1}{2}.EJ.EF \\ &= \frac{1}{2}.[P^*(t^*(0),0) - (\delta + ce_d(t^*(0),0))].[\frac{P^*(t^*(0),0)-\delta}{c} - e_d(t^*(0),0)] \\ &= \frac{1}{2}.\frac{ac+b\delta}{b+4c}.\frac{ac+b\delta}{c(b+4c)} \\ &= \frac{1}{2c}(\frac{ac+b\delta}{b+4c})^2 \end{aligned} \tag{3.G.1}$$

$$\begin{aligned}
\triangle FGB &= \frac{1}{2}.FG.[\text{Perpendicular distance of edge } FG \text{ from } B] \\
&= \frac{1}{2}.[D(P^*(t^*(0),0)) - \frac{P^*(t^*(0),0)-\delta}{c}].[P_d^*(t=\delta) - P^*(t^*(0),0)] \\
&= \frac{1}{2}.\frac{2(ac+b\delta)}{b(b+4c)}.\frac{2c(ac+b\delta)}{(b+c)(b+4c)} \\
&= \frac{2c}{b(b+c)}(\frac{ac+b\delta}{b+4c})^2 \qquad (3.G.2)
\end{aligned}$$

$$\text{Therefore,} \quad \triangle FGB - \triangle EFJ = (\frac{ac+b\delta}{b+4c})^2.[\frac{2c}{b(b+c)} - \frac{1}{2c}] \qquad (3.G.3)$$

Thus, $\triangle FGB - \triangle EFJ$ is positive if $4c^2 - bc - b^2 > 0$ that is $c > \frac{1+\sqrt{17}}{8}b$.

Thus we can have two cases:

- Case A: $4c^2 - bc - b^2 < 0$

  In this case, $w(0) - w(\overline{g}) < \pi(0) = \{\frac{(b+2c)^2(ac+b\delta)^2}{bc\overline{g}^2(b+c)(b+4c)^2}\}\overline{g}^2 < i\overline{g}^2$ for all $i > \frac{(b+2c)^2(ac+b\delta)^2}{bc\overline{g}^2(b+c)(b+4c)^2}$. Thus, $w(0) - i\overline{g}^2 < w(\overline{g})$ for all $i > \frac{(b+2c)^2(ac+b\delta)^2}{bc\overline{g}^2(b+c)(b+4c)^2}$

- Case B: $4c^2 - bc - b^2 > 0$

  In this case, $w(0) - w(\overline{g}) > \pi(0) = \frac{(b+2c)^2(ac+b\delta)^2}{bc\overline{g}^2(b+c)(b+4c)^2}$.

Now,

$$\begin{aligned}
w(0) - w(\overline{g}) &= \text{Area of } \quad EKLG + \text{Area of } \triangle FGB - \text{Area of } \triangle EFJ \\
&= P(t^*(0),0).e_g(t^*(0),0) + \text{Area of } \triangle FGB - \text{Area of } \triangle EFJ \\
&= \frac{(ac+b\delta)^2(b+2c)^2}{bc(b+c)(b+4c)^2} + [(\frac{ac+b\delta}{b+4c})^2.[\frac{2c}{b(b+c)} - \frac{1}{2c}]] \\
&= \frac{(b+3c)(ac+b\delta)^2}{2bc(b+c)(b+4c)} \\
&= > \pi(0) \quad \text{as} \quad 4c^2 - b(b+c) > 0
\end{aligned}$$

Thus, $\frac{(b+3c)(ac+b\delta)^2}{2bc\overline{g}^2(b+c)(b+4c)}$ is the highest level of i from which a subsidy that encourages R & D can be welfare improving.

3.H Appendix for section 3.3.3.5: Proof of Proposition 9

The firm chooses $g \in [0, \overline{g}]$ to maximize net profit which is given by 3.3.17. The first and second order conditions are obtained from 3.F.2 and 3.F.2 respectively. Substituting $g = \overline{g}$ in 3.F.2, we get $\frac{d\Pi(g)}{dg}\Big|_{\overline{g}} < 0$. The net profit curve is convex if

$$i < \frac{(b+c)(b+2c)^2}{bc(b+4c)^2}$$

and the curve is negatively sloped at $g = 0$ if

$$i < \frac{(ac+b\delta)(b+2c)^2}{bc\overline{g}(b+4c)^2}$$

Thus if $i < \frac{(ac+b\delta)(b+2c)^2}{bc\overline{g}(b+4c)^2}$, optimal g is 0. For values of i greater than this cut-off, we have an interior solution that is obtained by setting the FOC to zero. The interior solution is:

$$g = \frac{bci\overline{g}(b+4c)^2 - 4(b+2c)^2(ac+b\delta)}{bci(b+4c)^2 - (b+2c)^2(b+c)}$$

If s is the rate of subsidy on investment, the net profit function is:

$$\begin{aligned} \Pi(g) &= \frac{(b+2c)^2}{bc(b+c)(b+4c)^2}[ac+b\delta-(b+c)g]^2 - i(1-s)(\overline{g}-g)^2 \\ &= \frac{(b+2c)^2(b+d)}{bc(b+4c)^2}[P_d^*(\delta)-g]^2 - (1-s)i(\overline{g}-g)^2 \end{aligned} \quad (3.H.1)$$

$$\frac{d\Pi}{dg} = -\frac{2(b+2c)^2}{bc(b+4c)^2}[ac+b\delta-(b+c)g] + 2(1-s)i(\overline{g}-g) \quad (3.H.2)$$

Initially $s = 0$ and we assume that the optimum g is greater than zero [17]. Differentiating the equation $\frac{d\Pi}{dg} = 0$, with respect to s, we get:

$$\frac{\partial g}{\partial s} = \frac{i(\overline{g}-g)}{\frac{(b+c)(b+2c)^2}{bc(b+4c)^2} - (1-s)i} < 0 \quad (3.H.3)$$

[17] If initial g is zero, then a subsidy is ineffective as marginal cost is already at it's lowest possible level

$$\text{as} \quad \frac{d^2\Pi}{dg^2} = 2\frac{(b+c)(b+2c)^2}{bc(b+4c)^2} - 2(1-s)i < 0 \tag{3.H.4}$$

Now, social welfare as a function of $g(s)$ is as follows:

$$w(g(s)) = Y + a.e - \frac{b}{2}e^2 - \frac{c}{2}e_d^2 - \delta e_d - ge_g \tag{3.H.5}$$

where: e_d, e_g and e are functions of g obtained by substituting the government's optimal choice of tax in Equations: 3.3.11, 3.3.13 and 3.3.12.

$$\frac{dW}{dg} = \frac{-(b+3c)(ac+b\delta-(b+c)g)}{bc(b+4c)} + 2i(\overline{g}-g)$$

Substituting from the first order condition ((3.H.2)),

$$\left.\frac{dW}{dg}\right|_{s=0} = \frac{ac+b\delta-(b+c)g}{bc(b+4c)^2}(b^2+bc-4c^2) \tag{3.H.6}$$

A marginal subsidy is welfare improving if $c > \frac{1+\sqrt{17}}{8}b$ and welfare reducing if $c < \frac{1+\sqrt{17}}{8}b$ Now holding i constant at a particular level greater than $\frac{(ac+b\delta)(b+2c)^2}{bc\overline{g}(b+4c)^2}$, $W(g,i)$ is a smooth and continuous function of g. Now,

$$\left.\frac{dW}{dg}\right|_{g=\overline{g}} = \frac{-(b+3c)(ac+b\delta-(b+c)\overline{g})}{bc(b+4c)} < 0$$

$$\frac{d^2W}{dg^2} = \frac{(b+3c)(b+c)}{bc(b+4c)} - 2i$$

$W(h,i)$ is globally concave or convex depending on the value of i and is negatively sloped at $\overline{g}$. If a marginal subsidy is welfare reducing, it means that $W(g,i)$ curve is positively sloped in the neighborhood of the no-subsidy equilibrium value of g. Given the above two observations, the curve should be positively sloped for all values of g to the left of no-subsidy equilibrium value of g. Thus if a marginal subsidy is welfare reducing, so is a higher amount of subsidy.

3.I Appendix for section 3.3.4: Proof of Proposition 10

As $\overline{g} > P_d^*(\delta)$, the optimal cost curves are step functions in both regimes, as depicted in 3.3.11.

For $i > \frac{(b+2c)^2(ac+b\delta)^2}{bc\overline{g}^2(b+c)(b+4c)^2}$, that is when there is no R & D in both regimes, welfare is equal to $\triangle ABC$ (in Figure 3.3.12) in both regimes.

For $i < \frac{4(ac+b\delta)^2}{b(b+4c)^2\overline{g}^2}$, that is when $g = 0$ in both the regimes, a tax regime provides higher welfare than a quota regime. Since the choice of g is same in both regimes, the R & D cost is equal and hence comparing gross welfare is sufficient to make net welfare comparisons. When $g = 0$, optimal quota is given by $q(0) = \frac{a-4\delta}{b+4c}$. Substituting $q = q(0)$ and $g = 0$ in the gross welfare function we get

$$\begin{aligned} w(g=0)\Big|_{Quota} &= a\Big(\frac{a + b\frac{a-4\delta}{b+4c}}{2b}\Big) - \frac{b}{2}\Big(\frac{a + b\frac{a-4\delta}{b+4c}}{2b}\Big)^2 - \delta\Big(\frac{a-4\delta}{b+4c}\Big) - \frac{c}{2}\Big(\frac{a-4\delta}{b+4c}\Big)^2 \\ &= \frac{a^2(b+3c) - 2b\delta(a-2\delta)}{2b(b+4c)} \end{aligned} \quad (3.I.1)$$

When $g = 0$, optimal tax is given by $t(0) = \frac{ac+2\delta(b+2c)}{b+4c}$. Substituting $t = t(0)$ and $g = 0$, we obtain:

$$\begin{aligned} e(g=0) &= \frac{1}{2}\Big[\frac{a-t(0)}{b+c} + \frac{a-0}{b}\Big] \\ &= \frac{ab^2 + 4abc + 2ac^2 - b^2\delta - 2bc\delta}{b(b+c)(b+4c)} \\ e_d(g=0) &= \frac{1}{2}\Big[\frac{a-t(0)}{b+c} + \frac{0-t(0)}{c}\Big] \\ &= \frac{ac^2 - b^2\delta - 4bc\delta - 4c^2d}{c(b+c)(b+4c)} \end{aligned}$$

Substituting $e = e(g=0)$ and $e_d = e_d(g=0)$ in the gross welfare function, we get:

$$\begin{aligned} w(g=0)\Big|_{Tax} &= ae(g=0) - \frac{b}{2}e(g=0)^2 - \delta e_d(g=0) - \frac{c}{2}e_d(g=0)^2 \\ &= \frac{a^2b^2c + 5a^2bc^2 + 3a^2c^3 - 2abc^2\delta + b^3\delta^2 + 4b^2c\delta^2 + 4bc^2\delta^2}{2bc(b+c)(b+4c)} \end{aligned} \quad (3.I.2)$$

Now,

$$w(g=0)\Big|_{Quota} - w(g=0)\Big|_{Tax} = -\frac{(ac+b\delta)^2}{2c(b+c)(b+4c)} < 0 \quad (3.I.3)$$

It follows that $W(g=0)\Big|_{Quota} < W(g=0)\Big|_{Tax}$.

Now we consider the interior range of i i.e. $\frac{4(ac+b\delta)^2}{b(b+4c)^2\overline{g}^2} < i < \frac{(b+2c)^2(ac+b\delta)^2}{bc\overline{g}^2(b+c)(b+4c)^2}$. We consider two cases:

- Case (a): $c > \frac{1+\sqrt{17}}{8}$ From earlier discussions we know that a investment tax that changes optimal choice of g from 0 to $\overline{g}$ is welfare reducing in this case. Thus for any i in the interval $[\frac{4(ac+b\delta)^2}{b(b+4c)^2\overline{g}^2}, \frac{(b+2c)^2(ac+b\delta)^2}{bc\overline{g}^2(b+c)(b+4c)^2}]$, $g = 0$ ensures higher net welfare than $g = \overline{g}$. Moreover, we know that both regimes give equal welfare for $g = \overline{g}$. Thus in this interval of i, a tax regime ensures higher net welfare than a quota regime.

- Case (b): $c < \frac{1+\sqrt{17}}{8}$ At $i = \frac{(b+2c)^2(ac+b\delta)^2}{bc\overline{g}^2(b+c)(b+4c)^2}$, a marginal investment tax that changes optimal choice of g from 0 to $\overline{g}$ is welfare improving in this case. $\frac{w(0)-w(\overline{g})}{\overline{g}^2} = \frac{(b+3c)(ac+b\delta)^2}{2bc\overline{g}^2(b+c)(b+4c)}$ is the minimum value of i, from which a tax can improve welfare.

  Suppose, $\frac{(b+3c)(ac+b\delta)^2}{2bc\overline{g}^2(b+c)(b+4c)} < \frac{4(ac+b\delta)^2}{b(b+4c)^2\overline{g}^2}$. This implies

$$\begin{aligned} \frac{(b+3c)}{2c(b+c)} &< \frac{4}{(b+4c)} \\ \text{or} \quad (b+3c)(b+4c) &< 8c(b+c) \\ \text{or} \quad 4c^2 - bc + b^2 &< 0 \end{aligned}$$

  This inequality cannot be satisfied by any real and positive value of b and c. Thus, $\frac{(b+3c)(ac+b\delta)^2}{2bc\overline{g}^2(b+c)(b+4c)} > \frac{4(ac+b\delta)^2}{b(b+4c)^2\overline{g}^2}$.

  Thus for $i < \frac{(b+3c)(ac+b\delta)^2}{2bc\overline{g}^2(b+c)(b+4c)}$, the tax regime ensures higher welfare, where as for $i >$

$\frac{(b+3c)(ac+b\delta)^2}{2bc\overline{g}^2(b+c)(b+4c)}$, the quota regime ensures higher welfare.

3.J Appendix for section 3.4: Proof of Proposition 11

If $g \in \left[P_d^*(\delta), \overline{g}\right]$, the firm makes net loss equal to the magnitude of investment, even when optimal quota is chosen. This hold true even after introduction of uncertainty (substituting $\pi(g) = 0$ and $\pi^n = 0$ in Equation (3.4.1)). Note that $E[\Pi(P_d^*(\delta))] = -I(\delta) < 0$. Since choosing $g > P_d^*(t = \delta)$ is ruled out, the choice of g has to be from $\left[0, P_d^*(\delta)\right) \bigcup \left\{\overline{g}\right\}$.

In the range $\left[P_d^*(0), P_d^*(\delta)\right)$, the expected net profit function is:

$$E[\Pi(g)] = p.\pi(g) - I(g)$$

Using the logic used in the case with certainty, we can argue that no value of g above $P_d^*(0)$ can be optimum. This is because

$$E'[\Pi(g = P_d^*(t = \delta))] > 0$$

ensuring that there cannot be an interior solution from $\left[P_d^*(0), P_d^*(\delta)\right)$, irrespective of the curvature of expected net profit curve. Thus the global equilibrium must always be from the set $\left[0, P_d^*(0)\right] \bigcup \left\{\overline{g}\right\}$.

In the range $[0, P_d^*(0)]$,

$$\begin{aligned} E[\Pi(g)] &= p.\pi(g) + (1-p)\pi^n(g) - I(g) \\ &= \frac{4p}{b(b+4c)^2}(ac + b\delta - (b+c)g)^2 \\ &\quad + \frac{(1-p)}{4bc(b+c)}(ac - (b+c)g)^2 - i(\overline{g} - g)^2 \end{aligned}$$

The first and second derivatives with respect to g is:

$$\begin{aligned}\frac{dE[\Pi(g)]}{dg} &= -\frac{8p(b+c)}{b(b+4c)^2}(ac+b\delta-(b+c)g)-\frac{(1-p)}{2bc}(ac-(b+c)g)+2i(\overline{g}-g)\\ \frac{d^2e[\Pi(g)]}{dg^2} &= \frac{8p(b+c)^2}{(b+4c)^2}+\frac{(1-p)(b+c)}{2bc}-2i\end{aligned}$$

The expected profit curve in this range is convex if

$$i < \frac{4p(b+c)^2}{(b+4c)^2}+\frac{(1-p)(b+c)}{4bc}$$

Now,

$$\frac{dE[\Pi(g)]}{dg}\Big|_{P_d^*(0)} = -\frac{8p(b+c)}{b(b+4c)^2}b\delta+2i(\overline{g}-\frac{ac}{b+c})$$

Thus the curve is upward-sloping in the left neighborhood of $P_d^*(0)$ if

$$i < \frac{4p\delta(b+c)^2}{(b+4c)^2[(b+c)\overline{g}-ac]}$$

Thus whenever the curve is concave, it is upward sloping at $P_d^*(0)$. Then the optimum in this range is $P_d^*(0)$. When the curve is convex, the optimum for this range is one of the two corner points: 0 and $P_d^*(0)$. Thus we now have three candidates for global optimum: 0, $P_d^*(0)$ and $\overline{g}$.

Claim 1 *$P_d^*(t=0)$ cannot be the optimum for any $i>0$ and $p \in [0,1]$*

Proof: Let G_u^* and G_v^* be the values of i below which $g=0$ gives lower net profits than that obtained with $g=P_d^*(t=0)$ and $g=\overline{g}$ respectively. Note that both G_u^* and G_v^* are linear functions of p. Thus $\triangle_u(p)=G_v^*-G_u^*$ is linear in p.

Let $p=1$. Whenever $E[\Pi(P_d^*)] = e[\Pi(0)]$, the net profit curve is convex in range $[0, P_d^*(t=\delta)]$ and hence $e\Pi(P_d^*)=e\Pi(0)<0$. Hence G_v^* is to the left of G_u^*.

Let $p=0$. Thus $E[\Pi(P_d^*]<0$. Thus at $i=G_u^*$, $E[\Pi(0)]<0$. Thus G_v^* will be to the left of G_u^*.

Thus $\triangle_u(0)<0$ and $\triangle_u(1)<0$. Linearity of $\triangle_u(p)$ in p ensures that $\triangle_u(p)<0 \forall p\in[0,1]$. ■

Hence, the firm chooses 0 when $E[\Pi(0)] > E[\Pi(\overline{g})]$ and $\overline{g}$ otherwise. Thus the optimal choice of marginal cost is:

$$g^{Q_u}(i) = \begin{cases} 0, & \text{if} \quad i < \frac{1}{\overline{g}^2}[\frac{4p(ac+b\delta)^2}{b(b+4c)^2} + \frac{(1-p)a^2c^2}{4bc(b+c)}] \\ \overline{g}, & \text{otherwise} \end{cases} \tag{3.J.1}$$

4

A Note on: Equity and Communal Control: The Community Forestry Program in Nepal

4.1 Introduction

In this chapter, the central question of interest is: Are villages under communal modes of resource control less egalitarian in terms of distribution of forest resources collected, compared to villages that don't have communal control of forests? More specifically, I try to test empirically if social identity and economic circumstances are more important as determinants of resource collection in geographical units with communal modes of resource control than in those without.

Since Hardin (1968) cogently described the problem with private provisioning of impure public goods like common property resources, a large literature suggesting alternative policies to deal with the problem has come into being. The policies being recommended can be broadly classified into three groups, each suggesting a different kind of resource management, which in turn implies different schemes of ownership on common property resources (CPR). In the 1960-70s, most experts favoured state control of CPRs like forests, grazing land and water resources (Ophuls, 1973; Heilbroner, 1974; Ehrenfield, 1972; Carruthers and Stoner, 1981). It was widely believed that a benevolent social planner would internalize externalities associated with the use of CPRs and would ensure efficient use of scarce natural resources. Issues of information and costly regulation were ignored. On the other end of the ideological divide were the proponents of the free market who advocated privatization of CPRs (Demsetz, 1967; Johnson, 1972; Smith, 1981; Welch, 1983). These people argued that privatization would ensure the removal of externalities as the private owner would internalize the negative effects of resource use. However the adverse distributional consequences of such a step were often not taken into account.

Since the early 1980's a group of researchers challenged the prevailing orthodoxy by stating that while Hardin's "Tragedy of the Commons" might have elements of truth; it is not an accurate description of the situations of various local commons around the world (Acheson, 1988; Ostrom, 1990; Berkes, 1986; Bromley and Feeny, 1992; Baland and Platteau, 1996). They documented cases from round the world where users of CPRs had come together and shown cooperative behavior to ensure efficient use of CPRs. It was shown that often in situations that resemble "tragedy of the commons"; individual users have often acted cooperatively to defy simplistic game theoretic predictions. What started as a challenge to the orthodoxy of earlier times quickly established itself as the prevailing orthodoxy of the day. By the beginning of this century decentralized communal control of resource was considered to be the solution for all forms of CPR management problems. What was often ignored was the distributional performance of various modes of resource control. These issues of distributional fairness are of great importance in developing countries like Nepal and India because a large section of rural poor directly depend on environmental resources for their livelihood. In this paper I investigate whether communal control systems are more or less egalitarian than resources controlled by state.

This study deals with the community forestry program in Nepal. In 1978, the government of Nepal formally launched a program of community forest management that recognizes use rights of local people in the management of forests. This marked a major shift in the government of Nepal's policy of nationalizing forests since 1957. In the face of acute deforestation that happened during the phase of state control, the new Forest Policy of 1978 promoted people's participation in the development and protection of forests. The initial success of communal forestry ensured that the program quickly spread and several legislative measures were taken to strengthen the institution. By 2002, 847,282 hectares of forest land was being managed by 10,969 community forest user groups (CFUG) across Nepal. Around 15 percent of total forest land is now managed by CFUGs with little state intervention (Acharya, 2002). In Nepal, all accessible forests are to be handed over to users without any limitation on area, geography and time under the community forestry programme. Thus the presence of a community forest in a ward (the smallest administrative unit in Nepal), conditional on the presence of forests, depends largely on the accessibility of the ward from centres of forest administration (Edmonds, 2002). Since forest user groups are formed by officials, the problem of self selection is limited.

There might be several reasons for a changed distributional outcome due to a change in resource regime. It has been widely documented that the history of state control of forests is also a history of widespread forest degradation. It was suggested that heavy deforestation occurred during the years following the nationalisation because people felt that their forest had been taken away from them (Gilmour, King, and Hobley, 1989). Since the government did not have the ability to monitor and control collection, forests were in effect converted to open access resources. It might be the case that as free entry ensured zero rents, the village elite had no incentive to monitor and control collection. On the other hand restrictions on entry imposed by communitarian regimes creates possibilities for rent and hence creates an environment where the community elite has an incentive to restrict forest use by the marginalized within the community. Besides as policy making process at the village level was free from the scrutiny of national media and civil society, it might have been easier to adopt policies that adversely affected the poor. Bardhan (2010) points out two reasons why elite capture might increase in a decentralized environment:

1. In a decentralized environment, the elite find it is easier to form collusions at a proximate local level. Under a centralized structure, there is more competition among disparate group and it is costlier to form collusions.

2. Besides, there is also greater media scrutiny of malfeasance of central governments and civil society institutions are often weak in poor backward regions.

Bardhan (2010) also mentions that when the elite cannot capture access to public goods [1], there is a danger of the elite seceding from the system. In absence of active support from the elite, the institutional structure at the local level might collapse. This is specially the case in situations where local institutions are dependent on the resources and technical expertise of the elite. The non-elite can foresee this sequence of events and hence might accept elite capture to sustain local level institutions.

Mukarji (1989), on the other hand, feels that in a democracy, centralized state control enhances the possibility of elite capture as the poor are required to organize a larger geographical unit before exercising power. In other words, centralization increases the cost of participation in political process and thus creates opportunities for elite capture. He suggests that empirical evidence from the Indian states of Karnataka and West Bengal prove that decentralization of power enhances the ability of the poor to participate in the political process.

In this chapter, I try to test empirically if ethnicity and economic circumstances are more important as determinants of resource collection in wards with community forestry than in those without. The next section focuses on the existing literature on inequality and decentralized communal control. Section 4.3 explains the history and nature of the community forestry program in Nepal while section 4.4 gives an idea of the social hierarchies that shape intergroup inequality in Nepal. Section 4.5 explains the data sources and section 4.6 discusses the empirical results. Section 4.7 concludes.

4.2 Review of Existing Literature

There is a huge literature on the relationship between inequality and cooperative communal control of common property resources (Olson, 1965; Bardhan, Ghatak, and Karaivanov, 2007; Bardhan, 2000; Dayton-Johnson, 1998; Mukhopadhyay, 2008). However studies on the impact of a resource control regime on the distribution of resource collected is much harder to come

[1] The argument holds good for impure public goods like common property resources as well.

by. Most studies on this issue look at inequities across income levels, often neglecting inequities across social groups. Studying equity issues in community forestry in the middle hills of Nepal, Adhikari (2008) observes “Local elites are found to be advantaged in both accessing the decision making committee and extracting benefits from the forest”. Sociologists writing on community control programs in India have often observed that such programs benefit the rural elite at the cost of the marginalized: poor, women and Dalits. Omvedt (1997) documents how Hadis (an untouchable caste) were not allowed to fish in the Chilka Lake (Orissa) when fishing in the area was communally organized. She notes how things improved for the Hadis when the Tatas[2] took control of fishing in the area to encourage prawn cultivation. The entry of the Tatas was opposed by the Ketuas, the dominant fishing community in Chilka. She also gives examples of communally controlled traditional irrigation systems in Maharashtra. She writes: “Much today is written about traditional water harvesting systems. One example of these is the phad system in Maharashtra, and it seems to be what all environmentalists say it was: ecologically sustainable and providing equal water access to all cultivators. What is usually not said is that only ‘cultivators’ had the right to water - Other Backward Class artisans and untouchable service castes of the village, who were socially excluded from cultivation, were also excluded from water rights. Raising questions of equal water rights or land to the tiller entails challenging tradition as well as the current capitalist structures of domination, but the silence of most environmental descriptions here is disturbing.”

Sundar (2000) argues that community forestry schemes like joint forest management (JFM) in India, adversely affect the poor by closing access to nearby forests. The rich who have access to alternate sources of firewood and can afford non-biomass fuels are not affected. Sarin, Ray, Raju, Chatterjee, Bannerjee, and Hiremath (1998); Kumar (2002) support the view of Sundar (2000). Agarwal (2001) studies issues of gender equity and observes that women, who have no role in the decision making process of JFM, is the group that is most adversely affected by JFMs. Agarwal (2007) shows that women-who are the household members with the responsibility of firewood collection-often have to bear large share of costs associated with community forestry. In Nepal, studies have shown that many of the forest user groups suffer from elite

[2] An industrial house in India

capture. Low castes and the poor are often excluded from the decision making process, which ensure that funds are often invested in projects that are advantageous for the rich (Banjade, Luintel, and Neupane, 2004; Malla, Neupane, and Branney, 2003; Timsina, 2003).

Though these studies highlight the existing inequities under communal management of resources, they don't study how such systems perform compared to other modes of resource control like centralized state control, private ownership in terms of equity. There is a huge literature that documents the marginalization of poor people when CPRs are explicitly or implicitly controlled by the state. In a case study based on two villages in the Pyuthan district of Nepal, Khatri-Chetri (2008) compares the distribution of non timber forest products (NTFP) collection in a village with self initiated forest user group (Informal FUG) to one with government initiated forest user group (Formal FUG). Khatri-Chetri (2008) observes "In a comparison between the two institutions, the poorer households pay a higher cost for forest resource extraction than do the rich due to the ban on seasonal NTFP extraction in the formal FUG-managed system". Guha and Gadgil (1993) and Rangarajan (1996) document how nationalization of forests in British India led to a loss of livelihood and forest rights of rural poor in Uttarakhand and Central India respectively. It was also shown how the forest administration collaborated with the elite in this process of marginalization. Guha and Gadgil (1993) cites Brara (1987) to provide an example where state control of common property resources has "hastened the process of privatisation and degradation". Brara's case study of Rajasthan suggests that the derecognition of traditional CPR institutions created incentives for the rural rich to encroach on common land and get them 'regularized'. Thus destruction of communitarian institutions in Rajasthan was "intimately connected with the declining fortunes of the rural poor". Similarly, Ribot (1995) shows how a century of centralized forestry policies have excluded Senegal's forest villagers from charcoal production and marketing and has ensured a skewed distribution of the income generated from exploitation of forest resources.

Since the literature on CPRs show inequality in resource extraction in both state governed and community managed CPRs, it is important to compare the magnitude of inequality in these regimes. While inequity might be a reality in areas under communal ownership, its magnitude might be lower than what exists under other modes of resource control.

4.3 A Brief Sketch of Community Forestry in Nepal

According to Hobley (1996), the history of forestry in Nepal can be divided into three eras: a period of private control of forests till 1956, to be followed by a period of centralized state control till 1978, when it was discarded in favour of community forestry.

The period before 1957 was an era marked by private and communal control of forests. In this period, the government encouraged individuals to convert forestland to agriculture. In the mountains and hills, talukdars (village headman appointed by the ruling family of Nepal-the Ranas) had the responsibility of regulating forest use, but there was hardly any restriction on forest product extraction for subsistence (Mathema, Shrestha, and Sthapit, 1999). In the Terai plains, forests were left undisturbed till 1920s. With the rise of timber demand from the colonial government in India, the government started clearing forest to export timber for revenue purposes (Joshi, 1993). Besides this many forest-land were given as 'birtas' to members of Rana family and as 'jagir' to influential officials. According to one estimate, almost one-third of total forests and cultivated lands were under 'birta' tenure by 1950, 75% of that belonged to the Ranas (Joshi, 1993). According to some writers, though most forest was owned by the ruling classes, forests in many places were managed by local population (Ojha, Subedi, Dhungana, and Paudel, 2008). In many places there existed a form of land tenure called Kirat in which land was considered as the common property of the local ethnic group and was managed from within the ethnic group's organization (Fisher, 1989). In other words, local populations had developed rules of forest management, though in all probability such rules reflected the realities of patron-client relationship between the owners and users of forests.

After the Rana government was overthrown in the 1950s, the new government of Nepal nationalized all forests in 1957 through the Private Forests (Nationalization) Act. Nationalization was expected to prevent destruction of forests and ensure protection, maintenance and utilization of privately owned forests. However critics argued that nationalization destroyed the indigenous forest management systems depriving the local people of their right to manage and benefit from the forests and as a result forests effectively became open access resources (Hobley, 1985; Messerschmidt, Richard, Srestha, Rayamajhi, and Gautam, 1994; Palit, 1996). There are others who argue nationalization was necessary to prevent the deposed Rana rulers from using the Terai forests as private property and that deforestation followed because the government was not prepared to assume the management responsibilities of newly formalized forest ownership after nationalization.

In response to the rapid deforestation that followed nationalization, the government drafted a national forestry plan in 1976 that recognized the role of local communities and emphasized the importance of local people's participation in forest management. This represented a major shift in Nepal's forestry policy. The Community Forestry (CF) programme was formally launched in Nepal in 1978 with the enactment of the Panchayat Forest Rules and the Panchayat Protected Forest Rules. From 1978, there have been several legislative changes aimed at facilitating the handing over of management responsibility of the government controlled lands to local populations. The process was more or less progressive towards formulation of legal base until the promulgation of the Forest Act of 1993. The Forest Act of 1993 provided full authority to the users for management of forest resources and can be regarded as one end of a co-management spectrum between the Government and forest users. It recognized the dominant role of local people in the decision-making process and provided grounds for benefiting local people from forest management.

According to Acharya (2002), the most important characteristics of the community forestry (CF) program in Nepal are:

1. all accessible forests can be handed over to users without any limitation on area, geography and time.

2. land ownership remains with the state, while the land use rights belong to the community forest user groups (CFUGs).

3. all management decisions (land management and forest management) are taken by the CFUGs.
4. each member of the CFUG has equal rights over the resources.
5. each household is recognized as a unit for the membership.
6. CFUGs will not be affected by political boundaries.
7. outsiders are excluded from access.
8. there are mutually recognized user-rights.
9. there will be an equitable distribution of benefits.
10. the State provides technical assistance and advice.

The role of community forestry in reducing deforestation and pressure on forest resources in Nepal is well documented (Schereier, Brown, Schmidt, Srestha, Nakarmi, Subba, and Wymann, 1994; Virgo and Subba, 1994; Jackson, Tamrakar, Hunt, and Shepherd, 1998; Edmonds, 2002). These studies (though often based on small areas in the middle hills) show improving forest conditions after implementation of community forest programs. According to Edmonds (2002), transferring of forests to local groups is associated with a significant reduction in resource extraction. This clearly shows the causal impact of community forestry on resource extraction and it's beneficial impact on the state of forests in Nepal.

While it is important to note that communal control can coexist with unequal and unjust distribution (Adhikari, 2008; Khatri-Chetri, 2008), it is more important to study how communal modes of resource control compare to centralized state control in terms of its distributional effects. This is important from a policy perspective. If community forest management fares as badly as government forests in terms of distribution, then one can make an unqualified case for community forests on the grounds that it is pretty well established that their perform better in preventing deforestation. On the other hand, if community control enhances existing inequities of resource use, then policy makers must make a trade-off between efficiency and equity.

4.4 Caste and Horizontal Inequality in Nepal

Nepal being a country based on agriculture (around 80 percent directly involved in agriculture), economic inequality is expected to be closely related to skewness in land distribution. According to the 2001 population census about one million households in Nepal do not own agricultural land, and over two hundred thousand households do not even own homestead land plots. Table 4.4.1 below shows the distribution of land in Nepal during 2001-02 census.

Size in hectares →	< 0.5	< 1	< 2	< 3	< 4	< 5	< 10	> 10
Percentage of Holding	47	74	92	96	98	98	99	99
Percentage of Land	15	39	69	83	89	93	98	100

Table 4.4.1: Distribution of Agricultural Holdings in Nepal during 2001-2002

Source: Sharma (2009) cites Central Bureau of Statistics (2003)

As is evident from the table that the level of inequality is moderately high. Besides land, inequality finds expression in the form of differential access to education, health and employment opportunity (Sharma, 2009). There is a great deal of caste inequality that exists in Nepal. According to the 1991 census, 81 percent of population in Nepal are Hindus. For the last few centuries, all Nepalis including non Hindus have been socially defined through the prism of caste system (Bennett, Dahal, and Govindswamy, 2008). At the top of the social ladder are the Brahmins, Chetris, Upper Caste Madhesis and Newars. Below these group are the various indigenous groups (Janjatis) belonging to the Tibeto-Burman language group. This group were further classified into two groups: those who were enslavable (Bhote, Chepang, Gharti, Hayu, Tharu) and non-enslavable (Gurung, Magar, Newar). At the lowest rung of the social ladder were the Dalits or the 'untouchable' castes like Kami (blacksmiths), Damai (tailor/musicians) and the Sarki (cobblers). Missing from this hierarchy are many castes and groups from the Terais. Given that this paper deals with the mountainous and middle hills of Nepal, we avoid an explanation of their position in this hierarchy.

Table 4.4.2 presents inequality across caste lines, a powerful form of horizontal inequality. It compares the economic achievements of Brahmins-the group belonging to the highest rung of the caste hierarchy to the economic achievements of the two marginalized groups- Dalits and Janjatis.

Human Development Indicators	**Nepal**	**Brahmin**	**Hill Janjatis**	**Dalit**
Life Expectancy	55	60.8	53	50.3
Adult Literacy	36.72	58	35.2	23.8
Mean Years of Schooling (1996)	2.254	4.647	2.021	1.228
Per Capita Income(NRs) (1996)	7673	9921	6607	4940
Per Capita PPP (US $) (1996)	1186	1533	1021	764
HDI	0.325	0.441	0.299	0.239
Ratio to national HDI	100	135.87	92.21	73.62

Table 4.4.2: Human Development by Caste and Ethnicity
Source: Pradhan and Srestha (2005) cites from NESAC, Nepal Human Development Report (Nepal South Asian Centre (NESAC), Kathmandu 1998) and J. Gurung, Promotion of Sociocultural, Economic and Political Participation of Dalits and Other Disadvantaged Groups: A Strategic Approach (Draft).

Note: Hill Janjatis include only, Sherpa, Gurung, Magar, Rai and Limbu. The Dalit category includes Dalits from the hills and tarai

This divide between ethnic groups extends to the political and administrative class as well. Table 4.4.3 shows the representation of different castes in the administrative apparatus of Nepal.

Given such skewed representation of marginalized groups in Nepal's administrative machinery, it might be the case that forest policies will be designed to serve the interests of the elite. Our question of interest is important as it tries to identify the regime under which elite capture is greater.

4.5 Data

This paper uses data from Round 2 of Nepal Living Standard Survey (NLSS2) [3]. The cross sectional survey enquiry was carried out in the whole of Nepal in 2003 – 2004. NLSS follows

[3]The Development Economics Research Group of the World Bank conducts Living Standards Measurement Study (LSMS) Surveys in many countries. The LSMS survey for Nepal is called the Nepal Living Standard Survey

High Level Officials in:	**Brahmins and Chetris**	**Hill Janjatis**	**Dalit**
Judiciary	80.85%	1.28%	0%
Constitutional Body and Commissions	77.02%	1.70%	0%
Council of Ministers	56%	8%	0%
Public Administration	62.50%	12.50%	0%
Legislature	60%	13.58%	1.51%[a]
Political Parties	58.79%	15.15%	0%
DPCC President, Municipality Mayor, Vice- Mayor	55.50%	12.04%	0%
Industry and Trade Sector	16.67%	0%	0%
Education Sector	77.32%	2.06%	1.03%
Cultural Sector	75.22%	5.31%	0%
Science and Technology	58.06%	3.23%	0%
Civil Society Sector	66.13%	1.61%	0%
Total Percentage	66.5	7.1	0.3
% of population	31.6	22.2[b]	8.7[c]
Difference	34.9	-15.1	-8.4

Table 4.4.3: Integrated National Caste-Ethnicity Index of Governance, 1999
Source: Pradhan and Srestha (2005). Adapted from G. Neupane, Nepalko Jatiya Samasya. Samajik Banot ra Sajhedariko Sambhavana. (Caste/ethnic problems in Nepal. Social Structure and the Possibility of Cooperation) (Centre for Development Studies, Kathmandu 2000).

Note: [a] Nominated members of the Upper House; [b] Not inclusive of all Janjatis; [c] Includes hill Dalits only

a two stage stratified sampling technique to select a nationally representative sample.

The 2001 Population Census of Nepal provided the sampling frame for this survey. The size of each ward (as measured by number of households) was taken as a unit of sample frame.The resulting sampling frame consisted of 36,067 enumeration areas (wards or sub-wards).

The sample size for the NLSS2 is 3912 second stage sampling units (households) from 326 first stage sampling units (wards). The NLSS2 cross-section sample was allocated into six explicit strata as follows: Mountains, Kathmandu valley urban, Other Urban areas in the Hills, Rural Hills, Urban Tarai and Rural Tarai.

		Mean	Standard Deviation
Household Variables	**No. of Households**		
Cooking Energy Consumed (in Kilocalories)	1523	1574310	1087229
Firewood collected in *bharis*	1523	85.194	55.366
Firewood bought (in Kilograms)	1523	146.215	997.456
	1523		
Household Size	1523	5.018	2.237
Dummy: Poor	1523	0.337	0.473
Per Capita Expenditure (excl. Fuel) in 1000 Nepali rupees	1523	15.241	14.405
Dummy: Land Ownership	1523	0.936	0.245
Value of land owned(in 1000 Nepali rupees)	1523	276.333	560.988
Dummy: Dalit	1523	0.125	0.331
Dummy: Janjati	1523	0.359	0.480
Dummy: Access to Piped Water	1523	0.666	0.472
Dummy: Kerosene Purchased	1523	0.912	0.283
Dummy: Open Stove	1523	0.542	0.498
Dummy: Presence of kitchen garden	1523	0.758	0.428
Dummy: Pakka Roof	1523	0.533	0.499
Dummy: Access to Irrigated Land	1523	0.561	0.496
Time taken to reach paved road (in minutes)	1523	1345.635	2188.696
Dummy: Access to Road	1523	0.325	0.469
Ward- VDC level Variables	**No. of Wards**		
Dummy: Community Forestry-FUG	127	0.582	0.495
Dummy: Police Station	127	0.134	0.342
Dummy: Post Office	127	0.890	0.314
Dummy: Telephone Service	127	0.299	0.460
Dummy: Paved Road	127	0.150	0.358
Dummy: Krishi (Agricultural) Centre	127	0.157	0.366
Dummy: Bank Branch Office	127	0.079	0.270
Distance to Forest	127	95.953	195.982
Dummy: Electricity in Ward	127	0.425	0.496
Dummy : Ward in Maoist Affected District	127	0.457	0.500

Table 4.5.1: Mean Value of Variables

Note: 1 US dollar ≈ 73 Nepali Rupees in 2004-05.The description of each of the variables can be found in Appendix 4.A.

The primary sampling unit of this survey is the ward.[4] Within each geographical stratum, wards have been selected on the basis of their population. The likelihood that a ward selected was proportional to the number of people living in that ward. Within each ward, 12 households were interviewed. In this way data was collected from 3912 households from 326 wards of the country. For my study, I only include rural households from non-Terai regions of Nepal. After dropping households from urban and terai regions of Nepal, the sample size is 1524 rural households from 127 rural wards of non-terai regions of Nepal. Of the 127 wards in the sample, 74 (58.27% of total number of wards) report the presence of a forest user group.[5]

Table 4.5.1 describes the data in greater detail.

4.6 Results

The hypothesis we want to test is whether a shift to community forestry changes the relationship between firewood collection and economic (or social) status in a way that adversely effects the poor or the socially marginalized. We initially assume a linear regression model that satisfies all the classical assumptions. While the amount of firewood collected in *bharis* is the dependent variables, the explanatory covariates are:

- A measure of economic well being of the household: Per-capita non-fuel expenditure of the household (in 1000 Nepali rupees).[6]
- A dummy indicating the presence of a community forest user group (FUG) in the village of the household.
- The interaction of the above two variables.

Our parameter of interest is the coefficient of the third variable. A positive and significant coefficient indicates either of the two situations:

[4]A ward is the lowest administrative unit in Nepal. It is similar to the concept of village in India. An average of nine wards constitute a village development committee (VDC). There are 3913 VDCs spread over 75 districts of Nepal.

[5]Throughout this chapter, whenever I say 'clustered standard errors', I mean 'standard errors clustered at a ward level'.

[6]Fuel expenditure is excluded to reduce the problem of potential endogeneity

- If the non-poor collect more firewood than the poor in a non-community forestry situation, then the difference increases when there is a regime change and the forests are transferred to the community.

- If the non-poor collect less firewood than the poor in a non-community forestry situation, then the difference dampens when there is a regime change and the forests are transferred to the community.

In either of the two situations the poor are worse off compared to their initial situation, vis a vis the non-poor. The average reduction of firewood collection for the poor exceeds the reduction made by the non-poor. The results of the simple linear model estimated using ordinary least squares is reported below in Table 4.6.1.

Dependent Variable: Firewood Collected (in *bharis*)	
Community Forestry: FUG (Dummy)	-15.963
	(2.32)**
PC Expenditure (In 1000 Nepali rupees)	-0.775
	(4.47)***
Community Forestry* PC Expenditure (excl. Fuel)	0.652
	(3.18)***
Constant	100.242
	(18.04)***
Observations	1523
Number of Clusters	127
R-squared	0.02
Cluster robust t statistics in parentheses	
*significant at 10%, **significant at 5%, *** significant at 1% (all for a two tailed test)	

Table 4.6.1: OLS Regression of firewood collected on basic controls.
Note: 1 US dollar ≈ 73 Nepali Rupees in 2004-05.

In Table 4.6.1, we consider the just three regressors. We have a dummy variable that takes the value 1 when the household lives in a ward that reports to have community forestry i.e. reports the presence of a forest user group. We also include the per capita expenditure measured in 1000 Nepali rupees as an indicator of the household's economic status. We exclude the fuel expenditure from total expenditure to reduce the problem of endogeneity. We also include the interaction of these two variables. The coefficient of the FUG dummy is negative and significant indicating that a shift to FUG regime reduces firewood collection by households. It is the coefficient of the interaction term that is of interest. Table 4.6.1 shows that the coefficient is positive and highly significant. This implies that people with different per-capita expenditure are not affected similarly due to a change in forest management regime. The reduction faced by the poor is larger than the reduction faced by the non-poor. The positive coefficient of 0.652 indicates that an increase in per capita expenditure by 1000 Nepali rupees, reduces the gap between FUG and non-FUG collection by 0.652 *bharis.* I also introduce square and cube of per capita expenditure and their interaction with the community forestry dummy in the regression, but they always turn out to be insignificant. Hence those regressions are not reported in the text.[7]

In figure 4.6.1 below, we show the forecasted firewood collection for different values of per capita expenditure under the two regimes: regime with forest user groups (FUGs) and regime without FUGs.[8] The curves for the non-FUG scenario is downward sloping in accordance with the poverty environment hypothesis. However the curve is flat under the FUG scenario [9]. The FUG curve starts below the non-FUG curve but crosses the later from below at a per capita expenditure level of Rs.24,483. For per capita expenditure levels above this cut off a shift to FUG regime leads to higher firewood collection. In figure 4.6.3, we show the proportional decile in firewood collection due to a regime change towards community forestry as a percentage of per capita expenditure. This curve is upward sloping and convex. This seems to suggest that it is the poor who bear the major burden arising from reduced firewood collection in a FUG regime.

Table 4.6.1 seems to suggest that the economically disadvantaged reduce their consumption of firewood when a ward becomes an FUG ward. Thus it is the poor who actually bear the brunt of forest conservation. However estimates obtained from such simple regressions might be inconsistent as FUG and non-FUG households might be systematically different in terms of various variables like access to alternative fuels and other facilities. Unless all such

[7]Results of these regressions can be found in Table 4.E.1.

[8]We restrict our attention to the range staring from the 5th percentile to the 95th percentile of the per capita expenditure distribution.

[9]Working with the same data, Baland, Bardhan, Das, Mookherjee, and Sarkar (2010) find no evidence for poverty-environment hypothesis. However their analysis involved the whole of Nepal, while this study excludes the Terai Region. Besides introduction of household size as an explanatory variable without introducing community forestry as an explanatory variable makes the negative coefficient of per capita expenditure insignificant.

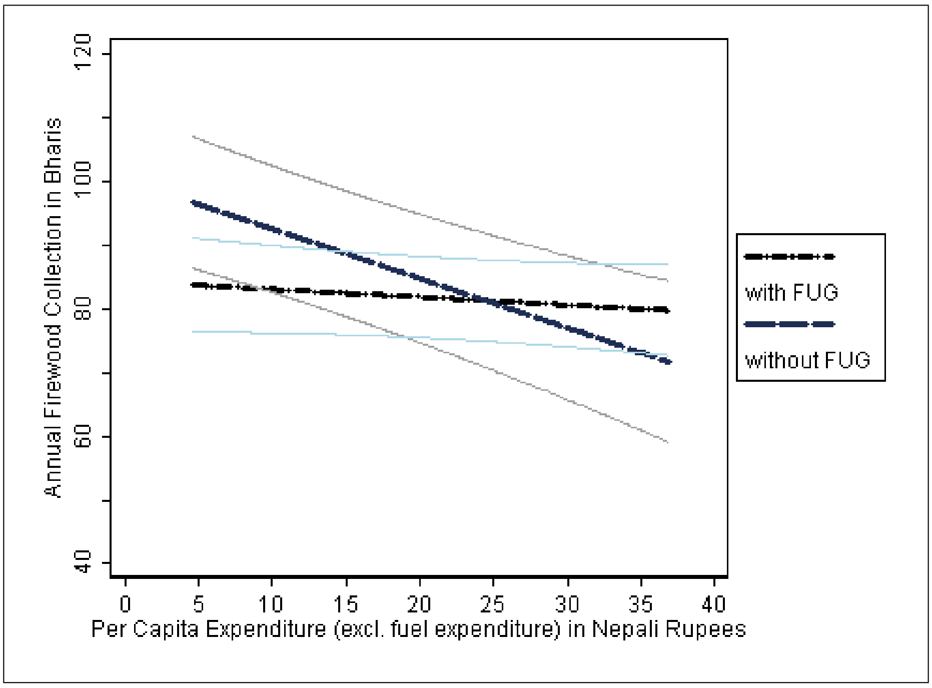

Figure 4.6.1: Predicted Firewood Collection under the two regimes (as a function of per capita expenditure)

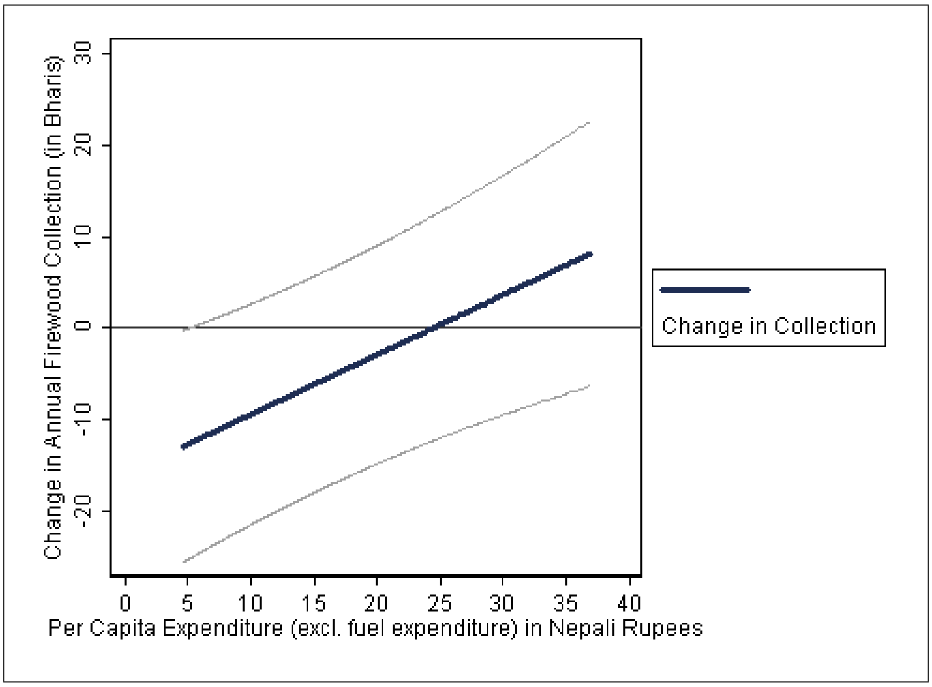

Figure 4.6.2: Predicted absolute change in firewood collection due to a shift to FUG regime (as a function of per capita expenditure)

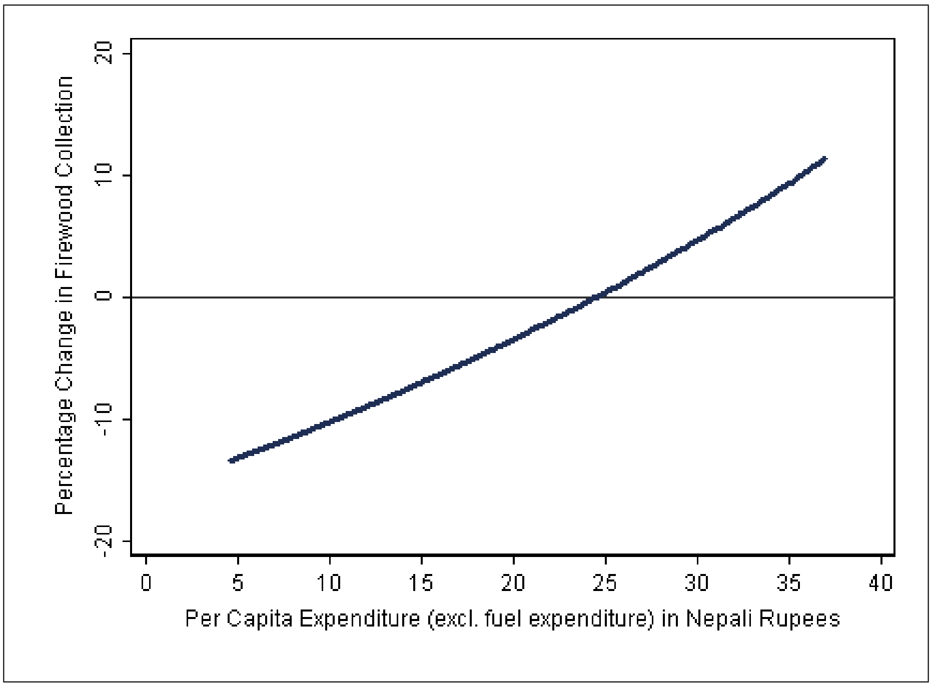

Figure 4.6.3: Predicted change in firewood collection as a proportion of predicted collection in absence of FUG (as a function of per capita expenditure)
[Percentage decline in firewood collection $= \frac{\text{Change in firewood collection due to regime change}}{\text{Predicted firewood collection in a non CF regime}} * 100$]

things are taken into account, we might wrongly attribute to FUG presence what is actually arising from other sources.

Table 4.6.2 shows that there are some systematic differences between FUG households and non-FUG households. FUG households are more likely to be classified as 'non-poor', compared to non FUG households. The caste composition of the two categories are also different. A non-FUG household has a higher probability of being a Janjati household. There also exists significant differences with respect to access to piped water and electricity. We thus try to incorporate such controls into the regression exercise, to correctly identify the impact of community forestry. Table 4.6.3 shows the results of the OLS regressions with various alternative set of controls.

In column (1) of Table 4.6.3, we include 3 additional control variables in addition to the existing controls of per capita expenditure, community forestry and the interaction of the two. These are household size, distance to the nearby forest and a dummy indicating land

Variables	Without FUG	With FUG	Difference
	(S.E)	(S.E)	(t-stat)
Cooking Energy used in Kilocalories	1642767	1522058	-120708.6
	(838880.74)	(62434.18)	(1.15)
Firewood collected in *bharis*	88.911	82.302	-6.609
	(5.234)	(3.314)	(1.07)
Firewood Bought in Kgs.	132.556	148.87	16.32
	(43.837)	(43.683)	(0.26)
Household Variables			
Household Size	5.075	4.937	0.527
	(0.112)	(0.095)	(0.20)
Dummy: Poor	0.398	0.300	-0.099**
	(0.038)	(0.027)	(2.10)
Per Capita Expenditure (In 1000 Nepali rupees)	14.620	16.076	1.455
	(1.050)	(0.799)	(1.10)
Dummy: Land Ownership	0.919	0.939	0.020
	(0.021)	(0.012)	(0.79)
Value of land owned(in 1000 Nepali rupees)	277.034	277.190	0.155
	(49.613)	(20.983)	(0.00)
Dummy: Dalit	0.121	0.130	0.009
	(0.022)	(0.020)	(0.31)
Dummy Janjati	0.423	0.322	-0.102*
	(0.049)	(0.037)	(1.64)
Dummy: Access to Piped Water	0.566	0.736	0.169***
	(0.052)	(0.030)	(2.82)
Dummy: Kerosene Purchased	0.927	0.911	-0.016
	(0.018)	(0.021)	(0.57)
Dummy: Open Stove	0.528	0.550	0.021
	(0.049)	(0.038)	(0.35)
Dummy: Presence of kitchen garden	0.703	0.800	0.097**
	(0.040)	(0.028)	(1.98)
Dummy: Pakka Roof	0.476	0.575	0.098
	(0.051)	(0.042)	(1.49)
Dummy: Access to Irrigated Land	0.504	0.584	0.080
	(0.040)	(0.034)	(1.51)
Time taken to reach paved road (in minutes)	1260.255	1141.319	-118.936
	(291.87)	(188.512)	(0.34)
Dummy: Access to Road	0.319	0.342	0.023
	(0.063)	(0.053)	(0.28)

Table 4.6.2: Characteristics by Community Forestry Location

The number of wards with FUG is 74, which is 58.27% of the total number of wards. Note: Cluster Robust Standard Errors are reported within parenthesis in column (1) and column (2) respectively. In column (3) t statistics are reported for the hypothesis that the means in column (1) and (2) are equal. *** significant at 1% level, ** significant at 5% level and * significant at 10% level. The construction of the various variables are described in Appendix 4.A.

Variables	Without FUG	With FUG	Difference
	(S.E)	(S.E)	(t-stat)
Ward-VDC Level Variables			
Distance to forest	96.196	116.958	20.76
	(13.792)	(42.266)	(0.47)
Dummy: Electricity in Ward	0.214	0.453	0.239***
	(0.056)	(0.067)	(2.72)
Dummy: Village in Maoist Affected Districts	0.428	0.463	0.035
	(0.082)	(0.067)	(0.34)
Dummy: Police Station	0.084	0.081	-0.003
	(0.034)	(0.029)	(0.07)
Dummy: Post Office	0.867	0.902	0.034
	(0.059)	(0.035)	(0.50)
Dummy: Telephone Service	0.229	0.256	0.027
	(0.062)	(0.056)	(0.32)
Dummy: Paved Road	0.124	0.085	-0.039
	(0.042)	(0.033)	(0.73)
Dummy: Krishi (Agricultural) Centre	0.085	0.158	0.073
	(0.035)	(0.050)	(1.20)
Dummy: Bank Branch Office	0.033	0.082	0.048
	(0.020)	(0.034)	(1.21)

Continuation of Table 4.6.2

ownership.[10] The coefficient of FUG dummy is negative and significant as before indicating that FUG formation has a significant influence in reducing firewood collection. Household size and land ownership both have a positive and significant coefficients. As expected distance to forests have a negative impact on collection implying that further the forests from the ward, lower the collection.[11] However the coefficient of interest i.e. the interaction term between per capita expenditure and community forestry continue to be positive and significant. In fact the coefficient of the interaction term has a greater magnitude than the coefficient of per capita expenditure indicating that there exists a positive relationship between firewood collection and per-capita expenditure under FUG regime.

[10]In addition to this we include dummy variables indicating the month of interview in all regressions. This is important as the household questionnaire asks each household *On average, how many bharis/carts of firewood did you collect each month in the past one year?*. Since collection varies widely over different months of a year and rural households have imperfect recall, it might be that respondents answers are effected by the time in which they are interviewed. Since the survey happened over a span of one year, I include dummy variables to indicate month of survey (*Baisakh* is the omitted month). Edmonds (2002) employs a similar strategy.

[11]I did not include "time to collect an average *bhari*" as a variable in place of distance to forest as such information is only available for the households collecting firewood. Restricting the sample to collecting households will bias the results. Besides distance to forest is expected to be more exogenous than "time too collect a bhari", which is expected to have a simultaneous relationship with the amount of firewood collected.

In column (2) and (3), we add a few more variable each representing the household's economic status. The FUG dummy continues to be negative and significant. As expected, household using energy inefficient open stoves collect more firewood compared to those who do not. However purchase of kerosene does not have a negative impact on collection. This seems to suggest that kerosene is a lighting fuel in rural Nepal and does not substitute for biomass cooking fuels like firewood. Households who have better access to paved roads collect lower amount of firewood suggesting closeness to towns and urban centres can reduce collection. Of the two caste variables, the one for Janjatis turn out to be positive and significant, while Dalit dummy is not significantly different from zero. In column (2) and (3), the coefficient of the interaction term is positive but insignificant for a two tailed test. However if one believes that the poor are likely to be more adversely affected due to a FUG regime, the proper test should be one where the null hypothesis is that the coefficient of the interaction term is negative. The alternate hypothesis is that the coefficient is strictly positive. The coefficient of the interaction term is significant at a 10% level of significance for such a one-tailed test.

In column(4) and (5), we add two more variables indicating the household's economic status: access to piped water and a dummy indicating a pakka roof. Also included are a host of ward/VDC/district level variables indicating remoteness and the quality of public infrastructure in each ward. Including these characteristics are important as they may be important determinants for location of community forestry. Edmonds (2002) suggests that remoteness or the lack of it is the factor that determines the location of forest user groups in Nepal.[12] Access to piped water and pakka roof have insignificant negative coefficients. The coefficient of being a electrified ward is also insignificant. Most of the VDC level variables are insignificant. However the presence of a bank branch in the VDC reduces the collection of firewood by the households. Lastly being in a Maoist district reduces collection.[13] The coefficient of the FUG dummy and its interaction with the per capita expenditure have their expected signs. However they lose their significance when a two tailed test is considered. However for a one tailed test of kind mentioned earlier, the effect is significant at a 10% level of significance. In

[12] Edmonds (2002) study is restricted to the Arun River Valley in Nepal.

[13] According to the specification in column (5), 82% of the population experience a reduction in collection as we move from a non-FUG regime to FUG regime.

all the specification, the magnitude of the coefficient for the interaction term is higher than the coefficient for per-capita expenditure. Thus there is a positive relationship between firewood collection and per-capita expenditure under the FUG regime. The coefficients of the two terms indicate that all other variables (variables other than FUG dummy, per capita expenditure and their interaction) remaining constant at some level, the curves depicting the relationship between firewood collection and per-capita expenditure intersects each other at Rs 21,000 Nepali Rupees, which constitutes the 82nd percentile of per-capita expenditure distribution.[14] These regressions suggest that the while formation of FUG restricts firewood collection, the impact is largest on the poor as they do not have access to alternative sources of firewood like trees on private lands and private forests.

Till now economic disadvantage was considered to be the dimension in which inequality exists. However in the column from (5) to (10) caste is assumed to be the dimension along which inequality exists. We interact the caste dummies with the community forestry dummy and observe the sign of these interaction terms. As before I try out different specifications i.e. different set of controls. The Dalit dummy and its interaction with the FUG dummy are insignificant in all specifications, indicating that the collection behaviour of Dalits are similar to that of others in both a FUG regime and a non-FUG regime. The Janjati dummy is positive and significant in all specifications indicating that Janjatis (tribes) collect more firewood than others in a non FUG regime. However the coefficient of the interaction term (FUG* Janjati) is negative but insignificant in all the specifications. Thus the data seems to suggest that community forestry does not effect the distribution of firewood collection across castes. However the coefficient of the interaction between Janjati dummy and FUG dummy is large (It is in the range of 9-10). Thus the coefficient of the interaction term has to be substantially large (around 18-20 *bharis*) to be statistically significant. Given that the mean collection of firewood is around 85 *bharis*, such an effect is large (around 20 % of mean collection) and highly implausible. Thus we can conclude that the data does not have enough information to detect an economically significant effect. However the standard deviation for the coefficient of the interaction between Dalit dummy and FUG dummy is not high and we can conclude that

[14]Details of the per-capita expenditure distribution can be found in Appendix 4.D

the effect is two small to matter in an economic sense.

Column(11) to Column(15) are a replication of the first five columns of Table 4.6.3, with the square of per capita expenditure added as an additional variable. In each of the columns (11) to (15)), the coefficient of the interaction between per-capita expenditure and the dummy for community forestry is positive and significant. Column(16) to Column(18) are a replication of columns (8), column(9) and column(10) of Table 4.6.3 respectively, with the square of per capita expenditure added as an additional variable. In each of the columns (16) to (18), the interaction of the Dalit/ Janjati dummy with the FUG dummy is insignificant.

Till now we have used classical regression techniques. However the distribution of firewood collection is left censored at 0 and has a large mass at this point. Around 7 percent of the population does not collect firewood , which is approximately equal to the percentage of people who do not report firewood as their main cooking fuel. The correlation between the dummy denoting firewood collection and per capita expenditure is negative and significant. Thus the earlier analysis has the usual problems of using classical regression techniques on censored data. Thus we estimate the earlier specifications using a tobit model.[15]

Table 4.6.4 gives us the marginal effects of the the relevant interaction term for each of the specifications.This is equal to the marginal effect of per- captita expenditure conditional on the presence of a FUG minus the marginal effect of per-capita expenditure conditional on the absence of a FUG, evaluated at the median value of all variables. The first five columns consider the interaction between per capita expenditure and community forestry. The interaction term between per capita expenditure and FUG dummy is positive and significant at a 10% significance level for columns (1), (2) and (4). This provides additional evidence that the difference in firewood collection between the non-FUG and FUG regime is higher at lower levels of per-capita expenditure.

[15]We use the same controls that we used in the classical regression analysis. The details of tobit coefficients and the interpretation of coefficient of interaction terms are discussed in Appendix 4.B.

The next five columns for Table 4.6.4 show the coefficients for interaction between caste variables and FUG dummy. The interaction term for Dalits is never significant as was seen in the OLS regressions. Similarly, the interaction term between Janjati and FUG is consistently negative but insignificant.

Columns (11) to column (15) in Table 4.6.4 have the same functional specification as column(1) to column(5) respectively, except for the fact that square of per capita expenditure is added as a new variable. The coefficients of the interaction terms is positive and significant after the addition of this new variable. Columns (16) to column (18) in Table 4.6.4 have the same functional specification as column(7) to column(10) respectively, except for the fact that square of per capita expenditure is added as a new variable. None of the interaction terms are significant for these three columns. This suggests that the differnce in firewood collection between the non-FUG and FUG regime is not different across ethnic groups.

I now estimate a non-parametric relationship between per capita firewood consumption and per capita expenditure using locally weighted scatter-plot smoothing.[16] Figure 4.6.4 shows the non parametric relationship. For lower values of per capita expenditure, the 95% confidence band for the FUG regime lies below the 95% confidence band for the non-FUG regime. This is true till a per capita expenditure level of about Rs. 16,000. Thus for 70 % of the population, being in a FUG regime entails lower firewood collection than being in a non-FUG regime. One interpretation of this reduction is that a FUG regime entails more restrictions on firewood collection than a non-FUG regime. However the reduction becomes low as per-capita expenditure increases. This might be because the non-poor have access to other sources of firewood, for examples, trees planted on own land or private forests. The poor, who don't have access to such alternative sources, are the adversely affected by the formation of FUGs. The gap between the FUG and non-FUG gap reduces as per capita expenditure increases with the FUG curve intersecting the non-FUG curve from below at around Rs 37,000, which is the 95th percentile of per-capita expenditure distribution. How-

[16]Unlike other regressions, here the dependent variable is per capita firewood collection. Thus we are controlling for household size in a way, though the only control variable is per capita expenditure

ever the confidence bands of the two regimes overlap each other at higher levels of per capita expenditure. However this figure suggests that for levels of expenditure that are not very high, there is some evidence to suggest that the poor are affected adversely due to presence of FUGs.

In Figure 4.6.4, we did not use any controls other than per capita expenditure. Now I use a semi-parametric technique of residual regression to establish the relationship between firewood collection and per capita expenditure under the two regimes. I regress firewood collection on a small set of controls that does not include per capita expenditure, community forestry dummy and any interaction of the two. I use the functional specification of column(1) of Table 4.6.3. The results of this first stage regression are reported in column (1) of Table 4.E.2 of Appendix 4.E. Once the OLS coefficients are estimated, I use them to predict the residuals. Then I estimate a non parametric relationship between firewood residuals and per capita expenditure for both community forestry scenario and non community forestry scenario separately. To estimate the non parametric relationship I use locally weighted scatter-plot smoothing. The results of this exercise is in the Figure 4.6.5.

In Figure 4.6.5 [17], the FUG curve starts belows the non-FUG curve. For low values of per capita expenditure, the confidence band don't over lap each other thus providing some evidence for the hypothesis that the poor witness larger reduction in firewood collection due to a shift to a FUG regime. Thus for the majority of households situated below the mean per capita expenditure level (65 percent of total population), there exists a positive relationship between firewood collection and per- capita expenditure. Thus the confirmation of the poverty-environment hypothesis that I obtained earlier in the OLS regressions are a result of the linear structure imposed on the relationship.

I now use a richer set of controls for the first stage regression from which we obtain the residuals. I first regress firewood collection on a rich set of controls that does not include per capita expenditure, community forestry dummy and any interaction of the two. I use

[17] The distribution of per capita expenditure has long tails. Thus the bottom 1% and the top 1% percent of the distribution are spread over a large range of expenditure values. Though the estimation is done for the entire sample, the figure shows middle 98% of the expenditure distribution

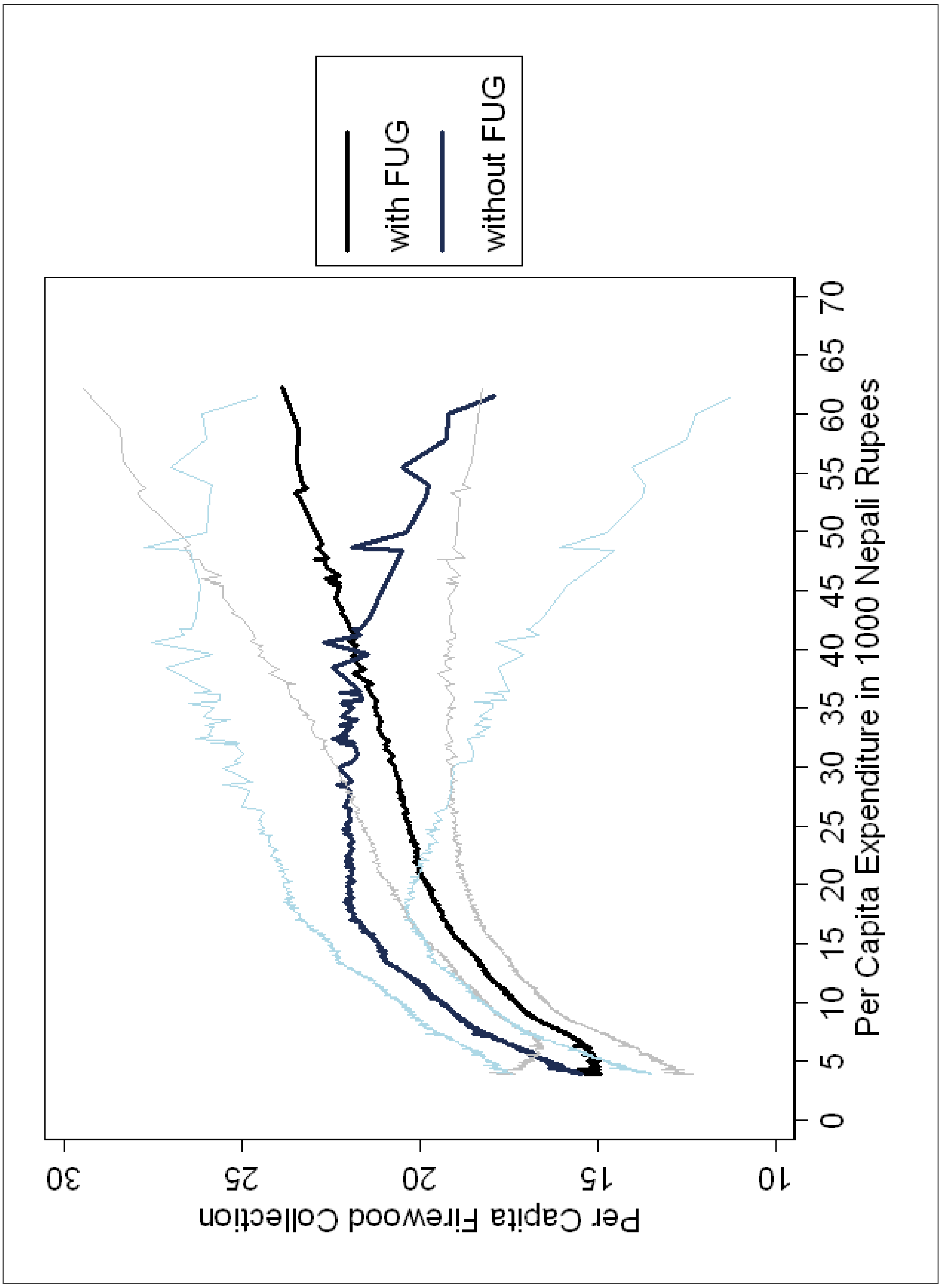

Figure 4.6.4: Non- Parametric Relationship between per capita firewood and Per Capita Expenditure
The lines in light blue denote denote confidence intervals for the non-FUG situation while the lines in black denote the confidence interval for FUG regime.

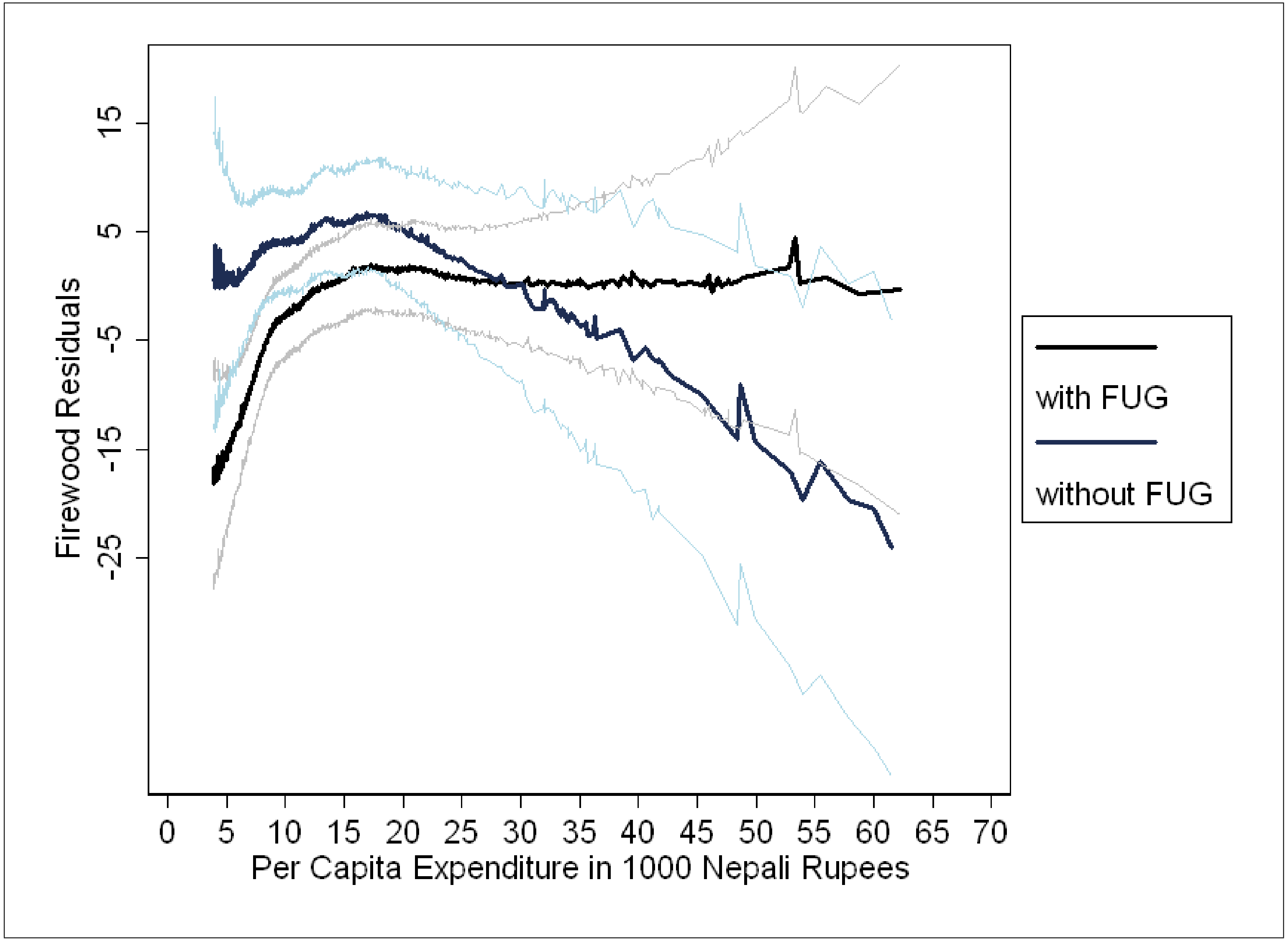

Figure 4.6.5: Relationship between Firewood Residuals and Per Capita Expenditure
The lines in light blue denote denote confidence intervals for the non-CF situation while the lines in black denote the confidence interval for CF regime.
Residuals obtained from a regression with minimal controls.

the functional specification of column(5) of Table 4.6.3. The results of this first stage regression are reported in column (2) of Table 4.E.2 of Appendix 4.E. The non parametric relationship between firewood residuals and per capita expenditure is given in the Figure 4.6.6.

In Figure 4.6.6 [18], the FUG curve starts belows the non-FUG curve. However for higher values of per capita expenditure the FUG curve lies above the non-CF curve. However the 95% confidence intervals for the two curves overlap each other. Thus one cannot conclude that the poor experience a larger reduction in firewood consumption when a community forestry program is initiated. Thus semi-parametric estimation does not provide enough evidence for the hypothesis that the poor suffer a larger reduction in firewood collection due to community forestry. Also, Figure 4.6.6 does not provide any evidence for the poverty-environment hypothesis. The confidence band for the FUG scenario is upward sloping for low values of per-capita expenditure and then flattens out. The confidence band for non-FUG scenario does not show any specific trend or pattern. Thus the weak "evidence" of poverty - environment hypothesis that I obtained in the OLS regressions are an outcome of the linearity restrictions imposed on the structure of relationship between firewood collection and per capita expenditure.

Till now I had focused on firewood collection as an independent variable. Since around 93% of households in Non-Terai Regions of Nepal state firewood to be thir primary cooking fuel and around 90% of households never purchase firewood, firewood collection is to a large extent an indicator of cooking energy consumption. To do some robustness checks I actually make some calculations of the effective cooking energy consumed by each household [19] and use that as a dependent variable. Like in the case of firewood collection, the OLS regressions do not give significant coefficients for the interaction term in most of the functional specifi-

[18] The distribution of per capita expenditure has long tails. Thus the bottom 1% and the top 1% percent of the distribution are spread over a large range of expenditure values. Though the estimation is done for the entire sample, the figure shows middle 98% of the expenditure distribution

[19] I only consider cooking energy consumed from four sources: firewood (including a small amount of firewood purchased by the economically well off households), liquefied petroleum gas and kerosene. I exclude cooking energy consumed from sources like leaves, straw, thatch and dung as their collection/consumption is not reported in the survey. Details of the method in which cooking energy is calculated is given in Appendix 4.A.

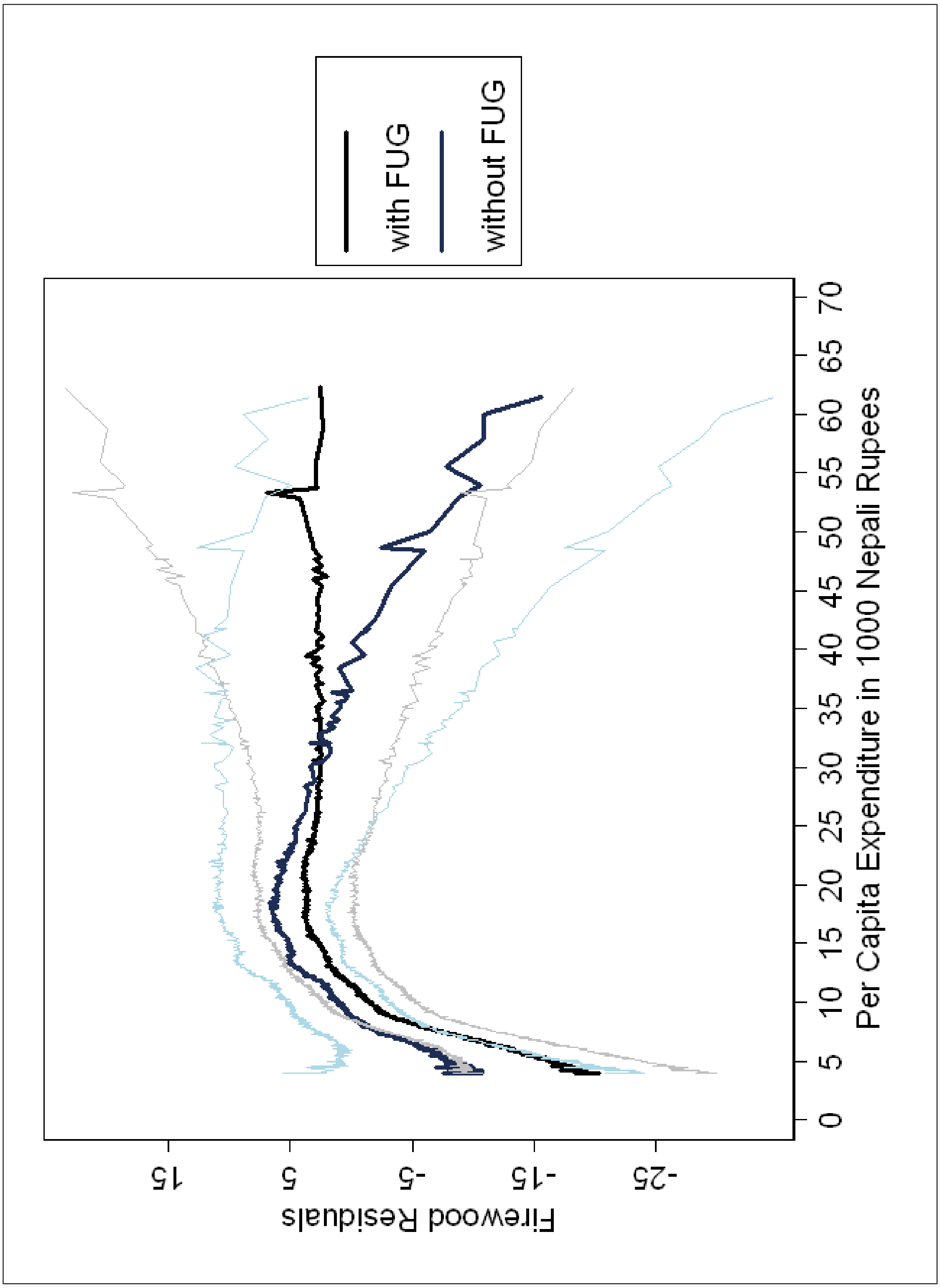

Figure 4.6.6: Relationship between Firewood Residuals and Per Capita Expenditure
The lines in light blue denote denote confidence intervals for the non-FUG situation while the lines in black denote the confidence interval for FUG regime.
Residuals obtained from a regression with a rich set of controls.

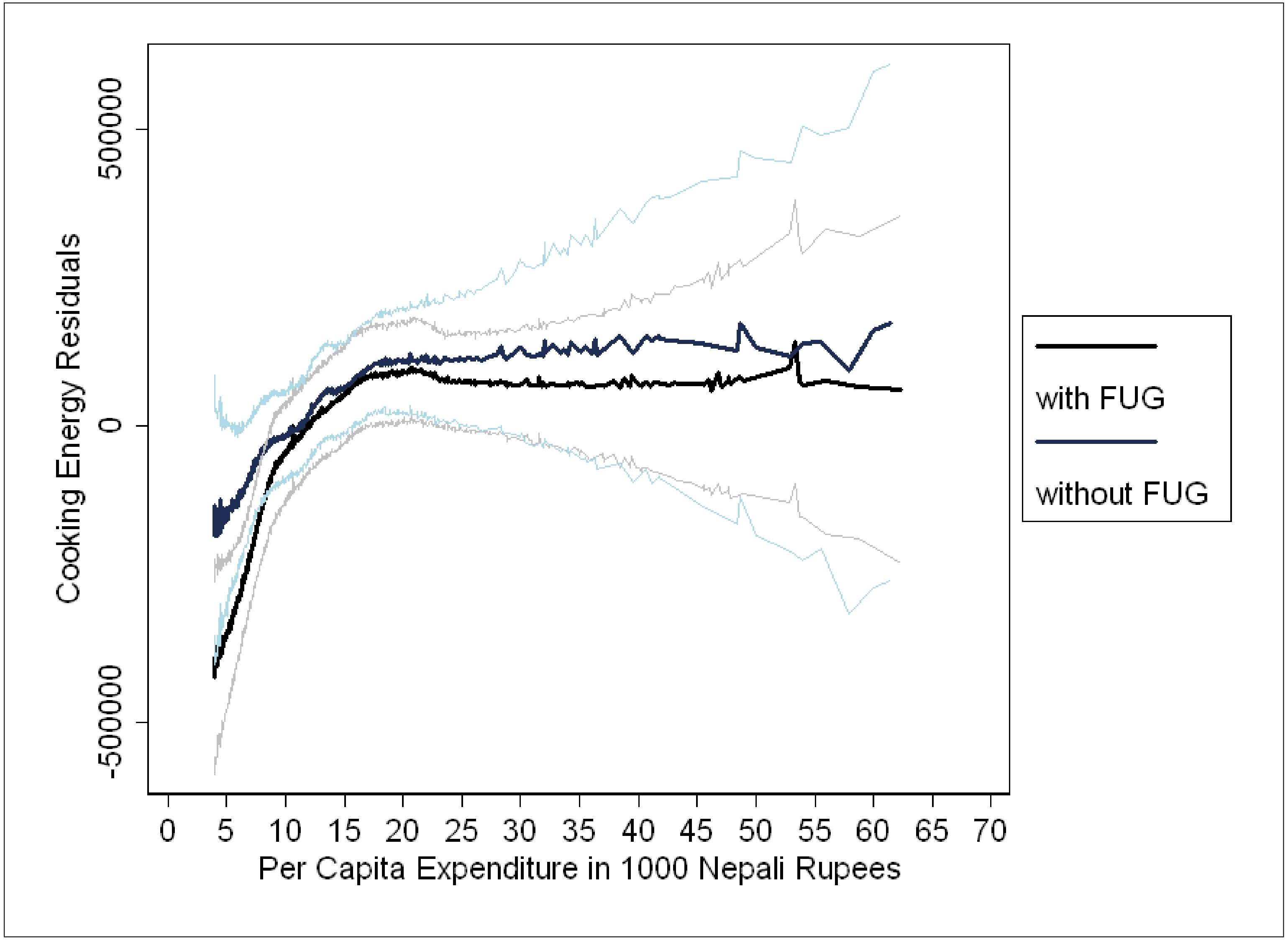

Figure 4.6.7: Relationship between Cooking Energy Residuals and Per Capita Expenditure
The lines in light blue denote denote confidence intervals for the non CF situation while the lines in black denote the confidence interval for CF regime.

cations. Figure 4.6.7 gives the results of a semi-parametric exercise (similar to the one I did with firewood collection as the dependent variable) with Energy residuals.[20]

In Figure 4.6.7, the FUG curve starts belows the non-FUG curve. However for higher values of per capita expenditure the distance between the FUG and non-FUG curve reduces. For low values of per-capita expenditure, the pattern is similar to the pattern we found in the semi parametric regression on firewood residuals. This is not surprising collected firewood is the major source of cooking energy in Nepal, with just about 4-5 % households stating LPG and kerosene as their main cooking fuel. Unlike the figure on firewood-residuals, the non FUG curve does not intersect the FUG curve from above. This might be because at higher levels of per capita expenditure, households substitute firewood for fossil fuels. However the 95% confidence intervals for the two curves overlap each other. Thus there is no systematic difference between FUG and non-FUG regime at higher levels of per-capita expenditure, though a lower levels of expenditure there seems to be a reduction in cooking energy usage due to FUG regime. While the confidence band do overlap, there is a suggestion that the lower end of the distribution witness a reduction in cooking energy usage.

In this paper , I concentrated on the impact of government initiated community forestry program. Thus the presence of community forestry in a ward was indicated by the presence of an active forest user group in the ward. However the community questionnaire of Nepal Living Standards Survey has a question which asks the following: *Do the people of this ward have any community forests?*. I also construct an alternative community forestry dummy on the basis of the answers to this question. The number of wards reporting community forestry increases when we use this alternative definition. This might be due to the inclusion of informal community forestry groups.[21] However the results of my analysis is robust to the definitional change.

[20]In the first stage , I regress Cooking Energy Consumption (in Kilocalories) on a rich set of controls which does not include CF dummy and per capita expenditure. Then I use locally weighted scatter-plot smoothing to establish a relationship between energy residuals and per capita expenditure

[21]However few wards that report the presence of FUGs, answer in negative when asked about the presence of community forests. This might be reporting error.

Thus while this paper finds some suggestive results for the fact that the poor experience a larger reduction in collection due to community forestry, such evidence is not robust to specificational changes. I plan to do future research on this question to deal with various issues that have not been answered in this chapter. The most important issue arises from the potential endogeneity in forest user group location. If forest user group locations are endogenous, then the results obtained from classical regression analysis might be biased. However there are some suggestions that FUG locations in Nepal are mainly conditioned by the remoteness of a ward/VDC.[22] Unlike it neighbour India, the government did not impose any restrictions on the kind of forests that were to be transferred to community management. The fact that all accessible forest lands were to be transferred ensures that endogeneity might not be a major issue. Edmonds (2002) suggests that closeness to range-posts (ie. office of government forest staff) is the factor that decides whether a ward has an FUG ward or not. Thus to deal with this, I include indices of remoteness in our regressions as remote villages are expected to be far away from range posts. Unlike Edmonds (2002), I don't have access to the government of Nepal's FUG database for recent years. Hence using an index denoting accessibility from range posts is not an option. However Edmonds (2002) uses a crude measure of accessibility of villages from range posts- a dummy indicating whether a VDC containing the ward has a range post. Since Edmonds (2002) study was done just after the FUG legislation was passed, he could use such a measure as a valid instrument. With the passage of time more wards have come under the preview of community forestry and we will need a better measure (for example, distance of the ward from the nearest range post in kilometers or time taken to reach the nearest range-post) to use as a instrument. However Edmonds (2002) was based on data on the Arun Valley in Nepal. Thus his contention of FUG location being conditioned only on distance from FUG might not be true for Nepal as a whole. In further research on this question, I would like to deal with the above mentioned problem of endogeneity (probably by finding good instruments).

[22]According to Edmonds (2002), "...in 1993, the government of Nepal abandoned national management, passing the Forest Act of 1993 that transferred all accessible forest land from the central government to local communities through the creation of "Forest User Groups" ...The Forest Act does not stipulate how foresters decide what areas get user groups first, because all accessible forests are to be transferred to user groups immediately (Community Forestry Manual 1995)".

4.7 Conclusion

In political economy, devolution of administrative power has often been questioned regarding its distributional impacts. It has often alleged in popular media that devolution leads to elite capture. Others have argued that devolution makes the process of administrative decision making more democratic and hence such devolution is expected to improve distributional outcomes. Academic evidence in economics seems to be divided: while Dasgupta and Beard (2007); Prinsen and Titeca (2008) show that elite capture cannot be an argument against devolution, there are a number of case studies that seems to suggest the opposite (Omvedt, 1997; Kumar, 2002). This question attains great importance in the context of devolution of forest administration as large sections of poor people in under-developed countries depend on forest products to fulfill their fuel and non-fuel needs. This chapter tries to answer this question in the context of community forestry in Nepal.

I find some evidence to suggest that formation of FUGs impose restrictions on firewood collection and thus leads to reduced collection of firewood by households. The reduction in collection is significant and higher at the lower end of the per-capita expenditure distribution. Richer households with access to alternative sources of firewood (like private forests and trees on agricultural lands), do not experience a reduction as high as poorer households. Thus in my study, I do find some systematic difference between the FUG and the non-FUG regime in terms of their distributional outcomes, the result is not robust to changes in the set of controls. I start with the assumption of linearity. I do find the interaction term of community forest and per capita expenditure to be negative and significant when the set of controls is small. It loses it's significance as more controls are introduced. I also study the impact of FUG formation on firewood collection by different castes. The data suggest that the there is no economically significant differences in the collection behaviour of Dalits and the general castes. The coefficients of interaction between the Janjati dummy and the FUG dummy has high standard errors making the coefficient to be insignificant. Thus the data at hand does not support a statistically significant differential effect of FUG on different castes. Non-parametric estimation of firewood residuals also provides some evidence in favour of our hypothesis. However this is not robust to the specificational changes in the first stage regression. While this paper provides some evidence that community forestry can have adverse distributional consequences, it is unable to establish the robustness of such a result. Further research using larger datasets is required to study the distributional consequences of community management. It is also important to extend such study to commons other than forests, for example, community managed irrigation projects. I plan to continue my research in this area to have a better understanding of the distributional effects of community management as a nuanced understanding of the issue can be a useful input in the designing of community institutions.

	(1)	(2)	(3)	(4)	(5)
Dependent Variable: Firewood Collected in *bharis*					
Community Forestry: FUG	-13.694	-10.895	-8.566	-7.737	-7.567
	(2.17)**	(1.70)*	(1.38)	(1.31)	(1.28)
Per Capita Expenditure	-0.456	-0.284	-0.224	-0.278	-0.265
	(2.18)**	(1.36)	(1.05)	(1.40)	(1.35)
Community Forestry*Per Capita Expenditure	0.535	0.376	0.362	0.380	0.350
	(2.28)**	(1.53)	(1.45)	(1.55)	(1.45)
Household Size	8.350	8.333	8.350	8.173	8.316
	(10.47)***	(10.63)***	(11.21)***	(11.15)***	(11.47)***
Dummy: Land Ownership	19.217	14.921	15.825	15.914	15.802
	(1.92)*	(1.66)	(1.85)*	(1.85)*	(1.85)*
Distance to Forests	-0.029	-0.025	-0.025	-0.018	-0.018
	(4.97)***	(4.05)***	(4.00)***	(2.32)**	(2.38)**
Dummy: Road Access		-9.606	-8.731	-7.181	-6.956
		(2.02)**	(1.82)*	(1.64)	(1.48)
Dummy: Kerosene Purchased		13.138	12.403	13.788	12.898
		(2.64)***	(2.49)**	(2.85)***	(2.44)**
Dummy: Open Stove		12.221	9.569	9.955	9.105
		(2.84)***	(2.37)**	(2.44)**	(2.26)**
Dummy: Dalits			0.500	-0.856	-1.003
			(0.13)	(0.21)	(0.24)
Dummy: Janjatis			11.046	8.268	8.949
			(2.30)**	(1.77)*	(2.03)**
Dummy: Pakka Roof				-1.405	-2.624
				(0.37)	(0.66)
Dummy: Access to Piped Water				-2.518	-2.567
				(0.59)	(0.63)
Dummy: Electricity in Ward				1.201	0.101
				(0.22)	(0.02)
Dummy: Police Station				13.100	15.013
				(1.27)	(1.42)
Dummy: Post Office				5.245	2.383
				(0.78)	(0.33)
Dummy: Telephone Service				-4.019	-4.343
				(0.69)	(0.73)
Dummy: Paved Road				-2.636	-2.170
				(0.35)	(0.29)
Dummy: Krishi (Agricultural) Centre				-6.480	-6.881
				(0.80)	(0.85)
Dummy: Bank Branch Office				-28.373	-27.389
				(2.04)**	(2.02)**
Dummy: Maoist District				-10.054	-12.057
				(2.03)**	(2.27)**
Constant	35.703	21.159	19.613	17.022	14.868
	(3.34)***	(1.74)*	(1.61)	(1.29)	(1.07)
Controls for Month of Interview	Yes	Yes	Yes	Yes	Yes
Controls for Geographical Region	No	No	No	No	Yes
Observations	1523	1523	1523	1523	1523
Number of Clusters	127	127	127	127	127
R-squared	0.18	0.21	0.22	0.24	0.24

Robust t statistics in parentheses
* significant at 10%; ** significant at 5%; *** significant at 1%

Table 4.6.3: OLS with richer set of controls: Part 1

	(6)	(7)	(8)	(9)	(10)
Dependent Variable: Firewood Collected in *bharis*					
Community Forestry: FUG	-1.034	-1.503	-0.986	1.470	1.338
	(0.16)	(0.24)	(0.16)	(0.24)	(0.22)
Dummy: Dalits	3.861	0.974	-0.268	0.027	0.450
	(0.55)	(0.15)	(0.04)	(0.00)	(0.07)
Dummy: Janjati	19.603	15.284	14.401	13.321	14.133
	(2.43)**	(1.99)**	(1.85)*	(1.83)*	(2.02)**
Dalits*Community Forestry	-1.450	0.617	1.156	-1.489	-2.496
	(0.17)	(0.08)	(0.14)	(0.19)	(0.31)
Janjati*Community Forestry	-7.854	-6.837	-5.974	-8.876	-9.020
	(0.80)	(0.71)	(0.61)	(0.96)	(0.98)
Household Size	8.450	8.343	8.324	8.153	8.310
	(11.19)***	(11.16)***	(11.01)***	(10.97)***	(11.33)***
Dummy: Land Ownership	21.714	16.837	16.585	16.653	16.497
	(2.18)**	(1.91)*	(1.92)*	(1.92)*	(1.91)*
Distance to Forests	-0.029	-0.026	-0.025	-0.017	-0.018
	(4.93)***	(4.06)***	(4.02)***	(2.30)**	(2.36)**
Dummy: Road Access		-10.287	-9.467	-7.711	-7.414
		(2.13)**	(1.97)*	(1.76)*	(1.58)
Dummy: Kerosene Purchased		12.963	13.040	14.415	13.373
		(2.58)**	(2.62)***	(2.97)***	(2.54)**
Dummy: Open Stove		9.865	9.795	10.025	9.073
		(2.39)**	(2.44)**	(2.47)**	(2.26)**
Per Capita Expenditure			0.008	-0.035	-0.042
			(0.06)	(0.31)	(0.37)
Dummy: Pakka Roof				-1.066	-2.355
				(0.27)	(0.59)
Dummy: Access to Piped Water				-2.521	-2.469
				(0.59)	(0.60)
Dummy: Electricity in Ward				1.063	-0.094
				(0.19)	(0.02)
Dummy: Police Station				11.932	13.904
				(1.17)	(1.33)
Dummy: Post Office				6.114	2.951
				(0.94)	(0.43)
Dummy: Telephone Service				-3.876	-4.252
				(0.67)	(0.72)
Dummy: Paved Road				-2.660	-2.203
				(0.35)	(0.29)
Dummy: Krishi (Agricultural) Centre				-6.938	-7.275
				(0.85)	(0.90)
Dummy: Bank Branch Office				-28.197	-27.279
				(2.08)**	(2.07)**
Dummy: Maoist District				-9.711	-11.807
				(1.99)**	(2.25)**
Constant	17.696	10.412	13.977	9.544	7.411
	(1.45)	(0.80)	(1.08)	(0.71)	(0.53)
Controls for Months of Interview	Yes	Yes	Yes	Yes	Yes
Controls for Geographical region	No	No	No	No	Yes
Observations	1523	1523	1523	1523	1523
Number of Clusters	127	127	127	127	127
R-squared	0.19	0.21	0.22	0.24	0.24

Robust t statistics in parentheses

* significant at 10%; ** significant at 5%; *** significant at 1%

Continuation of Table 4.6.3: Part 2

	(11)	(12)	(13)	(14)	(15)
Dependent Variable: Firewood Collected in *bharis*					
Community Forestry: FUG	-15.683	-13.444	-11.332	-10.279	-10.068
	(2.42)**	(2.06)**	(1.79)*	(1.70)*	(1.67)*
Per Capita Expenditure	-0.228	0.039	0.153	0.114	0.122
	(0.90)	(0.16)	(0.61)	(0.48)	(0.53)
Community Forestry*Per Capita Expenditure	0.653	0.527	0.537	0.550	0.519
	(2.80)***	(2.19)**	(2.23)**	(2.27)**	(2.17)**
Per Capita Expenditure^2	-0.002	-0.003	-0.004	-0.004	-0.003
	(1.98)*	(2.50)**	(2.73)***	(2.74)***	(2.76)***
Household Size	8.614	8.697	8.786	8.616	8.734
	(10.55)***	(10.86)***	(11.48)***	(11.40)***	(11.59)***
Dummy: Land Ownership	19.224	14.649	15.603	14.979	14.917
	(1.90)*	(1.61)	(1.81)*	(1.74)*	(1.74)*
Distance to Forests	-0.028	-0.025	-0.025	-0.017	-0.017
	(4.94)***	(3.98)***	(3.94)***	(2.25)**	(2.32)**
Dummy: Road Access		-10.497	-9.518	-7.319	-7.341
		(2.21)**	(2.00)**	(1.68)*	(1.57)
Dummy: Kerosene Purchased		13.090	12.328	13.701	12.589
		(2.62)***	(2.47)**	(2.82)***	(2.40)**
Dummy: Open Stove		12.861	9.930	10.289	9.539
		(3.01)***	(2.48)**	(2.53)**	(2.38)**
Dummy: Dalits			1.687	0.414	0.352
			(0.42)	(0.10)	(0.08)
Dummy: Janjatis			11.820	9.144	9.617
			(2.47)**	(1.96)*	(2.20)**
Dummy: Pakka Roof				-2.197	-3.328
				(0.58)	(0.85)
Dummy: Access to Piped Water				-2.464	-2.599
				(0.58)	(0.64)
Dummy: Electricity in Ward				0.242	-0.762
				(0.04)	(0.13)
Dummy: Police Station				13.308	15.082
				(1.30)	(1.43)
Dummy: Post Office				4.761	2.013
				(0.72)	(0.29)
Dummy: Telephone Service				-5.262	-5.443
				(0.90)	(0.91)
Dummy: Paved Road				-3.346	-2.835
				(0.45)	(0.38)
Dummy: Krishi (Agricultural) Centre				-5.855	-6.240
				(0.72)	(0.77)
Dummy: Bank Branch Office				-28.092	-27.095
				(2.09)**	(2.06)**
Dummy: Maoist District				-10.084	-12.002
				(2.05)**	(2.28)**
Constant	32.172	16.443	13.898	12.448	9.640
	(2.89)***	(1.30)	(1.09)	(0.92)	(0.67)
Controls for Month of Interview	Yes	Yes	Yes	Yes	Yes
Controls for Geographical Region	No	No	No	No	Yes
Observations	1523	1523	1523	1523	1523
Number of Clusters	127	127	127	127	127
R-squared	0.19	0.21	0.22	0.24	0.25

Robust t statistics in parentheses
* significant at 10%; ** significant at 5%; *** significant at 1%

Continuation of Table 4.6.3: Part 3

	(16)	(17)	(18)
Dependent Variable: Firewood Collected in *bharis*			
Community Forestry: FUG	-1.212	1.254	1.143
	(0.19)	(0.21)	(0.19)
Dummy: Dalits	0.369	0.626	1.129
	(0.05)	(0.09)	(0.17)
Dummy: Janjati	14.851	13.748	14.424
	(1.92)*	(1.91)*	(2.09)**
Dalits*Community Forestry	1.519	-0.941	-1.985
	(0.18)	(0.12)	(0.25)
Janjati*Community Forestry	-5.740	-8.441	-8.587
	(0.59)	(0.93)	(0.94)
Household Size	8.657	8.486	8.631
	(11.17)***	(11.15)***	(11.41)***
Dummy: Land Ownership	16.681	16.131	16.003
	(1.93)*	(1.87)*	(1.86)*
Distance to Forests	-0.025	-0.017	-0.017
	(3.98)***	(2.24)**	(2.30)**
Per Capita Expenditure	0.386	0.350	0.342
	(1.62)	(1.50)	(1.50)
Per Capita Expenditure ^{2}	-0.003	-0.003	-0.003
	(1.81)*	(1.84)*	(1.89)*
Dummy: Road Access	-10.331	-7.952	-7.828
	(2.17)**	(1.82)*	(1.67)*
Dummy: Kerosene Purchased	13.154	14.490	13.243
	(2.63)***	(2.96)***	(2.52)**
Dummy: Open Stove	10.205	10.387	9.488
	(2.56)**	(2.57)**	(2.37)**
Dummy: Pakka Roof		-1.624	-2.871
		(0.42)	(0.73)
Dummy: Access to Piped Water		-2.614	-2.603
		(0.62)	(0.64)
Dummy: Electricity in Ward		0.234	-0.883
		(0.04)	(0.16)
Dummy: Police Station		12.032	13.909
		(1.19)	(1.34)
Dummy: Post Office		5.822	2.650
		(0.91)	(0.39)
Dummy: Telephone Service		-4.844	-5.143
		(0.84)	(0.87)
Dummy: Paved Road		-3.364	-2.909
		(0.44)	(0.38)
Dummy: Krishi (Agricultural) Centre		-6.649	-6.969
		(0.82)	(0.87)
Dummy: Bank Branch Office		-27.759	-26.824
		(2.10)**	(2.09)**
Dummy: Maoist District		-9.614	-11.656
		(1.98)**	(2.24)**
Constant	8.170	4.840	2.090
	(0.61)	(0.35)	(0.14)
Controls for Month of Interview	Yes	Yes	Yes
Controls for Geographical Region	No	No	Yes
Observations	1523	1523	1523
Number of Clusters	127	127	127
R-squared	0.22	0.24	0.24

Cluster robust t statistics in parentheses

* significant at 10%; ** significant at 5%; *** significant at 1%

Continuation of Table 4.6.3: Part 4

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
	Marginal Effects on Firewood Collection									
Community Forestry* PC Expenditure	0.666	0.496	0.464	0.480	0.451					
	(2.31)**	(1.69)*	(1.61)	(1.67)*	(1.61)					
Community Forestry* Dalit						-1.450	0.768	1.452	-0.856	-1.768
						(0.17)	(0.09)	(0.17)	(0.10)	(0.22)
Community Forestry* Janjati						-7.581	-6.780	-5.712	-8.553	-8.610
						(0.81)	(0.72)	(0.60)	(0.93)	(0.96)
Cluster robust z statistics in parenthesis										

Table 4.6.4: Interaction Effects from Tobit estimation

Marginal Effects are unconditional marginal effects. They are NOT the marginal effects on the expectation of the dependent variable,conditional on the fact that it is positive. They are the marginal effects on the unconditional expectation. Number of households and clusters for each of the regressions is 1523 and 127 respectively.

	(11)	(12)	(13)	(14)	(15)	(16)	(17)	(18)
Marginal Effects on Firewood Collection								
Community Forestry* PC Expenditure	0.779	0.652	0.643	0.662	0.627			
	(2.64)***	(2.17)**	(2.20)**	(2.21)**	(2.15)**			
Community Forestry* Dalit						1.773	-0.347	-1.304
						(0.21)	(0.04)	(0.16)
Community Forestry* Janjati						-5.517	-8.166	-8.219
						(0.58)	(0.90)	(0.92)

Interaction Effects from Tobit estimation: Continuation of Table 4.6.4

Appendices for Chapter 4

4.A Description of Variables:

1. Firewood collected in *bharis*: This is annual collection obtained by multiplying collection in an average month by 12. Most household report collection in *bharis*. Only one household report collection in cart. Since the *bhari*-cart conversion rate is not available for that ward/VDC, the average conversion rate from the remaining sample that report conversion rates is used i.e. 1 cart=20 *bharis*.

2. Dummy Variable- Poor: Takes the value 1 if the annual per-capita expenditure (corrected for regional difference in prices) is less than the official nominal poverty line. It takes the value 0, otherwise. The variable is obtained from the data file titled $NLSS2\_poverty$ in the dataset.

3. Per Capita Expenditure: Total expenditure (excluding fuel expenditure) is calculated by adding up amounts spent on consumption of different food and non food items. Imputed monetary values of goods produced and consumed internally by the households are also included in the calculation of total expenditure. The non fuel total expenditure are then corrected for regional differences using price indices given in NLSS2 data. By diving the total expenditure by household size, we obtain the per capita expenditure. The unit in which per capita expenditure is reported in the chapter is 1000 Nepali rupees.

4. Dummy Variable- Land: Takes the value 0 for landless households and 1 for households with positive land-holdings , no matter how small.

5. Value of land owned: In NLSS2 questionnaire, households are asked to guess the hypothetical purchase/sale price of a piece of land (which resembles the land owned by the household in every way) in a situation where they are required to be purchased/sold in the date of interview. We aggregate this information over different plots owned by a household to obtain the value of land owned by the household.

6. Dalit and Janjati Dummy: The Dalit dummy takes the value 1 if the household belongs to any of the Dalit castes and zero otherwise. The Janjati dummy takes the value 1 if the household belongs to any of the Janjati castes and zero otherwise. The allotment

of different castes to these two categories is done on the basis of Table 2.2 of Bennett et al. (2008)

7. Dummy Variable- Access to road: A household is said to have access to road if it the time taken by the household to reach the nearest paved road is less than two hours. The dummy takes the value 1 in this case. If the time taken is more than 2 hours, the dummy takes the value 0.
8. Distance to forests: One Way Walking time to forests from the ward (in minutes).
9. Dalit: Dummy Variable that takes the value 1 if the household belongs to the Dalit community, 0 otherwise.
10. Janjati: Dummy Variable that takes the value 1 if the household belongs to the Janjati community, 0 otherwise.
11. Access to Piped Water: Dummy Variable that takes the value 1 if the household has access to piped water, 0 otherwise.
12. Kerosene Purchased: Dummy Variable that takes the value 1 if the household purchase non zero quantity of kerosene, 0 otherwise.
13. Open Stove: Dummy Variable that takes the value 1 if the household use open stove, 0 otherwise.
14. Presence of Kitchen garden : Dummy Variable that takes value 1 if the household has a kitchen garden, 0 otherwise.
15. Pakka Roof: Dummy Variable that takes the value 1 if the household's house has a pakka roof, 0 otherwise.
16. Time taken to reach paved road: Time (in minutes) taken by the household to reach the closest paved road using the mode of transport it generally uses to reach the paved road.
17. Access to Roads: Dummy variable that takes the value 1 if the household takes less than two hours to reach the nearest paved road, 0 otherwise.

18. Electricity in Ward: Takes the value 1 if at least one household in the ward has access to electricity.

19. Dummy Variable- FUG in Ward: Takes the value 1 if the ward reports the presence of a forest user group in the ward. It takes the value 0 in there are no FUGs in the ward.

20. Maoist District: Takes than value 1 if the ward and village development committee belong to a district that is affected by the ultra left Maoist movement in Nepal. (Hatlebakk (2009), Page 3, Column 1)

21. Police Station, Post Office, Telephone Services, Paved Road, Krishi Centre and Bank Branch Office: I consider these six kinds of public infrastructure. A dummy variable is created for each of them that takes the value 1 if the facility is present at the VDC and 0 if it is not present inside the VDC.

22. Cooking Energy Consumed: At first, I calculate the amount of each cooking fuel (Firewood, Kerosene and LPG) consumed for cooking purposes. Let F_i denote this amount. Let c_i and $_i$ denote the calorific value of fuel i and the thermal efficiency of stoves using fuel i respectively. Then cooking energy consumed is $\sum_i F_i.c_i.\alpha_i$.

    The calorific values are obtained from

    $$http://ces.iisc.ernet.in/energy/paper/alternative/calorific.html$$

    while the thermal efficiencies are obtained from Shrestha and Bhattarai (1995); Venkataraman, Sagar, Habib, Lam, and Smith (2010).

    To calculate the firewood consumed in Kilograms, we express the firewood collected in kilograms assuming 1 bhari = 30 Kilograms. This is the conversion rate used by Nepal, Nepal, and Grimsrud (2010); Richards, Maharjan, and Kanel (2003). As few households purchase firewood, the amount of firewood purchased in calculated by diving the amount of money spent on firewood purchase (obtained from consumption survey) by price of firewood (obtained from community questionnaire). The sum of firewood collected and purchases gives us a measure of firewood consumed.

To obtain the consumption of LPG, we divide the amount spent on LPG consumption by the price of LPG. Since the community questionnaire does not have the price of LPG, we use the national LPG price obtained from Nepal Rashtra Bank, Research Department (2006). Each cylinder of LPG weighs 14.2 kilograms.

To obtain the consumption of kerosene, we divide the amount spent on kerosene consumption by the price of kerosene (obtained from community questionnaire). However a large part of the kerosene purchased by households is used as a lighting fuel. To split the total purchase of kerosene into kerosene used as a lighting fuel and kerosene used as a cooking fuel, we use a technique that was developed by Prof. B. Ramaswami of the Indian Statistical Institute. [23]

We divide the sample of kerosene buyers (i.e., those who spend money on buying kerosene) into 5 categories:

(a) Households whose main source of lighting is kerosene and primary cooking fuel is not kerosene.

(b) Households whose main source of lighting is kerosene and primary cooking fuel is also kerosene.

(c) Households whose main source of lighting is electricity and primary cooking fuel is not kerosene.

(d) Households whose main source of lighting is electricity and primary cooking fuel is also kerosene.

(e) Households that do not fall into any of the above categories.

I use the following rule for splitting up kerosene consumption into cooking and lighting use.

[23] This is an unpublished work obtained through personal correspondence. Prof. Ramaswami used this technique to split kerosene consumption reported in the National Sample Survey of India.

(a) For the first group (Light = Kerosene and Cook $\neq$ Kerosene), the entire kerosene consumption is assigned to lighting use. This is because we know that firewood satisfies the cooking energy needs of a overwhelmingly large percentage of non-terai rural Nepal.

(b) For the second group (Light = Kerosene and Cook = Kerosene), the total consumption (purchase) of kerosene has to be split up into cooking and lighting demand. We use group 1, to predict the lighting demand for kerosene based on income and demographic characteristics of households. This gives us the imputed lighting demand for kerosene for group 2. Then cooking demand = kerosene consumption - imputed lighting demand.

(c) For the third group (Light = Electricity and Cook $\neq$ Kerosene), kerosene is not a primary fuel for either cooking or lighting. The kerosene bought by this group constitutes a supplemental fuel for either cooking or lighting. Since in rural Nepal, kerosene is mainly used for lighting, I impute the observed kerosene consumption as demand for lighting.

(d) For the fourth group (Light = Electricity Cook = Kerosene), in rural areas we allow for the possibility that part of the kerosene bought is used for lighting purposes as well. Therefore, in rural non-terai Nepal, cooking demand for kerosene = observed consumption - imputed demand for lighting. The imputed demand for lighting is calculated by using group 3 as the sample for predicting this demand based on income and other demographic characteristics of the households.

(e) As kerosene is not the primary cooking or lighting code here, the kerosene demand from this category is considered to be supplementary - for lighting.

In the case of groups 2 and 4 , there is a possibility of getting a negative cooking demand for kerosene since the imputed lighting demand may be greater than the total amount of kerosene bought. In these cases the cooking demand for kerosene was set equal to zero.

This techniques is entirely based on an unpublished chapter of the ESMAP report (World Bank, 2003) that was obtained from Prof. Bharat Ramaswami of the Indian

Statistical Institute, New Delhi through personal correspondence. The world bank wrote up a report that used this method in its appendix, which is available at $http : //vle.worldbank.org/bnpp/en/publications/energy - water/india - access - poor - clean - household - fuels$.

4.B Tobit with interaction terms

This Appendix is based on Chapter 16 of Wooldrige (2002) and Ai and Norton (2003). Consider a typical tobit model:

$$y^* = \mathbf{x}\beta + \mathbf{u}, \quad \mathbf{u}|\mathbf{x} \sim \text{Normal}(\mathbf{0}, \sigma^\mathbf{2}) \tag{4.B.1}$$

$$y = \max(0, y^*) \tag{4.B.2}$$

where y^* is a latent variable that satisfies the classical linear model assumption. Let us assume,

$$\mathbf{x}\beta = \beta_\mathbf{0}.\mathbf{1} + \beta_\mathbf{1}\mathbf{x_1} + \beta_\mathbf{2}\mathbf{x_2} + \beta_\mathbf{3}\mathbf{x_2}\mathbf{x_1} + \ldots + \mathbf{u}$$

.x_1 is an indicator variable while x_2 is continuous variable. There are no other interaction on non-linear terms.

Now, maximum likelihood tobit estimation (Wooldrige, 2002) leads to:

$$E(y|\mathbf{x}) = \mathbf{\Phi}(\frac{\mathbf{x}\beta}{\sigma})\mathbf{x}\beta + \sigma\phi(\frac{\mathbf{x}\beta}{\sigma}) \tag{4.B.3}$$

Thus,

$$\frac{\partial E(y|x_1 = 1, x_2, x_3, \ldots x_k)}{\partial x_2} = (\beta_2 + \beta_3)\Phi(\frac{\mathbf{x}\beta}{\sigma}) \tag{4.B.4}$$

$$\frac{\partial E(y|x_1 = 0, x_2, x_3, \ldots x_k)}{\partial x_2} = \beta_2\Phi(\frac{\mathbf{x}\beta}{\sigma}) \tag{4.B.5}$$

and

$$\text{Interaction Effect} \quad (\mu) = \beta_3\Phi(\frac{\mathbf{x}\beta}{\sigma}) \tag{4.B.6}$$

Thus the interaction effect is estimated by:

$$\hat{\mu} = \hat{\beta}_3 \Phi(\frac{\mathbf{x}\hat{\beta}}{\hat{\sigma}}) \tag{4.B.7}$$

The asymptotic variance of the interaction effect is:

$$\Sigma_\mu = \frac{\partial \mu}{\partial \beta'} . \Omega_\beta . \frac{\partial \mu}{\partial \beta} \tag{4.B.8}$$

which is consistently estimated by:

$$\hat{\Sigma_\mu} = \frac{\partial \hat{\mu}}{\partial \beta'} . \hat{\Omega_\beta} . \frac{\partial \hat{\mu}}{\partial \beta} \tag{4.B.9}$$

where $\hat{\Omega_\beta}$ is a consistent covariance estimator of β. The t statistic is $t = \frac{\hat{\mu}}{\sqrt{\hat{\Sigma_\mu}}}$, which has an asymptotic standard normal distribution under some regularity conditions. Use the t statistic to test the hypothesis that the interaction effect equals zero, for given x.

4.C Tobit Coefficients

These are the tobit coefficients with standard errors clustered at ward level. The interaction effects discussed in Table 4.6.4 are based on these coefficients. The marginal effects are calculated at the median of all variables.

	(1)	(2)	(3)	(4)	(5)
Dependent Variable: Firewood Collected in *Bharis*					
Community Forestry: FUG	-15.896	-12.424	-9.717	-8.526	-8.403
	(2.42)**	(1.87)*	(1.50)	(1.37)	(1.36)
Per Capita Expenditure	-0.670	-0.458	-0.379	-0.416	-0.406
	(2.29)**	(1.65)*	(1.36)	(1.60)	(1.59)
Community Forestry*Per Capita Expenditure	0.710	0.515	0.490	0.499	0.473
	(2.30)**	(1.69)*	(1.60)	(1.66)*	(1.61)
Household Size	8.588	8.580	8.626	8.453	8.614
	(10.18)***	(10.37)***	(10.95)***	(10.92)***	(11.26)***
Dummy: Land Ownership	29.443	24.689	25.568	24.896	24.680
	(2.29)**	(2.12)**	(2.29)**	(2.28)**	(2.28)**
Distance to Forests	-0.030	-0.026	-0.026	-0.018	-0.018
	(5.02)***	(3.99)***	(3.96)***	(2.19)**	(2.23)**
Dummy: Road Access		-11.312	-10.018	-8.060	-7.467
		(2.13)**	(1.88)*	(1.66)*	(1.45)
Dummy: Kerosene Purchased		15.212	14.467	15.848	15.413
		(2.76)***	(2.65)***	(2.98)***	(2.65)***
Dummy: Open Stove		13.962	11.026	11.218	10.262
		(3.08)***	(2.60)***	(2.63)***	(2.45)**
Dummy: Dalits			0.444	-0.821	-1.092
			(0.10)	(0.19)	(0.25)
Dummy: Janjatis			11.099	8.392	9.359
			(2.25)**	(1.74)*	(2.04)**
Dummy: Pakka Roof				-2.784	-4.076
				(0.70)	(0.98)
Dummy : Access to Piped Water				-2.960	-2.927
				(0.66)	(0.68)
Dummy: Electricity in Ward				0.330	-0.826
				(0.06)	(0.14)
Dummy: Police Station				15.074	17.256
				(1.28)	(1.42)
Dummy: Post Office				5.559	2.836
				(0.79)	(0.38)
Dummy: Telephone Service				-5.131	-5.612
				(0.80)	(0.86)
Dummy: Paved Road				-3.007	-2.580
				(0.34)	(0.29)
Dummy: Krishi (Agricultural) Centre				-7.800	-8.234
				(0.88)	(0.93)
Dummy: Bank Branch Office				-29.069	-28.216
				(1.95)*	(1.93)*
Dummy: Maoist District				-9.573	-11.653
				(1.85)*	(2.11)**
Constant	26.525	9.403	8.182	6.034	5.369
	(2.05)**	(0.65)	(0.57)	(0.41)	(0.35)
Controls for Month of Interview	Yes	Yes	Yes	Yes	Yes
Controls for Geographical Region	No	No	No	No	Yes
Observations	1523	1523	1523	1523	1523
Number of Clusters	127	127	127	127	127

Cluster robust t statistics in parentheses
* significant at 10%; ** significant at 5%; *** significant at 1%

Table 4.C.1: Tobit Coefficients with cluster robust standard errors : Part 1

	(6)	(7)	(8)	(9)	(10)
Dependent Variable: Firewood Collected in *Bharis*					
Community Forestry: FUG	-0.606	-1.005	-0.310	2.339	2.222
	(0.08)	(0.14)	(0.04)	(0.36)	(0.34)
Dummy: Dalits	4.828	1.492	-0.571	-0.312	-0.053
	(0.64)	(0.21)	(0.08)	(0.04)	(0.01)
Dummy: Janajati	21.246	16.188	14.526	13.514	14.628
	(2.50)**	(2.01)**	(1.78)*	(1.78)*	(2.01)**
Dalits*FUG	-1.562	0.802	1.525	-0.886	-1.850
	(0.17)	(0.09)	(0.17)	(0.10)	(0.22)
Janajati*FUG	-8.248	-7.130	-6.044	-8.910	-9.080
	(0.80)	(0.71)	(0.60)	(0.93)	(0.95)
Household Size	8.809	8.687	8.621	8.453	8.629
	(11.06)***	(11.02)***	(10.76)***	(10.74)***	(11.13)***
Dummy: Land Ownership	32.588	26.957	26.567	25.766	25.498
	(2.52)**	(2.35)**	(2.36)**	(2.33)**	(2.33)**
Distance to Forests	-0.030	-0.026	-0.026	-0.017	-0.018
	(4.99)***	(4.00)***	(3.99)***	(2.16)**	(2.20)**
Dummy: Road Access		-12.457	-10.958	-8.685	-8.018
		(2.27)**	(2.04)**	(1.78)*	(1.55)
Dummy: Kerosene Purchased		15.115	15.242	16.596	15.980
		(2.73)***	(2.78)***	(3.11)***	(2.76)***
Dummy: Open Stove		11.648	11.349	11.348	10.273
		(2.68)***	(2.69)***	(2.67)***	(2.46)**
Per Capita Expenditure			-0.052	-0.081	-0.090
			(0.37)	(0.63)	(0.71)
Dummy: Pakka Roof				-2.436	-3.802
				(0.60)	(0.91)
Dummy: Access to Piped Water				-3.078	-2.922
				(0.69)	(0.68)
Dummy: Electricity in Ward				0.088	-1.138
				(0.02)	(0.19)
Dummy: Police Station				13.800	16.034
				(1.18)	(1.34)
Dummy: Post Office				6.529	3.449
				(0.95)	(0.48)
Dummy: Telephone Service				-5.019	-5.566
				(0.79)	(0.86)
Dummy: Paved Road				-3.144	-2.770
				(0.35)	(0.31)
Dummy: Krishi (Agricultural) Centre				-8.377	-8.750
				(0.95)	(1.00)
Dummy: Bank Branch Office				-28.802	-28.015
				(1.98)**	(1.97)**
Dummy: Maoist District				-9.100	-11.263
				(1.79)*	(2.06)**
Constant	3.848	-4.687	0.941	-2.910	-3.655
	(0.25)	(0.30)	(0.06)	(0.19)	(0.23)
Controls for Month of Interview	Yes	Yes	Yes	Yes	Yes
Controls for Geographical Region	No	No	No	No	Yes
Observations	1523	1523	1523	1523	1523
Number of Clusters	127	127	127	127	127

Cluster robust t statistics in parentheses
* significant at 10%; ** significant at 5%; *** significant at 1%

Continuation of Table 4.C: Tobit Coefficients - Part 2

	(11)	(12)	(13)	(14)	(15)
Dependent Variable: Firewood Collected in *Bharis*					
Community Forestry: FUG	-17.888	-15.107	-12.693	-11.322	-11.140
	(2.63)***	(2.20)**	(1.90)*	(1.76)*	(1.74)*
Per Capita Expenditure	-0.477	-0.165	-0.025	-0.038	-0.037
	(1.43)	(0.53)	(0.08)	(0.13)	(0.13)
Community Forestry*Per Capita Expenditure	0.832	0.678	0.681	0.688	0.660
	(2.63)***	(2.17)**	(2.20)**	(2.21)**	(2.15)**
Per Capita Expenditure^2	-0.002	-0.003	-0.003	-0.004	-0.003
	(1.65)*	(2.20)**	(2.47)**	(2.51)**	(2.53)**
Household Size	8.818	8.919	9.044	8.885	9.020
	(10.23)***	(10.56)***	(11.19)***	(11.16)***	(11.38)***
Dummy: Land Ownership	29.381	24.347	25.265	23.912	23.759
	(2.27)**	(2.08)**	(2.26)**	(2.19)**	(2.20)**
Distance to Forests	-0.029	-0.025	-0.025	-0.017	-0.017
	(4.98)***	(3.92)***	(3.90)***	(2.11)**	(2.16)**
Dummy: Road Access		-12.149	-10.779	-8.188	-7.842
		(2.28)**	(2.04)**	(1.70)*	(1.52)
Dummy: Kerosene Purchased		15.124	14.354	15.724	15.064
		(2.73)***	(2.62)***	(2.95)***	(2.61)***
Dummy: Open Stove		14.541	11.347	11.534	10.678
		(3.24)***	(2.70)***	(2.72)***	(2.56)**
Dummy: Dalits			1.596	0.439	0.247
			(0.38)	(0.10)	(0.06)
Dummy: Janjatis			11.853	9.260	10.014
			(2.42)**	(1.92)*	(2.20)**
Dummy: Pakka Roof				-3.565	-4.765
				(0.90)	(1.16)
Dummy: Access to Piped Water				-2.905	-2.964
				(0.66)	(0.70)
Dummy: Electricity in Ward				-0.611	-1.666
				(0.11)	(0.29)
Dummy: Police Station				15.333	17.373
				(1.31)	(1.44)
Dummy: Post Office				5.076	2.468
				(0.73)	(0.33)
Dummy: Telephone Service				-6.357	-6.682
				(0.99)	(1.02)
Dummy: Paved Road				-3.766	-3.271
				(0.43)	(0.37)
Dummy: Krishi (Agricultural) Centre				-7.096	-7.520
				(0.80)	(0.85)
Dummy: Bank Branch Office				-28.860	-27.978
				(1.99)**	(1.96)*
Dummy: Maoist District				-9.621	-11.628
				(1.88)*	(2.13)**
Constant	23.601	5.252	2.952	1.777	0.494
	(1.77)*	(0.35)	(0.20)	(0.12)	(0.03)
Controls for Month of Interview	Yes	Yes	Yes	Yes	Yes
Controls for Geographical Region	No	No	No	No	Yes
Observations	1523	1523	1523	1523	1523
Number of Clusters	127	127	127	127	127

Cluster robust t statistics in parentheses

* significant at 10%; ** significant at 5%; *** significant at 1%

Continuation of Table 4.C: Tobit Coefficients - Part 3

	(16)	(17)	(18)
Dependent Variable: Firewood Collected in *Bharis*			
Community Forestry: FUG	-0.520	2.130	2.031
	(0.07)	(0.32)	(0.31)
Dummy: Dalits	-0.013	0.225	0.555
	(0.00)	(0.03)	(0.08)
Dummy: Janajati	14.936	13.909	14.887
	(1.84)*	(1.85)*	(2.06)**
Dalits*FUG	1.861	-0.359	-1.367
	(0.21)	(0.04)	(0.16)
Janajati*FUG	-5.840	-8.503	-8.677
	(0.58)	(0.89)	(0.92)
Household Size	8.920	8.763	8.925
	(10.85)***	(10.88)***	(11.17)***
Dummy: Land Ownership	26.609	25.257	25.022
	(2.36)**	(2.30)**	(2.30)**
Distance to Forests	-0.025	-0.017	-0.017
	(3.96)***	(2.10)**	(2.14)**
Per Capita Expenditure	0.289	0.277	0.264
	(1.09)	(1.09)	(1.06)
Per Capita Expenditure^2	-0.002	-0.002	-0.002
	(1.54)	(1.61)	(1.65)*
Dummy: Road Access	-11.731	-8.898	-8.391
	(2.20)**	(1.83)*	(1.63)
Dummy: Kerosene Purchased	15.333	16.657	15.841
	(2.79)***	(3.11)***	(2.74)***
Dummy: Open Stove	11.700	11.672	10.644
	(2.79)***	(2.75)***	(2.56)**
Dummy: Pakka Roof		-2.954	-4.277
		(0.73)	(1.03)
Dummy: Access to Piped Water		-3.178	-3.062
		(0.72)	(0.72)
Dummy: Electricity in Ward		-0.683	-1.861
		(0.12)	(0.32)
Dummy: Police Station		13.920	16.062
		(1.20)	(1.35)
Dummy: Post Office		6.262	3.173
		(0.92)	(0.45)
Dummy: Telephone Service		-5.915	-6.378
		(0.93)	(0.98)
Dummy: Paved Road		-3.832	-3.447
		(0.43)	(0.38)
Dummy: Krishi (Agricultural) Centre		-8.069	-8.429
		(0.92)	(0.97)
Dummy: Bank Branch Office		-28.435	-27.627
		(2.00)**	(1.99)**
Dummy: Maoist District		-9.006	-11.125
		(1.78)*	(2.06)**
Constant	-4.226	-7.250	-8.524
	(0.27)	(0.46)	(0.53)
Controls for Month of Interview	Yes	Yes	Yes
Controls for Geographical Region	No	No	Yes
Observations	1523	1523	1523
Number of Clusters	127	127	127

Cluster robust t statistics in parentheses
* significant at 10%; ** significant at 5%; *** significant at 1%

Continuation of Table 4.C: Tobit Coefficients - Part 4

4.D Distribution of Per Capita Expenditure

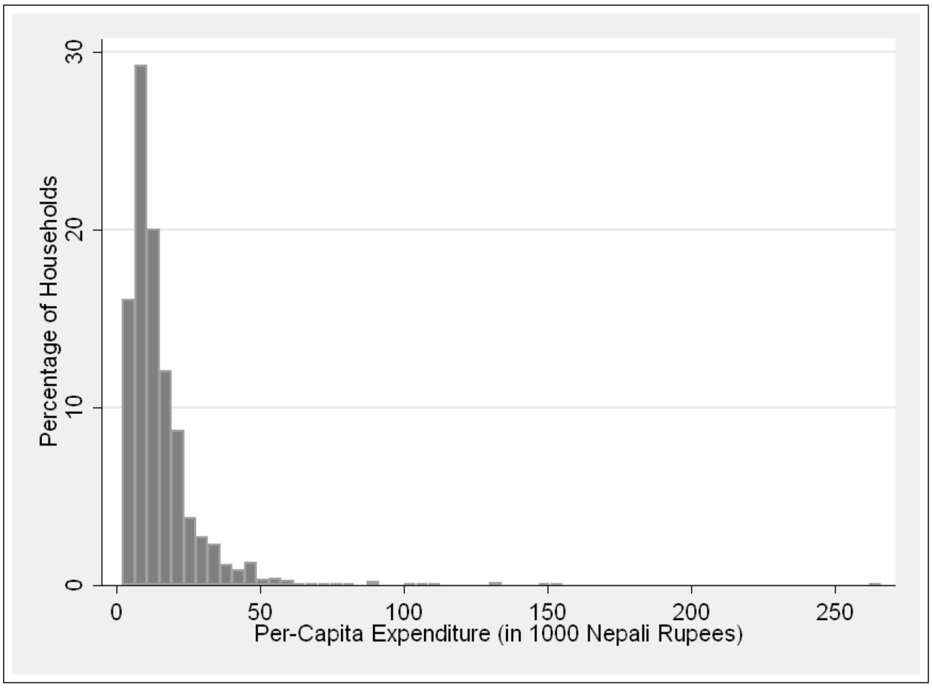

Figure 4.D.1: Frequency distribution of per-capita expenditure (in 1000 Nepali Rupees)

The 5^{th}, 25^{th}, 50^{th}, 75^{th} and 95^{th} percentile of the per-capita expenditure distribution are Rs. 4601, Rs. 8003, Rs. 11613, Rs. 18078 and Rs. 37030 respectively.

4.E Additional Tables and Figures

	(1)	(2)	(3)	(4)	(5)
Dependent Variables: Firewood Collected in Bharis					
Community Forestry: FUG Dummy	-15.436	-15.368	-15.441	-15.833	-12.396
	(2.20)**	(1.62)	(2.18)**	(1.93)*	(0.95)
Per Capita Expenditure	-0.832	-0.827	-0.793	-0.821	-0.618
	(3.39)***	(1.26)	(4.23)***	(1.91)*	(0.52)
Per Capita Expenditure^2	0.001	0.001			-0.005
	(0.53)	(0.10)			(0.25)
Per Capita Expenditure* FUG Dummy	0.621	0.615	0.619	0.651	0.243
	(2.94)***	(0.87)	(2.76)***	(1.38)	(0.19)
Per Capita Expenditure^2* FUG Dummy		0.000			0.009
		(0.01)			(0.42)
Per Capita Expenditure^3			0.000	0.000	0.000
			(0.53)	(0.17)	(0.35)
Per Capita Expenditure^2* FUG Dummy				-0.000	-0.000
				(0.11)	(0.45)
Constant	100.834	100.779	100.457	100.799	99.274
	(17.61)***	(12.51)***	(18.03)***	(15.02)***	(8.57)***
Observations	1523	1523	1523	1523	1523
R-squared	0.02	0.02	0.02	0.02	0.02

Cluster robust t statistics in parentheses
* significant at 10%; ** significant at 5%; *** significant at 1%

Table 4.E.1: OLS Regression on Basic Controls

	(1)	(2)
Dependent Variable: Firewood Collected in *Bharis*		
Household Size	8.8699	8.355
	(11.47)	(11.66)**
Dummy: Land Ownership		16.079
		(1.91)
Distance to Forests	-0.030	-0.018
	(5.10)	(2.46)*
Dummy: Dalits		-0.932
		(0.23)
Dummy: Janjatis		9.286
		(2.10)*
Dummy: Road Access		-7.542
		(1.61)
Dummy : Kerosene Purchased		13.403
		(2.54)*
Dummy:Open Stove		9.160
		(2.30)*
Dummy: Pakka Roof		-2.620
		(0.66)
Dummy : Access to Piped Water		-3.240
		(0.78)
Dummy :Electricity in Ward		-1.015
		(0.18)
Dummy: Police Station		15.088
		(1.42)
Dummy: Post Office		2.361
		(0.34)
Dummy: Telephone Service		-4.779
		(0.79)
Dummy:Paved Road		-1.905
		(0.24)
Dummy: Krishi (Agricultural) Centre		-7.497
		(0.95)
Dummy: Bank Branch Office		-26.835
		(2.05)*
Dummy: Maoist District		-11.988
		(2.24)*
Constant		9.631
		(0.70)
Control for Month of interview	Yes	Yes
Control for Geographical Region	No	Yes
Observations	1523	1523
Number of Clusters	127	127
R-squared	0.1661	0.24

Cluster robust t statistics in parentheses
* significant at 5%; ** significant at 1%

Table 4.E.2: Table showing coefficients of first stage OLS regression
From which I obtain residuals for non-parametric estimation

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