

ABSTRACT

Title of Dissertation: ENDOGENOUS PROPERTY RIGHTS REGIMES,
COMMON PROPERTY RESOURCES,
AND TRADE POLICIES

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International clamor regarding the potential degradation of the environment in developing countries due to opening to trade has been an important issue that has moved from the streets into academic studies. This dissertation links the effect of opening to trade on resource stocks in developing countries by endogenizing the property rights regime choice. The model explains how communities that have communal ownership of a resource stock select the property rights regime governing the use of their resource stock via a voting mechanism. Then, the impact of opening to trade is linked to the choice of the property rights regime and, ultimately, to stock changes over time.

We found that under some plausible assumptions, community members would vote to allow non-community members into the resource sector. Opening to trade,

when the country has comparative advantage in the production of resource intensive goods, does result in a decrease in the long-run equilibrium stock. However, as long as property rights regimes are endogenous and the country follows the optimal trajectory path, we find that degrading the resource stock can be an optimal solution.

A dynamic common property resource game with two sectors in the economy was designed and implemented to test some of the theoretical results. Experimental results indicated that subjects followed a dynamic path, but not the optimal one. The initial choices of the subjects greatly influenced the path which they take in the future. Without instruments or tools to correct for mistakes made during the initial time periods, communities will most likely follow a non-optimal dynamic path.

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COMMON PROPERTY RESOURCES,
AND TRADE POLICIES

by

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DEDICATION

For my Mama and Papa - the best role models a child can ever ask
for.

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TABLE OF CONTENTS

List of Tables	viii
List of Figures	x
1 Introduction	1
1.1 Literature Review	4
1.1.1 Property Rights and Natural Resource Use	4
1.1.2 Trade and the Environment	6
1.2 Main Results	9
2 Dynamic Two-Sector General Equilibrium Model	13
2.1 Analytical Framework	14
2.2 Endogenous Property Rights Regime	18
2.2.1 Theoretical Outline with Homogeneous Community Members	18
2.2.2 Numerical Example with Homogeneous Community Members	25
2.3 Endogenous Property Rights and Majority Voting	28
2.3.1 Theoretical Outline with Heterogeneous Community Mem-	
bers	28
2.3.2 Numerical Example with Heterogeneous Community Mem-	
bers	33

2.4	Endogenous Property Rights in an Infinite Horizon Model	36
3	Trade, Property Rights Regimes and Resource Stocks	54
3.1	Comparative Statics in Finite Horizon Model	55
3.2	Comparative Dynamics in Infinite Horizon Model	59
4	Endogenizing the Trade Policy Choice	67
4.1	Political Economy Structure	69
4.2	Dichotomous Trade Regime Choice	73
4.2.1	Single Lobby Group	75
4.2.2	Two Lobby Groups	79
4.3	Trade Liberalization Over Time	83
4.4	Tariff Rates, Property Rights and Labor Allocation	87
5	Dynamic Common Property Resource Experiment	95
5.1	Hypotheses	98
5.2	Experimental Design	101
5.3	Design Conditions and Parameterization of the Model	107
5.3.1	Functions and Parameters	107
5.3.2	Simulated Results	113
5.4	Descriptive Results	119
5.4.1	Background of Subjects	119
5.4.2	Labor Allocation, Stock Dynamics, Property Rights Regime Choices and Wages	119
5.5	Analysis of the Data	133
5.5.1	Labor Allocation and Property Rights Regime Choice	133
5.5.2	Effect of Trade on Stock	138

6 Conclusion	143
A Numerical Example in Finite Horizon Model	147
A.1 Second Order Conditions in Homogeneous Community Member Case	147
A.2 Second Order Conditions in Heterogeneous Community Member Case	150
B Deriving the Phase Diagram	154
B.1 Deriving the comparative statics	154
B.2 Deriving Isoclines in Each Region of the Phase Space	157
B.3 Characterizing the Steady State Solution	165
C Deriving Effect of Change in Terms of Trade on Stock	167
C.1 Comparative Statics in Two-Period Model	167
C.2 Comparative Dynamics in Infinite Horizon Model	169
C.2.1 Deriving Shifts in Long Run Supply and Long Run Demand Curves	169
C.2.2 Deriving the Change in Long-Run Equilibrium Stock and Marginal User Cost	172
D Phase Diagram Derivation with Endogenous Tariffs	174
E Laboratory Experiment	181
E.1 Sample Instruction Sheet	181
E.2 Computer Interface Screens	188
E.3 GAMS Program Commands	190
E.4 Nash Equilibrium Path for Heterogeneous Community Members .	195
E.5 Test for Ordering Effects	196

LIST OF TABLES

2.1	Optimal Labor Allocations in Two-Period Finite Model with Heterogeneous Community Members	35
5.1	Experimental Design	107
5.2	Parameters of the Laboratory Experiment	109
5.3	Dynamic Nash Equilibrium Paths for Homogeneous Community Members	115
5.4	Myopic Nash Equilibrium Paths for Homogeneous Community Members	116
5.5	Dynamic Nash Equilibrium Paths for Heterogeneous Community Members	117
5.6	Myopic Nash Equilibrium Paths for Heterogeneous Community Members	118
5.7	Background Information of Subjects from Group 1	120
5.8	Percentage of Clusters that Vote to Keep the Resource Stock Open	124
5.9	Mean Squared Deviation of Labor Hours and Property Rights Regime Choice by Community Members	135
5.10	Average Payoff of Subjects Relative to Optimal Solution	136
5.11	Differences in Average Stock Levels Across Treatments	139

5.12 Differences in Property Rights Regime and Labor Allocation Across Treatments	141
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LIST OF FIGURES

2.1	Regions in the Phase Diagram	44
2.2	Adjustment Path and Steady State Values of Resource Stock and Shadow Price of Stock	48
2.3	Potential Property Rights Regime Patterns in an Infinite Horizon Model	49
2.4	Adjustment Path with Multiple Equilibria	51
3.1	Comparative Dynamics in a Change in Relative Price Due to Open- ing to Trade	63
3.2	Property Rights Regimes and an Increase in Output Price due to Opening to Trade	65
4.1	Optimal Contribution of Owners of Capital when Social Welfare Change Coincide with Aggregate Welfare	78
4.2	Optimal Contribution of Owners of Capital when Social Welfare Change Does Not Coincide with Aggregate Welfare	79
4.3	Net Welfare for Owners of Resource Stock with Two Competing Lobby Groups in the Economy	83
4.4	Adjustment Path and Steady State Values of Resource Stock and Shadow Price of Stock with an Endogenous Tariff Rate	93

5.1	Sequence in the Experiment	104
5.2	Average Total Labor in Market 1 with Homogeneous Community Members - Base Treatment	121
5.3	Average Total Labor in Market 1 with Heterogeneous Community Members - Base Treatment	122
5.4	Average Total Labor in Market 1 with Homogeneous Community Members - Price Change Treatment	123
5.5	Average Total Labor in Market 1 with Heterogeneous Community Members - Price Change Treatment	123
5.6	Average Group 1 Labor in Market 1 with Homogeneous Commu- nity Members - Base Treatment	125
5.7	Average Group 1 Labor in Market 1 with Heterogeneous Commu- nity Members - Base Treatment	126
5.8	Average Group 1 Labor in Market 1 with Homogeneous Commu- nity Members - Price Change Treatment	127
5.9	Average Group 1 Labor in Market 1 with Heterogeneous Commu- nity Members - Price Change Treatment	127
5.10	Average Stock Over Time with Homogeneous Community Mem- bers - Base Treatment	128
5.11	Average Stock Over Time with Heterogeneous Community Mem- bers - Base Treatment	129
5.12	Average Stock Over Time with Homogeneous Community Mem- bers - Price Change Treatment	129
5.13	Average Stock Over Time with Heterogeneous Community Mem- bers - Price Change Treatment	130

5.14 Average Wage Over Time with Homogeneous Community Mem- bers - Base Treatment	131
5.15 Average Wage Over Time with Heterogeneous Community Mem- bers - Base Treatment	131
5.16 Average Wage Over Time with Homogeneous Community Mem- bers - Price Change Treatment	132
5.17 Average Wage Over Time with Heterogeneous Community Mem- bers - Price Change Treatment	132

Chapter 1

Introduction

Common pool resources, such as fisheries, irrigation systems and grazing areas, serve important roles in the development and livelihood of communities in developing countries. There may be no restriction on the use of the common pool resources (open access) or its use can be governed by an individual (private property) or a group of individuals (common property). Private-property ownership is a potentially effective way of managing the use of a resource. However, this type of ownership may not always be feasible. In developing countries where whole communities claim ownership to a particular resource, it is not uncommon to find community-based management schemes governing the use of common property resources.

Extraction from common pool resources is often characterized as over-harvested. Over extraction can be attributed to users of the resource stock failing to internalize two types of externalities. The first is an intra-temporal externality or “crowding out effect,” where own harvest affects the availability of harvest for other users during the current time. The second is an inter-temporal externality or “stock effect” in which current harvest decreases available stock for the future. The type of property rights regime governing the use of the resource stock is

instrumental in determining how well the resource stock is managed over time and the effect of any externality on harvest (Anderson and Simmons, 1993). As communities who have *de facto* rights over the use of the resource evolve and as the institutions governing resource use develop, the type of property rights regime can also change over time, which has a significant impact on the resource stock.

Studies have argued the need to model property rights regime as endogenous (Anderson and Hill, 1975; Field, 1989; De Meza and Gould, 1992; Hotte, et al., 2000). Property rights can evolve from an open-access regime to community-managed open access regime or even to private-property management. Factors such as the existing number of agents in the community, type of agents in the community, cost of enforcing property rights, availability of local government support to enforce laws and economic conditions affect the decision of the community to adopt a particular property rights regime (Baland and Platteau, 1997a, 1997b, Umbeck, 1981). However, one important factor that determines the choice of property rights regimes governing a particular common property resource is the political economy structure prevailing within communities.

Aside from the direct impact of the political economy structure of the governing community on resource stocks, we also look into the effect of opening the resource stock to trade via property rights regime changes. Opening to trade can adversely affect the natural resource stock, and consequently, welfare, of countries that have poorly-defined property rights regimes. Chichilnisky (1994) formulated a static model to show that developing countries with poorly defined property rights regimes will earn short-run gains from trade but their welfare decreases in the long-run. Similarly, Brander and Taylor (1997a) developed a two-sector

general equilibrium model with a dynamic resource stock showing the effect of opening to trade on a small open economy. Short-run welfare gains are derived from trade, but in the long run, these gains are offset by continual resource depletion. In both of these studies, the underlying assumption that drives the results of their models is that property rights regimes are exogenous. The lack of well-defined property rights causes over-use of the resource stock and can be exacerbated by increases in the demand of output derived from the stock. However, in reality, property rights regimes change over time.

In this dissertation, a thorough analysis of the dynamic link between international trade, property rights regimes in common property resources and resource stocks over time is provided. In order to understand the effect of trade on resource stocks, it is first important to understand how property rights regime change via a political economy process. Deriving and understanding how property rights regimes evolve over time is important because these institutions determine the long-run sustainability of any natural resource stock (Adger and Luttrell, 2000). Once we have established the link between endogenous property rights regimes and their effect on the resource stock, we can derive the total effect of opening to trade on resource stocks.

One of the main findings in this dissertation is that the choice of the property rights regime governing the use of the resource stock is affected by the crowding out effect and stock effect. A finite number of property rights regime patterns, which maximize the welfare of owners of a resource stock, are derived. Opening to trade affects the choice of property rights regimes as well as the resource stock. Communities that have comparative advantage in the production of a resource-based good may allow the stock to grow prior to the opening of trade. However,

the long-run equilibrium resource stock declines even with endogenous property rights regimes under communal management. The decision of the community to degrade their resource stock is not solely motivated by myopic welfare gains but by a solution that maximizes wealth over time.

1.1 Literature Review

This dissertation is related to two broad areas of the existing literature: (1) property rights and natural resource use; and (2) the effect of trade on the environment.

1.1.1 Property Rights and Natural Resource Use

Community-owned or community-managed resource stocks characterize a number of property rights regimes in developing countries (Maggs and Hoddinott, 1997). Coastal fishery resources, forest tracts, and grazing land are some of the examples of natural resources that are community-managed in developing countries. The type of property rights regime, whether formal or informal, can adversely or favorably impact the natural resource stock. In some countries occupying the Amazon Basin and in the outer islands of Indonesia, farmers clear unprotected forest areas because they fear that failure to do so would mean losing the land to their neighboring competitor (Rudel, 1995). Due to the open-access nature of the resource, as well as lack of formal social control by governments, open-access regimes are commonly believed to go hand in hand with resource depletion.

Conventional theorists assume that only an all powerful government can limit the use of a resource stock. However, informal social control from the community

using the resource stock also plays a significant role in determining the long-run stock of a resource. Indigenous groups have their own customary laws that can protect the resource stock. By imposing informal social controls, communities limit the access of the resource stock to non-community residents (McCay and Acheson, 1987). Such practices have been observed in countries such as Brazil, Colombia, Costa Rica, Japan, the Philippines, Spain and Switzerland (Reinhart, 1988; Ostrom, 1990; Cruz, et al., 1992; Wright, 1992).

Social controls, whether formal or informal, change over time. In Amazonian Ecuador, the Ecuadorian government passed a law which stated that claimants could establish ownership through use. A significant number of peasants migrated to the Amazon. This migration resulted in settlement and deforestation during the late 1960s. By 1970, a set of informal social controls among settlers began which discouraged land invasions and land clearings in disputed areas resulting in less deforestation (Rudel, 1995). In San Miguel Bay, Philippines, the fishery stock was depleted due to overfishing during the 1980s. However, after the institution of formal organizations aimed at managing the resource through the community, less pressure has been put on the fishery stock (Sumalde and Pedroso, 2001).

Aside from anecdotes relating property rights regimes and their effect on resource stocks, theoretical models also exist. The current property rights regime can significantly affect the use of a resource stock (Angelsen, 1999). Private-property ownership is usually deemed effective because owners internalize any existing externality associated with the use of a resource. However, shifting from complete open-access to private-property ownership is not always feasible. Given the difficulty in establishing government control of common property resources, especially in developing countries, several studies have advocated the development

of community-based management schemes to preserve and increase environmental quality (Ostrom, 1990; Sandler, 1992; Baland and Platteau, 1996).

The evolution of property rights regimes can not only protect the environment, but also reduce uncertainty and increase efficiency in the market of the resource (Feder and Feeny, 1991). The decision for any community to change the existing institution governing the use of a resource stock can be modelled using a voting mechanism (Vyrastekova and Van Soest, 2003). Different voting rules that govern a polity exist. The most common voting rule under a pure democratic regime is a majority voting rule. Under a majority voting rule, only half of the population plus one is required to support or carry out any issue (Mueller, 1979).¹ In this voting rule, the preference of the median voter determines the outcome of any election. Therefore, if the median voter derives more utility from the adoption of a particular program, he would vote to establish that program.

The literature has largely ignored the role of community voting in determining the governing institution that regulates the use of a resource stock. This dissertation develops a model about the voting equilibrium of a community that institutes the property rights regime governing the use of a resource stock.

1.1.2 Trade and the Environment

The pioneers in the trade and environment literature began publishing during the early 1970s (Baumol, 1971; Magee and Ford, 1972; Walter, 1973). However,

¹In reality, representative democracies that exist in various countries may not necessarily adhere to the majority voting rule. In the United States for example, the choice for presidency depends upon the electoral college and not the popular vote. Here, one may lose the popular vote but win the electoral college due to the preference of a "minority." Thus, caution must be taken in interpreting and applying results from the model to the real world.

increased public awareness of the potential threat on environmental quality by opening to trade has resulted in a substantial expansion in the trade and environment literature. Panayatou (1993) defines the environment as “both the quantity and quality of natural resources, renewable and nonrenewable.” The environment can be categorized into two types: natural resource stocks, such as mines, forests and fisheries; and the ambient environment, which consists of water, air, landscape and the atmosphere. In the model, we focus on the former type.

Little or no *direct* link (price effects) relating the effect of trade on the environment has been found empirically or theoretically (Antweiler, et al., 2001; Alpay, 2001; Copeland and Gulati, 2004; Copeland, 2000; Copeland and Taylor, 2004; Kahn and McDonald, 1994; Shafik, 1994).² However, trade policies can significantly affect either the natural resource stocks or the ambient environment through factors that influence the comparative advantage of countries. Some of the determinants of comparative advantage among countries through which trade may affect the environment are the differences in endowments of natural resources, technological efficiency, governing institutions, and property rights regimes (Abler, et al., 1999; Antweiler, et al., 2001; Alpay, 2001; Bourgeon and López, 1999; Brander and Taylor, 1997a and 1997b; Chichilnisky, 1994; Copeland and Taylor, 1994; López and Galinato, 2005; Chintrakarn and Millimet, 2006).

Countries that specialize in dirty (clean) technologies will increase dirty (clean) output as trade liberalization occurs, consequently depreciating (improving) en-

²There is a related strand in the literature that evaluates the potential causal link between the environment and trade flows. Tightening of environmental regulations have been shown to significantly impact the choice of plant location and trade flows at the margin (see Copeland and Taylor, 1994 for a review of these studies).

vironmental quality (Grossman and Krueger, 1991). Similarly, countries that are endowed with more natural resources tend to specialize in goods that are natural resource intensive. As the economy of these countries opens to trade, more pressure is put on the natural resource stock during trade liberalization (Alpay, 2001).

Countries with more open access to natural resources or less stringent environmental regulations gain comparative advantage in the production of resource-based goods relative to other countries with more developed institutions. Developing countries have relatively less developed property rights regime governing the use of a resource stock compared with more developed countries. Consequently, developing countries with weak institutions will likely see a degradation of natural resource stock and decline in social welfare (Chichilnisky, 1994; Brander and Taylor, 1997a and 1998).

However, existing institutions can evolve from an open-access regime to a more protected system. Margolis and Shogren (2002) extend the North-South trade model of Chichilnisky by allowing for endogenous property enforcement rights. Given a specific set of world prices, they show that welfare losses can occur even when local governments make choices to close the hinterland. Hotte, et al. (2000) develop a model of trade and dynamic resource stock with the cost of enforcing property rights endogenized. They show that by opening to trade, a country changes the enforcement level governing resource use, which results in a greater resource stock. Social welfare could decrease if the gains from the current owner of the resource from enforcing the property right are outweighed by the loss of income from poachers of the resource stock. In reality, individuals have the option of working in various sectors of an economy. It would be interesting to look at how members of a community, who have *de facto* property rights to a resource

stock, govern its use when employment opportunities are available elsewhere.

This dissertation investigates how the choice of a community to manage a particular resource stock is affected by economic conditions, such as trade. Since we focus mostly on small communities within an economy, we disregard any potential feedback that resource regulation may create on trade flows. Of particular interest in this study is to model how property rights evolve via a voting mechanism within agents of a community. The effect of voting on the choice of the governing rule of the use of a resource stock in a dynamic economic framework has largely been ignored by the literature so far.

1.2 Main Results

The remainder of the dissertation is organized as follows. Chapter 2 introduces a dynamic two-sector general-equilibrium model that analyzes the type of property rights regime governing the use of a dynamic common property resource. Chapter 3 links the effect of opening to trade on the choice of the property rights regime and the resource stock. Chapter 4 extends the basic theoretical framework by endogenizing the trade regime choice by the government. Chapter 5 tests selected hypotheses derived from the theoretical results of the model using a laboratory experiment. Chapter 6 concludes the dissertation.

The general framework that is used in the dissertation is a dynamic two-sector general equilibrium model, which is akin to a dynamic version of a Ricardo-Viner model. There are two sectors in the economy, a resource sector and a manufacturing sector, and three types of inputs: capital, a dynamic resource stock, and labor. The type of labor can come from two sources: the community and non-community. The main difference between the two sources of labor is that

individuals from the community have *de facto* property rights over the use of a resource stock while non-community members do not. The owners of capital maximize quasi-rent from capital by hiring labor while the owners of labor maximize earnings by allocating labor hours in the two sectors over time.

The general framework is analyzed in a two-period finite horizon model and an infinite period horizon model to determine potential property rights regimes adopted by the community. In both models, two externalities influence the choice of property rights regimes chosen by the community: the crowding out effect and the stock effect. In the two-period finite horizon model, the resource stock may be kept open to non-community members during any period. The marginal gains from keeping the resource stock open are equal to the increase in wage in the manufacturing sector plus the gains in preserved stock by crowding out harvest by other community members. If the marginal gains of allowing entrance are greater than the marginal cost, some non-community members would be allowed to enter the resource sector. When we analyze an infinite horizon model, we eliminate the possibility of a cyclical property rights regime pattern as an optimal solution because of the ability of the community to internalize some of the stock effect in the future (see Chapter 2).

Trade policy effects are introduced in two ways in the general equilibrium model. First, we introduce an exogenous shock affecting the terms of trade. In the two-period model, the effect of an announced opening to trade during the second period leads to an increase in the resource stock prior to trade liberalization. Once free trade is implemented, the resource stock may or may not decline in the next period. However, in the infinite horizon model, we find that the equilibrium long-run resource stock decreases given a permanent increase in the relative price

in the resource sector. Thus, if the country can optimally select the property rights regime governing the resource stock and follow the optimal dynamic path, degrading the resource stock would lead to maximizing community welfare. It is important to note that observing a decrease in stocks due to opening to trade is not sufficient to conclude that the community maximizes welfare. The decline in stock must follow the optimal dynamic path to ensure that welfare is maximized (see Chapter 3).

The second way the trade policy effects are introduced in the model is through the government endogenously determining the trade policy in the presence of various lobby groups within the economy. If only a single lobby group exists, the lobby group can influence the government to select a trade regime, free trade or autarky, that maximizes their welfare as long as the political weight placed by the government on lobby contributions are significant. When two equally powerful lobby groups exist, the lobby group with policy preferences that maximize social welfare will lobby in order to ensure that its preferred trade regime is chosen. We also analyze the effect of an endogenous tariff rate in the political economy model. We find that the optimal tariff rate protecting a particular sector should vary over time and depends upon the contributions received by the government, marginal returns from the tariff as well as the marginal impact of the tariff on the resource stock. Similar to the baseline infinite horizon model, we derive the same potential property rights regime patterns when tariff rates are endogenous (see Chapter 4).

A dynamic common property resource laboratory experiment was designed to determine the decision rules affecting labor allocation decisions and property rights regime patterns; and to determine the effect of trade on the resource stock.

We find that labor allocation decisions and the choice of property rights regimes do not follow the optimal dynamic equilibrium path. The initial choice during the first few rounds, have a significant effect on future choices. If subjects start with the wrong choices in the initial round, they would never reach the optimal path. Furthermore, groups have been found to increase the stock prior to the price increase in the future round and degrade the resource stock once the price increase is in effect. This behavior does seem to indicate that subjects do internalize some of the stock effect over time but they are on a non-optimal dynamic path because they choose the wrong labor allocations in the first few round (see Chapter 5).

Chapter 2

Dynamic Two-Sector General Equilibrium

Model

A two-sector general equilibrium model is developed that incorporates an endogenous change in the property rights regime governing the use of a dynamic resource stock. This model adapts the Ricardo-Viner model commonly used in analyzing international trade. Jacob Viner (1937) first examined the specific factors model, a variation of the Ricardian model that allows for diminishing returns to a mobile input as output increases. The model was popularized by Jones (1971) and Samuelson (1971), while Mussa (1974) developed the well-known graphical results from the model. The Ricardo-Viner model is a type of specific factors model where there are two sectors and three inputs. Two of the inputs are fixed and specific to the two sectors while a third input is mobile.

In the first section of this chapter, the basic structure of the model is presented. Then, the optimal property rights regime patterns governing the use of the resource stock are determined under three scenarios: two-period model with homogeneous community members; two-period model with heterogeneous community members; and an infinite horizon model with homogeneous community

members.

2.1 Analytical Framework

The two sectors in the economy are the manufacturing sector and the resource sector. There are three factor endowments available in the economy. The manufacturing sector and the resource sector are endowed with capital and a resource stock, respectively; while labor is a mobile input that can be used in either sector.

One unit of labor is interpreted as an hour of hired labor in the manufacturing sector or an hour devoted to harvesting in the resource sector. From this point forward, the terms *community* and *non-community* refer to the two main sources of labor. Community members have *de facto* property rights to the resource stock while non-community members do not. That is, the level of labor that can be allocated by non-community members to the resource sector is subject to direct control by the community members. The distribution of community and non-community members are exogenously determined. Labor allocated at time t in the resource sector and the manufacturing sector by the community member is represented by l_{ct} and l_{ct}^* , respectively. Also, labor allocated at time t in the resource sector and the manufacturing sector by the non-community member is denoted by l_{nt} and l_{nt}^* , respectively. The maximum available labor hours at time t for any individual is h . The total number of community members and non-community members are C and N , respectively. We assume in most of our analysis that $C = N$.

Production in the manufacturing sector at time t is characterized by an increasing, concave, constant returns production function, $Y_x(K, L_{xt})$ where L_{xt} is the total labor allocated at time t in the manufacturing sector and K is capital

endowment in the manufacturing sector. Here, total labor allocated in the manufacturing sector, L_{xt} , is equal to $\sum_{c=1}^C l_{ct}^* + \sum_{n=1}^N l_{nt}^*$. The objective of the owners of capital at period t is to maximize quasi-rent from capital, r_t , by optimally choosing labor given a market wage rate at time t , w_t . Normalizing output price to 1 results in the following objective function,

$$\max_{L_{xt}} r_t = Y_x(K, L_{xt}) - w_t L_{xt}. \quad (2.1)$$

The first order condition that determines the optimal value is the following,

$$\frac{\partial Y_x(K, L_{xt})}{\partial L_{xt}} = w_t. \quad (2.2)$$

At each time, the value of marginal product is equal to the equilibrium wage rate.

The resource sector is initially characterized as an open access resource with no single owner. Entrants into the sector, who devote a positive amount of effort, derive earnings from harvest. Effort is a function, f , which captures partial returns from the resource sector given own labor and labor from other entrants into the sector. Assuming that the harvest per unit effort is directly proportional to the stock, the harvest, H , for the j^{th} individual at time t can be expressed as (Clark, 1985),

$$H_j(S_t, L_{-jt}, l_{jt}) = \alpha_j S_t f(L_{-jt}, l_{jt}), \quad (2.3)$$

where $f(L_{-jt}, l_{jt}) : D \rightarrow [0, \frac{1}{\alpha_j}]$ is continuously differentiable. Here, D are labor hours in the domain, α_j is the harvestability coefficient of the j^{th} individual, S_t is the resource stock at time t , l_{jt} is the labor devoted by the j^{th} individual at time t , and L_{-jt} is the summation of all labor hours devoted by other individuals at time t . For example, for the c^{th} community member, $L_{-ct} = \sum_{i \neq c}^C l_{it} + \sum_{n=1}^N l_{nt}$

but for the n^{th} non-community member, $L_{-nt} = \sum_{c=1}^C l_{ct} + \sum_{i \neq n}^N l_{it}$. Total harvest is nondecreasing in the stock and if there is no stock, harvest is zero. The effort function by the j th individual is assumed to be $f(L_{-jt}, 0) = 0$, $\partial f(L_{-jt}, l_{jt})/\partial l_{jt} \geq 0$, and $\partial^2 f(L_{-jt}, l_{jt})/\partial l_{jt}^2 \leq 0$. Furthermore, we assume that $\partial f(L_{-jt}, l_{jt})/\partial l_{-jt} \leq 0$, $\partial^2 f(L_{-jt}, l_{jt})/\partial l_{-jt}^2 \geq 0$ and $\partial^2 f(L_{-jt}, l_{jt})/\partial l_{jt} \partial l_{-jt} \leq 0$ where $l_{-jt} \in L_{-jt}$ representing labor from an individual other than j at time t .

Given the common-property nature of the resource stock, two types of externalities are examined: a *crowding out effect* during each period, $\partial H_j/\partial l_{-jt}$, and a *stock effect* across time, $\mu_{t+1} \partial H_j/\partial l_{jt}$, where μ_{t+1} is the marginal user cost of the resource stock at time $t + 1$. The marginal user cost of the resource stock is derived from the costate variable in the dynamic optimization problem in the next section. The crowding out effect results from congestion when effort applied by other individuals interferes with the current harvest. The stock effect refers to the reduction in future harvest due to individuals ignoring the effect that their own action has on future stock productivity.

One critical assumption that is made throughout the analysis is that the harvestability coefficient of community members are always greater than non-community members. The differences arise from the inherent capabilities of community members to harvest given that they have had rights over the use of the resource stock and have had more experience and developed more efficient technologies to harvest. New entrants into the resource stock, such as non-community members, would still have to develop their skills or acquire new technology to extract from the resource stock. In this way, the assumption made in this analysis is plausible.

Individuals allocate labor in either sector depending on their returns from

each sector. A laborer from the resource sector can harvest from the resource stock and is faced with the wage in the manufacturing sector as his opportunity cost. Total income, I_{jt} , by the j^{th} individual at time t can be shown as follows,

$$I_{jt} = w_t l_{jt}^* + p_t \alpha_j S_t f(L_{-jt}, l_{jt}) \quad (2.4)$$

where p_t is the price of the harvested output from the resource sector relative to price of the output in the manufacturing sector at time t . Total wealth, W_j , by the j^{th} individual is the summation of discounted income from a starting period, 0, until the end period, T ,

$$W_j = \sum_{t=0}^T I_{jt} = \sum_{t=0}^T (w_t l_{jt}^* + p_t \alpha_j S_t f(L_{-jt}, l_{jt})) \delta^t \quad (2.5)$$

where δ is the discount factor.

The change in stock over time depends on the natural growth function of the stock and harvest by all individuals from the community and non-community. The stock dynamics are expressed as,

$$S_{t+1} - S_t = G(S_t) - \sum_{c=1}^C \alpha_c S_t f(L_{-ct}, l_{ct}) - \sum_{n=1}^N \alpha_n S_t f(L_{-nt}, l_{nt}). \quad (2.6)$$

Here, $S_{t+1} - S_t$ is the change of stock over time, $G(S_t)$ is the natural growth function of stock when there is no harvest, and α_c and α_n are the harvestability coefficients of community and non-community members, respectively. Total harvest does not exceed the available stock at any time t , *i.e.* $S_t \geq \sum_{c=1}^C \alpha_c S_t f(L_{-ct}, l_{ct}) + \sum_{n=1}^N \alpha_n S_t f(L_{-nt}, l_{nt})$. A steady state resource stock occurs when the natural growth of the stock is equal to the harvested amount at a particular time, *i.e.* $G(S_t) = \sum_{c=1}^C \alpha_c S_t f(L_{-ct}, l_{ct}) + \sum_{n=1}^N \alpha_n S_t f(L_{-nt}, l_{nt})$.

2.2 Endogenous Property Rights Regime

2.2.1 Theoretical Outline with Homogeneous Community Members

This section investigates when the community, which has *de facto* rights to the resource stock, will choose to close or keep the resource stock open to non-community members. Results from this section provide a baseline for comparing more realistic cases that examine endogenous changes in property rights regimes through voting. Two property rights regimes are examined: limited open-access and community-managed open-access. The former refers to entrance by any community member and a limited number of non-community members into the resource sector, where the limit is determined by community members. The latter refers to entrance of community members only into the resource sector. Under community-managed open access, even though non-community members are not allowed into the resource sector, open access amongst community members still prevails. To simplify the analysis, assume that there is no cost of enforcement. Perfect information among all players and perfect foresight are assumed in this analysis. The equilibrium concept is Nash.¹ It gives the set of labor hours and wage rate in all periods that maximizes earnings for each individual while taking the behavior of all other individuals as given. The optimal Nash strategy solution is assumed to follow an open loop solution. The optimal open loop strategy for

¹Walker, Gardner and Ostrom (1990) conducted a common pool resource laboratory experiment to test if Nash equilibrium is a good predictor of behavior. They found that aggregate groups do follow a Nash equilibrium pattern in some treatments (see Chapter 5 for a more in depth discussion of the common pool resource experimental literature).

a subject shows that the labor allocation in the two sectors during each period of the economy are contingent upon the initial stock, termination time and the current period. This implies that all community members must simultaneously commit to a particular strategy during the initial period and follow it through the entire game. Subjects do not adjust their strategy based on their observation of the current stock level nor do they receive any new information during the planning horizon (Amir and Nannerup, 2004).

In this baseline model, community members live a finite period of time and only care about their own welfare over this period. To simplify our analysis, we assume that there are only two periods with community members and non-community members having harvestability coefficients α_c and α_n , respectively, where $\alpha_c > \alpha_n$. The objective of each community member is to maximize own earnings over two periods given the stock dynamics. Community members are only endowed with their own labor, which they can allocate in either the resource sector or the manufacturing sector. Community members can earn a wage rate from the manufacturing sector or the value of their harvest from the resource stock. However, since community members also have *de facto* property rights over the use of the resource stock, they also choose the amount of labor that non-community members are allowed to use within the resource sector. Thus, a community member chooses the amount of labor allocated in both sectors in each period, l_{c0}^* , l_{c1}^* , l_{c0} , and l_{c1} , and the amount of non-community labor, l_{n0} , and l_{n1} , allowed into the resource sector in both periods. In order to ensure that non-community members enter into the resource sector whenever l_{nt}^* is offered by community members, the value of marginal product of non-community members evaluated at l_{nt}^* must be greater than or equal to the prevailing wage rate, i.e.

$p_t \alpha_n S_t \frac{\partial f(L_{-nt}, l_{nt}^*)}{\partial l_{nt}} \geq \frac{\partial Y_x}{\partial L_{xt}}$. Using equations (2.5) and (2.6) and assuming homogeneous community members, the maximization problem of the representative c^{th} community member is written as,

$$\max_{l_{c0}^*, l_{c1}^*, l_{c0}, l_{c1}, l_{n0}, l_{n1}} W_j = \sum_{t=0}^1 (w_t l_{ct}^* + p_t \alpha_c S_t f(L_{-ct}, l_{ct})) \delta^t$$

$$s.t. \quad S_1 = S_0 + G(S_0) - C \alpha_c S_0 f(L_{-c0}, l_{c0}) - N \alpha_n S_0 f(L_{-n0}, l_{n0}); \quad l_{ct} + l_{ct}^* = h;$$

where δ is the discount factor; $L_{-c0} = \sum_{i \neq c}^C l_{i0} + \sum_{n=1}^N l_{n0}$; and $L_{-n0} = \sum_{c=1}^C l_{c0} + \sum_{i \neq n}^N l_{i0}$. By substituting S_1 from the stock dynamics and l_{ct}^* from the labor constraint into the objective function, the community member's objective function can be re-written as,

$$\max_{l_{c0}, l_{c1}, l_{n0}, l_{n1}} W_j = \sum_{t=0}^1 (w_t (h - l_{ct}) + p_t \alpha_c S_t f(L_{-ct}, l_{ct})) \delta^t, \quad (2.7)$$

where $S_1 = S_0 + G(S_0) - C \alpha_c S_0 f(L_{-c0}, l_{c0}) - N \alpha_n S_0 f(L_{-n0}, l_{n0})$. The community member's problem is reduced to that of optimally choosing his/her own and non-community labor allocations in the resource sector.

The owners of capital in the manufacturing sector maximize quasi-rent from capital by optimally choosing labor as shown in equation (2.1). The Nash equilibrium wage rate is endogenously determined during both periods t .² More (less) labor in the manufacturing sector decreases (increases) the value of marginal product of labor, consequently, (increasing) lowering the equilibrium wage. How-

²The equilibrium wage is assumed to be endogenously determined from a competitive market. However, the output price is assumed to be exogenous for this exercise. The presence of close substitutes to the resource based output justifies this assumption.

ever, from the community member's point of view, wage is exogenous because no single individual can influence the wage rate.

Equation (2.2) shows the necessary condition for quasi-rent maximization. By substituting w_t using (2.2) into the first-order conditions from the community member's maximization problem, the conditions that solve for the Nash equilibrium are,

$$\begin{aligned} \frac{\partial W_j}{\partial l_{c0}} &= (p_0 - \mu_1 C) \alpha_c S_0 \frac{\partial f(L_{-c0}, l_{c0})}{\partial l_{c0}} - \mu_1 N \alpha_n S_0 \frac{\partial f(L_{-n0}, l_{n0})}{\partial l_{c0}} - \frac{\partial Y_x}{\partial L_{x0}} \leq 0; \\ (h - l_{c0}) \frac{\partial W_j}{\partial l_{c0}} &= 0; \end{aligned} \quad (2.8)$$

$$\frac{\partial W_j}{\partial l_{c1}} = p_1 \alpha_c S_1 \frac{\partial f(L_{-c1}, l_{c1})}{\partial l_{c1}} \delta - \frac{\partial Y_x}{\partial L_{x1}} \leq 0; \quad (h - l_{c1}) \frac{\partial W_j}{\partial l_{c1}} = 0; \quad (2.9)$$

$$\frac{\partial W_j}{\partial l_{n0}} = p_0 \alpha_c S_0 \frac{\partial f(L_{-c0}, l_{c0})}{\partial l_{n0}} - \mu_1 \alpha_c S_0 C \frac{\partial f(L_{-c0}, l_{c0})}{\partial l_{n0}} - \mu_1 N \alpha_n S_0 \frac{\partial f(L_{-n0}, l_{n0})}{\partial l_{n0}} \leq 0; \quad (2.10)$$

$$l_{no} \frac{\partial W_j}{\partial l_{n0}} = 0;$$

$$\frac{\partial W_j}{\partial l_{n1}} = p_1 \alpha_c S_1 N \frac{\partial f(L_{-c1}, l_{c1})}{\partial l_{n1}} \delta \leq 0; \quad l_{n1} \frac{\partial W_j}{\partial l_{n1}} = 0. \quad (2.11)$$

Here, $\mu_1 \equiv p_1 \alpha_c f(L_{-c1}, l_{c1}) \delta$ is the marginal user cost or the shadow price of the resource stock. The shadow price of the resource stock is the "implicit" or "planning" price that a stock, as a productive input, will take if labor is optimally allocated over time.

Simultaneously solving for equation (2.8) to (2.11) along with the market clearing conditions during each time, $l_{ct} + l_{ct}^* = h$ and $l_{nt} + l_{nt}^* = h$, will yield the Nash equilibrium values for labor devoted by each individual as well as the optimum wage rate. Given the assumption that all community members have the same harvesting coefficient, a symmetric Nash equilibrium is derived where all the labor decisions within the community are the same. In order to ensure that we have derived a local maximum, the second order conditions associated with the model must be satisfied. Suppose that x^* satisfies the necessary conditions in our general equilibrium problem. A local maximum is achieved if the determinants of principal minors of the Hessian evaluated at x^* alternate in sign. The Hessian in this two-period model is shown to be,³

$$H = \begin{bmatrix} \frac{\partial^2 W_j}{\partial l_{c0}^2} & \frac{\partial^2 W_j}{\partial l_{c0} \partial l_{c1}} & \frac{\partial^2 W_j}{\partial l_{c0} \partial l_{n0}} & \frac{\partial^2 W_j}{\partial l_{c0} \partial l_{n1}} \\ \frac{\partial^2 W_j}{\partial l_{c1} \partial l_{c0}} & \frac{\partial^2 W_j}{\partial l_{c1}^2} & \frac{\partial^2 W_j}{\partial l_{c1} \partial l_{n0}} & \frac{\partial^2 W_j}{\partial l_{c1} \partial l_{n1}} \\ \frac{\partial^2 W_j}{\partial l_{n0} \partial l_{c0}} & \frac{\partial^2 W_j}{\partial l_{n0} \partial l_{c1}} & \frac{\partial^2 W_j}{\partial l_{n0}^2} & \frac{\partial^2 W_j}{\partial l_{n0} \partial l_{n1}} \\ \frac{\partial^2 W_j}{\partial l_{n1} \partial l_{c0}} & \frac{\partial^2 W_j}{\partial l_{n1} \partial l_{c1}} & \frac{\partial^2 W_j}{\partial l_{n1} \partial l_{n0}} & \frac{\partial^2 W_j}{\partial l_{n1}^2} \end{bmatrix}. \quad (2.12)$$

In this Hessian, different principal minors can be formed. Denote the principal minor containing $\frac{\partial^2 W_j}{\partial l_{c1}^2}$, as the last element of the principal diagonal as, H^1 . If we include one more column and one more row such that the last principal diagonal contains, $\frac{\partial^2 W_j}{\partial l_{n0}^2}$, we derive another principal minor called H^2 . With these notations, we can denote the conditions needed to ensure a maximum. If the sign of the determinants of the principal minors alternate in sign, then we derive a maximum, i.e. $\det |H^1| > 0$, $\det |H^2| < 0$, and $\det |H| > 0$.

The interpretation of equations (2.8) and (2.9) is straightforward and mani-

³See Appendix A.1 for formulas derived for second order conditions.

festes the optimal conditions for labor allocation in a Ricardo-Viner Model. Equation (2.9) tells us that if an interior solution exists, the optimal labor allocation is satisfied when the values of marginal product in both sectors are equal during the second period. Because individuals live only until the second period, they do not internalize the stock effect nor the crowding out effect of other individuals.⁴ From (2.8) we see that during the first period, the value of marginal product in the manufacturing sector is equal to the value of marginal product in the resource sector minus the marginal crowding out effect of non-community members. Here, the value of marginal product from the resource sector is adjusted for the stock effect from all entrants into the resource sector during the first period. Thus, we see that community members partially internalize the stock effect and the crowding out effect over the two-period horizon model.

Equations (2.10) and (2.11) show the marginal contribution of non-community labor to the income of the representative community member. If the representative community member earns negative marginal returns from the inclusion of non-community members into the resource sector, the representative community member would prefer to close the resource sector to non-community members. The community members would always opt to close off the resource stock during the second period since their returns from allowing non-community labor is always negative as shown in (2.11). During the first period, increasing non-community labor crowds out some harvest by the community. The community member in-

⁴If we solve for the social planner's problem, the crowding out effect and stock effect will fall out from the model. In this case, the social planner can employ instruments, such as a Pigouvian tax, to capture all the rent from the resource stock. However, for the purposes of this study, the focus is only on the endogenous choice of the community to keep the resource stock open or closed.

ternalizes some of the crowding out effect from the entrance of non-community members as shown by the positive effect on community earnings from the second term in (2.10), $-\mu_1 \alpha_c S_0 C \frac{\partial f(L_{-c0}, l_{c0})}{\partial l_{n0}}$. Allowing entrance of non-community labor in the first period decreases marginal returns for all entrants into the resource sector. Because the crowding out effect is internalized by community members, they are willing to shift labor from the resource sector to the manufacturing sector. Less pressure is put on the resource stock and may result in more stock available for future harvest. Thus, allowing non-community members into the resource stock in the first period results increasing future benefits in the form of more resource stock in the next period. Whenever these marginal gains of allowing entrance into the resource sector is larger than the marginal cost, the community will open the resource sector.⁵ The critical assumption that leads to a potential opening of the resource stock in the second period is the difference in the harvestability coefficient between community and non-community members. The assumption stating that community members have a higher harvestability coefficient than non-community members is a necessary condition that would lead to opening the resource sector. In this two-period general equilibrium model, there are two property rights regime patterns that emerge: closed during both periods, and open in the first period and then closed in the last period.

⁵A simple mechanism that allows a limited amount of non-community members is a freely-distributed capped permit system for non-community members.

2.2.2 Numerical Example with Homogeneous Community Members

We prove that opening the resource stock during the first period can be an optimal decision by using a numerical example. Total labor endowment for each individual in the economy, h , is equal to 10. Here, any community member or non-community member can allocate at most 10 labor hours in the two sectors in the economy. There are a total of 5 community members and 5 non-community members, i.e. $C = N = 5$. The production function in the manufacturing sector is specified to be quadratic in total labor hired and the capital is normalized to 1. Thus, the objective function faced by the owners of capital can be written as,

$$\max_{L_{xt}} Y_x(L_{xt}) = aL_{xt} - bL_{xt}^2 - w_t L_{xt},$$

where a and b are parameters of the production function. The optimal condition that solves the problem of the owners of capital shows that the marginal product of labor must equal the wage rate. From this, the variable wage during each time period is derived to be,

$$w_t = a - 2bL_{xt}.$$

The parameters a and b take the value of 400 and 2 respectively. Wage is non-negative as long as $\frac{a}{2b} \geq L_{xt}$ and this assumption is satisfied given the parameters chosen in the model. Since we have assumed that the maximum labor hours per person is 10 and there are a total of 10 individuals in the economy, the maximum number of labor hours allowed in the manufacturing sector can only be 100. Given the value of the parameters for a and b , we find that wage can never be negative

since, $\frac{a}{2b} = 100 \geq 100 = \max Lx_t$.

The production function for entrants into the resource sector follows the same functional form as specified in equation (2.3). We specify the effort function as $L_{rt}^\gamma \frac{l_{jt}}{L_{rt}}$. This effort function depends on the total labor in the resource sector, L_{rt} , as well as a proportion of own labor relative, l_{jt} , to total labor in the resource sector. This simplifies to $L_{rt}^\beta l_{jt}$ where $\gamma - 1 \equiv \beta < 0$. The harvest from the resource sector is expressed as,

$$H_j(S_t, L_{jt}, l_{jt}) = \alpha_j S_t L_{rt}^\beta l_{jt},$$

where β takes a value of -0.5; α for community members and non-community members are equal to 0.5 and 0.1, respectively; and $L_{rt} = \sum_{c=1}^C l_{ct} + \sum_{n=1}^N l_{nt}$. Whenever the amount of own labor in the resource sector is equal to zero, the harvest is zero as well. Furthermore, a marginal increase in own labor results in a marginal change in harvest equal to $\alpha_j S_t (L_{rt}^\beta + \beta L_{rt}^{\beta-1} l_{jt})$. For the marginal change in stock to be positive, it must be the case that, $(L_{rt}^\beta + \beta L_{rt}^{\beta-1} l_{jt}) > 0$ or, rearranging, $-\frac{1}{\beta} > \frac{l_{jt}}{L_{rt}}$. The largest possible value of $\frac{l_{jt}}{L_{rt}}$ is equal to 1 but $-\frac{1}{\beta} = 2$, thus, this conditions holds. The crowding out effect of all other individuals on own labor is equal to $\alpha S_t \beta L_{rt}^{\beta-1} l_{jt} < 0$. The value of harvest is equal to H^j multiplied by the relative price, p and is equal to 30. The discount factor δ is 0.90.

The stock in the next period is equal to the net growth of the stock during the initial period plus the initial stock, S_0 minus all the harvest by all individuals. The net growth function, $G(S_t)$, indicates the net biological growth in the stock as a function of the current available stock. We assume that the net growth function takes a logisitic functional form, $G(S_t) = eS_t \left(1 - \frac{S_t}{f}\right)$ where e is the

intrinsic growth rate of the stock and f is the natural carrying capacity. The growth rate of the stock is monotonically decreasing in the stock. Furthermore, the maximum sustainable yield of the stock is equal to $\frac{f}{2}$. The parameters used here are $f = 80$, $e = 0.60$ and an initial stock, $S_0 = 65$. The equation denoting the available stock in the next period is equal to,

$$S_1 = eS_0 \left(1 - \frac{S_0}{f}\right) + S_0 - \sum_{j=1}^{N+C} \alpha_j S_0 L_{r0}^\beta l_{j0}.$$

Using equations (2.8) to (2.11), we derive two potential optimal labor allocation in the resource sector, l_{c0} and l_{c1} , and the optimal number of non-community labor in the resource sector, l_{n0} and l_{n1} , during both periods. The two potential optimal solution sets $\{l_{c0}, l_{c1}, l_{n0}, l_{n1}\}$ are $\{0.409, 1.685, 2.988, 0\}$ and $\{0, 2.222, 0, 2.488\}$. To determine the solution set that yields a local maximum, we derive the determinant of the principal minors evaluated at these values. We find that the first solution set yields alternating signs, where $\det |H^1| = 461 > 0$, $\det |H^2| = -9573 < 0$, and $\det |H| = 21309 > 0$.⁶ However, the determinants of the principal minors in the second solution set does not yield alternating signs implying that this is a saddle point.⁷

Thus, the optimal labor allocation by community members during the first period and second period are, 0.409 and 1.685, respectively. The amount of non-community labor allowed by community members are 2.988 and 0 during the first and second periods, respectively. Non-community members would have an incentive to enter into the resource sector since their value of marginal product

⁶Appendix A.1 shows the elements of the Hessian evaluated at the optimal values.

⁷The determinants of the principal minors were found to be $\det |H^1| = -3942.1 > 0$, $\det |H^2| = -40338.8 < 0$, and $\det |H| = 122403 > 0$.

in that sector evaluated at 2.988 is 67.95 while the wage is 43.15. By allowing 2.988 units of non-community labor to enter into the resource sector, the marginal gains from the crowding out effect and the stock effect, $-\mu_1 \alpha_c S_0 C \frac{\partial f(L_{-c0}, l_{c0})}{\partial l_{n0}}$, is an additional 192 units. The marginal cost of allowing entrance into the resource sector, $p_0 \alpha_c S_0 \frac{\partial f(L_{-c0}, l_{c0})}{\partial l_{n0}}$, is approximately 191. Hence, the level of entrance of 1.685 units of non-community labor during the first period equates the marginal cost and marginal benefits from allowing entrance into the resource sector during the first period.

2.3 Endogenous Property Rights and Majority Voting

2.3.1 Theoretical Outline with Heterogeneous Community Members

The preceding section examined how a community composed of homogeneous members decide to close or keep a resource stock open to non-community members. In this section, the focus is turned to the implementation of the property rights regime for a community of heterogeneous members. Assume that community members differ and are ranked according to their extraction efficiency, while non-community members remain homogeneous with a harvestability coefficient, α_n . The harvestability coefficient is ranked from lowest to highest for all C community members such that, $\alpha_{c1} < \alpha_{c2} < \dots < \alpha_{cm} < \dots < \alpha_{cC-1} < \alpha_{cC}$ where subscripts on α_c denote the rank of the community member. Here, the C^{th} individual is the most efficient, with a harvestability coefficient α_{cC} , while the

1st individual is the least efficient, with a harvestability coefficient α_{c1} . The m^{th} individual is called the median voter and has a harvestability coefficient α_{cm} . Furthermore, it is assumed that $\alpha_{c1} > \alpha_n$. From this analysis, the optimal property rights regime pattern implemented through a majority voting rule is derived.

Under a majority voting rule, the median voter's preference determines the outcome. If the median voter earns more welfare by keeping the resource sector open (closed) to non-community members, the community will vote to (dis)allow entrance into the resource sector. The equilibrium concept is again an open loop Nash equilibrium strategy. The median voter's objective is to maximize wealth over two periods by allocating labor in both sectors in each period, l_{m0}^* , l_{m1}^* , l_{m0} , and l_{m1} . He also selects the amount of non-community labor, l_{n0} , and l_{n1} , allowed into the resource sector in both periods based on the majority voting rule. In order to ensure that non-community members enter into the resource sector whenever l_{nt}^* is offered by median voter, the value of marginal product of non-community members evaluated at l_{nt}^* must be greater than or equal to the prevailing wage rate, i.e. $p_t \alpha_n S_t \frac{\partial f(L_{-nt}, l_{nt}^*)}{\partial l_{nt}} \geq \frac{\partial Y_x}{\partial L_{xt}}$. His maximization problem can be written as,

$$\begin{aligned} \max_{l_{m0}^*, l_{m1}^*, l_{m0}, l_{m1}, l_{n0}, l_{n1}} W_m &= \sum_{t=0}^1 (w_t l_{mt}^* + p_t \alpha_{cm} S_t f(L_{-mt}, l_{mt})) \delta^t \\ \text{s.t. } S_1 &= S_0 + G(S_0) - \sum_{i=1}^C (\alpha_{ci} S_0 f(L_{-i0}, l_{i0})) - N \alpha_n S_0 f(L_{-n0}, l_{n0}); \\ l_{mt} + l_{mt}^* &= h; \end{aligned}$$

where l_{mt} and l_{mt}^* is the amount of labor allocated by the median voter in the resource sector and manufacturing sector at time t , respectively; $L_{-mt} =$

$\sum_{c \neq m}^C l_{ct} + Nl_{nt}$, $L_{-c0} = \sum_{i \neq c}^C l_{i0} + Nl_{n0}$, and $L_{-n0} = \sum_{i=1}^C l_{i0} + (N-1)l_{n0}$. By substituting S_1 from the stock dynamics and l_{mt}^* from the labor constraint into the objective function, the objective function can be re-written as,

$$\max_{l_{m0}, l_{m1}, l_{n0}, l_{n1}} W_m = \sum_{t=0}^1 (w_t(h - l_{mt}) + p_t \alpha_{cm} S_t f(L_{-mt}, l_{mt})) \delta^t \quad (2.13)$$

where $S_1 = S_0 + G(S_0) - \sum_{i=1}^C (\alpha_{ci} S_0 f(\sum_{i \neq c}^C l_{i0} + Nl_{n0}, l_{c0})) - N\alpha_n S_0 f(L_{-n0}, l_{n0})$. The median voter's problem is reduced to that of optimally choosing his own labor and non-community labor allocations in the resource sector. Other community members have similar objective functions but the subscript m is replaced by the subscript for the c^{th} community member.

The owners of capital in the manufacturing sector maximize quasi-rent from capital by choosing the amount of labor employed as shown in (2.1). Equation (2.2) shows the necessary condition for quasi-rent maximization.

By substituting for w_t using (2.2) into the first-order conditions from the median voter's maximization problem, we arrive at the following first-order conditions,

$$\frac{\partial W_m}{\partial l_{m0}} = p_0 \alpha_{cm} S_0 \frac{\partial f(L_{-m0}, l_{m0})}{\partial l_{m0}} - \mu_1 \sum_{i=1}^C \left(\alpha_{ci} S_0 \frac{\partial f(L_{-i0}, l_{i0})}{\partial l_{m0}} \right) - \mu_1 N \alpha_n S_0 \frac{\partial f(L_{-n0}, l_{n0})}{\partial l_{m0}} - \frac{\partial Y_x}{\partial L_{x0}} \leq 0 \quad (2.14)$$

$$(h - l_{m0}) \frac{\partial W_m}{\partial l_{m0}} = 0;$$

$$\frac{\partial W_m}{\partial l_{m1}} = p_1 \alpha_{cm} S_1 \frac{\partial f(L_{-m1}, l_{m1})}{\partial l_{m1}} - \frac{\partial Y_x}{\partial L_{x1}} \leq 0; \quad (h - l_{m1}) \frac{\partial W_m}{\partial l_{m1}} = 0; \quad (2.15)$$

$$\frac{\partial W_m}{\partial l_{n0}} = p_0 \alpha_{cm} S_0 \frac{\partial f(L_{-m0}, l_{m0})}{\partial l_{n0}} - \mu_1 \sum_{i=1}^C \left(\alpha_{ci} S_0 \frac{\partial f(L_{-i0}, l_{i0})}{\partial l_{n0}} \right) - \mu_1 N \alpha_n S_0 \frac{\partial f(L_{-n0}, l_{n0})}{\partial l_{n0}} \leq 0; \quad (2.16)$$

$$l_{n0} \frac{\partial W_m}{\partial l_{n0}} = 0;$$

$$\frac{\partial W_m}{\partial l_{n1}} = p_1 \alpha_{cm} S_1 \delta N \frac{\partial f(L_{-m1}, l_{m1})}{\partial l_{n1}} \leq 0; \quad l_{n1} \frac{\partial W_m}{\partial l_{n1}} = 0. \quad (2.17)$$

Here, $\mu_1 \equiv p_1 \alpha_m f(L_{-m1}, l_{m1}) \delta$ is the marginal user cost of the resource stock for the median voter.

There are $C - 1$ similar first order conditions as (2.14) and (2.15) from the maximization problem of the other community members except the m^{th} subscript would each be replaced with the c^{th} subscript. Simultaneously solving for labor allocated in the resource sector using all $2C + 2$ conditions along with the market clearing conditions during each time, $l_{ct} + l_{ct}^* = h$ and $l_{nt} + l_{nt}^* = h$, yields the Nash equilibrium allocation of labor and the optimum wage rate. The second-order conditions here are similar to that in the homogeneous community member case. The Hessian is shown to be,

$$H_c = \begin{bmatrix} \frac{\partial^2 W_j}{\partial l_{c1,0}^2} & \frac{\partial^2 W_j}{\partial l_{c1,0} \partial l_{c1,1}} & \cdots & \frac{\partial^2 W_j}{\partial l_{c1,0} \partial l_{cC,0}} & \frac{\partial^2 W_j}{\partial l_{c1,0} \partial l_{cC,1}} & \frac{\partial^2 W_j}{\partial l_{c1,0} \partial l_{n0}} & \frac{\partial^2 W_j}{\partial l_{c1,0} \partial l_{n1}} \\ \frac{\partial^2 W_j}{\partial l_{c1,1} \partial l_{c1,0}} & \frac{\partial^2 W_j}{\partial l_{c1,1}^2} & \cdots & \frac{\partial^2 W_j}{\partial l_{c1,1} \partial l_{cC,0}} & \frac{\partial^2 W_j}{\partial l_{c1,1} \partial l_{cC,1}} & \frac{\partial^2 W_j}{\partial l_{c1,1} \partial l_{n0}} & \frac{\partial^2 W_j}{\partial l_{c1,1} \partial l_{n1}} \\ \vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \vdots \\ \frac{\partial^2 W_j}{\partial l_{cC,0} \partial l_{c1,0}} & \frac{\partial^2 W_j}{\partial l_{cC,0} \partial l_{c1,1}} & \cdots & \frac{\partial^2 W_j}{\partial l_{cC,0}^2} & \frac{\partial^2 W_j}{\partial l_{cC,0} \partial l_{cC,1}} & \frac{\partial^2 W_j}{\partial l_{cC,0} \partial l_{n0}} & \frac{\partial^2 W_j}{\partial l_{cC,0} \partial l_{n1}} \\ \frac{\partial^2 W_j}{\partial l_{cC,1} \partial l_{c1,0}} & \frac{\partial^2 W_j}{\partial l_{cC,1} \partial l_{c1,1}} & \cdots & \frac{\partial^2 W_j}{\partial l_{cC,1} \partial l_{cC,0}} & \frac{\partial^2 W_j}{\partial l_{cC,1}^2} & \frac{\partial^2 W_j}{\partial l_{cC,1} \partial l_{n0}} & \frac{\partial^2 W_j}{\partial l_{cC,1} \partial l_{n1}} \\ \frac{\partial^2 W_j}{\partial l_{n0} \partial l_{c1,0}} & \frac{\partial^2 W_j}{\partial l_{n0} \partial l_{c1,1}} & \cdots & \frac{\partial^2 W_j}{\partial l_{n0} \partial l_{cC,0}} & \frac{\partial^2 W_j}{\partial l_{n0} \partial l_{cC,1}} & \frac{\partial^2 W_j}{\partial l_{n0}^2} & \frac{\partial^2 W_j}{\partial l_{n0} \partial l_{n1}} \\ \frac{\partial^2 W_j}{\partial l_{n1} \partial l_{c1,0}} & \frac{\partial^2 W_j}{\partial l_{n1} \partial l_{c1,1}} & \cdots & \frac{\partial^2 W_j}{\partial l_{n1} \partial l_{cC,0}} & \frac{\partial^2 W_j}{\partial l_{n1} \partial l_{cC,1}} & \frac{\partial^2 W_j}{\partial l_{n1} \partial l_{n0}} & \frac{\partial^2 W_j}{\partial l_{n1}^2} \end{bmatrix}. \quad (2.18)$$

Denote the principal minor containing $\frac{\partial^2 W_j}{\partial l_{c1,1}^2}$, as the last element of the principal diagonal as, H_c^1 . If we include one more column and one more row such that the last principal diagonal contains, $\frac{\partial^2 W_j}{\partial l_{c2,0}^2}$, we derive another principal minor called H_c^2 . If we continue for all C community members along with the two non-community member decisions, there are $(C - 1) + 2$ principal minors. With these notations, we can denote the conditions needed to ensure a maximum. If the sign of the determinants of the principal minors alternate, then we derive a maximum. Thus, $\det |H_c^1| > 0, \det |H_c^2| < 0, \dots$ evaluated at the optimal values shows that the optimal values are a local maximum.

Equations (2.14) and (2.15) tell us that the median voter allocates labor between the two sectors of the economy until the value of marginal product between the two sectors are equal. Like the previous case where all individuals are homogenous, the median voter does not internalize either the crowding out effect nor the stock effect during the last period. However, the median voter does partially internalize some of the stock effect and crowding out effect during the first period. Other community members face similar conditions when deciding to allocate labor between the two sectors.

Again, the stock effect and the crowding out effect play an important role in determining the Nash equilibrium sequence of property rights regime. Equations (2.16) and (2.17) show the marginal returns to the income of the median voter for a marginal increase in non-community labor in the resource sector. These equations reflect the median voter's preferences. The community will always vote to close the stock in the last period. Similarly, from (2.16), the median voter may or may not prefer to close the resource stock in the first period. Allowing non-community labor into the resource stock crowds out the harvest for all entrants

into the resource stock. This results in a shift in labor allocation from the resource sector to the manufacturing sector. If the amount of stock preserved through the crowding out of community members is sufficiently large, the median voter would allow non-community labor to enter the resource sector. The necessary assumption that allows for this result to occur is that the harvestability coefficient of the non-community members is lower than the harvestability coefficient of the lowest ranked community member. This particular assumption allows for more preservation of the stock per unit of community labor replaced by non-community labor.

2.3.2 Numerical Example with Heterogeneous Community Members

This numerical example shows a case where opening the resource stock during the first period is an optimal decision. Similar to the previous numerical example, the total labor endowment for each individual economy, h , is equal to 10. To simplify the analysis, we assume that there are a total of 3 community members and 3 non-community members, i.e. $C = N = 3$. We continue to assume that the production function follows a quadratic formulation,

$$\max_{L_{xt}} Y_x(L_{xt}) = aLx_t - bLx_t^2 - w_tLx_t,$$

where a and b are parameters of the production function. The optimal condition that solves the problem of the owners of capital shows that the marginal product of labor must equal the wage rate,

$$w_t = a - 2bLx_t.$$

The parameters a and b take the value of 240 and 2 respectively. Wage is non-negative as long as $\frac{a}{2b} \geq Lx_t$ and this assumption is satisfied given the parameters chosen in the model. Since we have assumed that the maximum labor hours per person is 10 and there are a total of 6 individuals in the economy, the non-negativity constraint on wage holds.

We continue to assume the same harvest function in the resource sector,

$$H^j(S_t, L_{jt}, l_{jt}) = \alpha_j S_t L_{rt}^\beta l_{jt},$$

where β takes a value of -0.5. Since β does not change, the marginal product is strictly positive while the crowding out effect is negative as before. The harvesting coefficient α for non-community members remain at 0.1, but the harvesting coefficient of the three community members are equal to 0.51, 0.50 and 0.49. The value of harvest is equal to H^j multiplied by the relative price, p and is equal to 13.

Similar to the previous example, the stock in the next period is equal to the net growth of the stock during the initial period plus the initial stock, S_0 minus all the harvest by all individuals. We continue to assume that the net growth function takes a logisitic functional form, $G(S_t) = eS_t \left(1 - \frac{S_t}{f}\right)$ where $f = 80$, $e = 0.60$ and an initial stock, $S_0 = 66$. The equation denoting the available stock in the next period is equal to,

$$S_1 = eS_0 \left(1 - \frac{S_0}{f}\right) + S_0 - \sum_{j=1}^{N+C} \alpha_j S_t L_{rt}^\beta l_{jt}.$$

We derive the optimal values for the three community members during both time periods as well as the amount of non-community members using equations (2.14) to (2.17). The optimal values are summarized in Table 2.1.

Time Period	Member 1	Member 2	Member 3	Non-community
1	0.013	0.151	0.152	2.420
2	0.116	2.805	3.868	0.000

Table 2.1: Optimal Labor Allocations in Two-Period Finite Model with Heterogeneous Community Members

The amount of labor allocated by community members are increasing in the harvesting efficiency. Less labor is allocated in the resource sector during the first period while non-community members are allowed into the resource sector but none in the last period. Allowing 2.42 units of non-community labor into the resource sector yields a value of marginal product of 55.78 in the resource sector while the prevailing wage is 20.98. Thus, non-community members would be willing to enter into the sector. To test if this solution is a maximum, we derive the determinants of the principal minors. Here, we find that $\det |H_c^1| = 398.5 > 0$, $\det |H_c^2| = -5649.9 < 0$, $\det |H_c^3| = 89609.5 > 0$, $\det |H_c^4| = -1.07 * 10^6 < 0$, $\det |H_c^5| = 1.02 * 10^7$, $\det |H_c^6| = -1.72 * 10^8 < 0$, and $\det |H_c| = 3.57 * 10^8 > 0$.⁸ Therefore, we find that the set of optimal values from Table 2.1 is a local maximum.⁹

Given the results from the baseline homogeneous community case, this outcome is not unexpected in the heterogenous community case. The voting equilibrium is counterintuitive since we would not expect the community to keep the resource stock open to non-community members. This may occur as long

⁸Appendix A.2 shows the elements of the Hessian evaluated at the optimal values.

⁹An alternative set of solutions were derived where $\{l_{10}, l_{11}, l_{20}, l_{21}, l_{30}, l_{31}, l_{n0}, l_{n1}\} = \{0, 0, 0, 2.11, 0, 4.77, 2.27, 0\}$. However, the determinants of the principal minors do not alternate in sign indicating that this is a saddle point.

as the marginal gains from allowing entrance into the resource sector, i.e., increase in stock from the crowding out effect, are greater than the marginal cost. Intuitively, this particular mechanism is a means of regulating the open access problem within the community itself, in the absence of any formal regulatory measure.

2.4 Endogenous Property Rights in an Infinite Horizon Model

So far, it was assumed that individuals live for a finite number of periods. In reality, older generations may care about the welfare of future generations.¹⁰ This section derives the equilibrium property rights regime patterns when a community comprised of homogeneous members live forever and maximizes their wealth over time.

The open loop Nash equilibrium solution is derived in the infinite horizon model. It gives a set of labor hours and a wage rate that maximizes earnings for all community members while taking the behavior of all other individuals as given during each period. To fully derive the solution to this general equilibrium, it is assumed that owners of each specific factor have perfect information and perfect foresight in the future. Furthermore, it is assumed that from the point of view of an individual, one person cannot affect the wage rate, thus all providers of labor take the wage as given.

¹⁰Positive bequest values have been found associated with preservation of the environment and resource stocks. Krutilla (1967) initially laid down the foundation for environmental preservation for the benefit of the future.

We also make some assumptions on the magnitude of the first derivative and second derivatives in the effort function. The absolute value of the change in effort level from own labor of the j^{th} individual is greater than the change in effort due to other labor, $\left| \frac{\partial f(L_{-jt}, l_{jt})}{\partial l_{jt}} \right| \geq \left| \frac{\partial f(L_{-jt}, l_{jt})}{\partial l_{-jt}} \right|$. Specific assumptions of the magnitude of the effort function of community and non-community members are also made. Recall that the harvesting coefficients for the c^{th} and n^{th} community member as α_c and α_n , respectively while their effort functions are $f(L_{-ct}, l_{ct})$ and $f(L_{-nt}, l_{nt})$. By assumption, $\alpha_c \frac{\partial^2 f(L_{-ct}, l_{ct})}{\partial l_{ct}^2} + \alpha_n \frac{\partial^2 f(L_{-nt}, l_{nt})}{\partial l_{nt}^2} > 0$, and $\alpha_c \frac{\partial^2 f(L_{-ct}, l_{ct})}{\partial l_{nt}^2} + \alpha_n \frac{\partial^2 f(L_{-nt}, l_{nt})}{\partial l_{ct}^2} > 0$. Lastly, we assume $\frac{\partial G(0)}{\partial (S_t)} \leq C \alpha_c f(L_{-ct}, l_{ct}) + N \alpha_n f(L_{-nt}, l_{nt})$. This implies that the intrinsic growth rate of the stock is less than or equal to the marginal change in total harvest given a change in stock. Similar to the two-period model, we assume that the value of marginal product of non-community members evaluated at the amount of labor allowed by community members, l_{nt}^* , must be greater than or equal to the prevailing wage rate, i.e. $p_t \alpha_n S_t \frac{\partial f(L_{-nt}, l_{nt}^*)}{\partial l_{nt}} \geq \frac{\partial Y_x}{\partial L_{xt}}$.

The owners of capital maximize quasi-rent from capital by optimally choosing laborers in the sector during each time period. This is represented by the following maximization problem,

$$\max_{L_{xt}} r_t = Y_x(K, L_{xt}) - w_t L_{xt} \quad \forall \quad t = 0, 1, \dots, \infty \quad .$$

The first-order condition that determines the optimal value during each time period is the following,

$$\frac{\partial Y_x(K, L_{xt})}{\partial L_{xt}} = w_t. \quad (2.19)$$

At each time, the value of marginal product is equal to the equilibrium wage rate.

Let us assume that all community members and non-community members are homogeneous with harvestability coefficients α_c and α_n , respectively, such that $\alpha_c > \alpha_n$. The problem faced by the representative community member is to maximize wealth subject to the dynamic resource stock and labor constraints. The representative community member chooses labor allocated in both sectors of the economy as well as non-community labor allowed into the resource sector in every period. The maximization problem of the representative community member is as follows,

$$\max_{l_{ct}^*, l_{ct}, l_{nt}} W_j = \sum_{t=0}^{\infty} (w_t l_{ct}^* + p \alpha_c S_t f(L_{-ct}, l_{ct})) \delta^t$$

$$s.t. \ S_{t+1} - S_t = G(S_t) - C \alpha_c S_t f(L_{-ct}, l_{ct}) - N \alpha_n S_t f(L_{-nt}, l_{nt}); \ S(0) = S_0; \ l_{ct} + l_{ct}^* = h;$$

By substituting the labor constraint into the objective function, the dynamic optimization problem simplifies to the following,

$$\max_{l_{ct}, l_{nt}} W_j = \sum_{t=0}^{\infty} (w_t (h - l_{ct}) + p \alpha_c S_t f(L_{-ct}, l_{ct})) \delta^t \quad (2.20)$$

$$s.t. \ S_{t+1} - S_t = G(S_t) - C \alpha_c S_t f(L_{-ct}, l_{ct}) - N \alpha_n S_t f(L_{-nt}, l_{nt}); \ S(0) = S_0; \ l_{ct} + l_{ct}^* = h;$$

A few comments on the maximization problem above are in order. The stock dynamics are a generalization of the stock transition in the two-period models. As stated earlier, the problem follows an infinite planning horizon so that the representative community member accumulates wealth from allocating labor into the two sectors of the economy during his lifetime as well as from the discounted

labor allocation decisions of future descendants. The discrete infinite horizon formulation does not alter the fundamental results of the model but is used for analytical simplicity. Furthermore, the maximization above also implies that the representative community member's decisions follow an optimal plan formulated in the base period given the initial parameters of the model. Lastly, we do not address the problems of uncertainty, thus, the results of the analysis may change upon the introduction of risk posture of community members in the model.

The current-value Hamiltonian is written as,

$$H = w_t(h - l_{ct}) + p\alpha_c S_t f(L_{-ct}, l_{ct}) + \delta\lambda_{t+1} (G(S_t) - C\alpha_c S_t f(L_{-ct}, l_{ct}) - N\alpha_n S_t f(L_{-nt}, l_{nt})).$$

where λ_{t+1} is the costate variable associated with the resource stock. The costate variable is the current value of the marginal user cost of the resource stock at time $t + 1$. The maximum labor allocated by the community member in the resource sector is h . Also, the minimum labor by non-community members in the resource sector is zero. We focus on these two constraints since we are interested in analyzing cases where full closure of the resource stock to non-community members and complete specialization of community members in the resource sector occurs.¹¹ The Lagrangean can be written as,

$$\mathcal{L} = H + \theta_t(h - l_{ct}) + \eta_t l_{nt},$$

where θ_t and η_t are multipliers for the constraints on the control variables.

¹¹The other constraints in this model are to allow for $l_{nt} = h$ and $l_{ct} = 0$. However, this would only introduce more complexity into the model without changing the basic results of the analysis.

By substituting w_t using (2.19) into the first order conditions from the representative community member, the conditions that solve for the dynamic Nash equilibrium model are,

$$\frac{\partial \mathcal{L}}{\partial l_{ct}} = (p - \delta \lambda_{t+1} C) \alpha_c S_t \frac{\partial f(L_{-ct}, l_{ct})}{\partial l_{ct}} - \delta \lambda_{t+1} N \alpha_n S_t \frac{\partial f(L_{-nt}, l_{nt})}{\partial l_{ct}} - \frac{\partial Y(K, L_{xt})}{\partial L_{xt}} - \theta_t \leq 0 \quad (2.21)$$

$$(h - l_{ct}) \frac{\partial \mathcal{L}}{\partial l_{ct}} = 0;$$

$$\frac{\partial \mathcal{L}}{\partial \theta_t} = h - l_{ct} \geq 0; \quad (h - l_{ct}) \theta_t = 0; \quad (2.22)$$

$$\frac{\partial \mathcal{L}}{\partial l_{nt}} = (p - \delta \lambda_{t+1} C) \alpha_c S_t \frac{\partial f(L_{-ct}, l_{ct})}{\partial l_{nt}} - \delta \lambda_{t+1} N \alpha_n S_t \frac{\partial f(L_{-nt}, l_{nt})}{\partial l_{nt}} + \eta_t \leq 0; \quad (2.23)$$

$$l_{nt} \frac{\partial \mathcal{L}}{\partial l_{nt}} = 0;$$

$$\frac{\partial \mathcal{L}}{\partial \eta_t} = l_{nt} \geq 0; \quad l_{nt} \eta_t = 0; \quad (2.24)$$

$$\lambda_{t+1} - \lambda_t = (1 - \delta) \lambda_{t+1} - \delta \lambda_{t+1} (G(S_t) - C \alpha_c f(L_{-ct}, l_{ct}) - N \alpha_n f(L_{-nt}, l_{nt})) - p \alpha_c f(L_{-ct}, l_{ct}); \quad (2.25)$$

$$S_{t+1} - S_t = G(S_t) - C \alpha_c S_t f(L_{-ct}, l_{ct}) - N \alpha_n \alpha_c S_t f(L_{-nt}, l_{nt}); \quad (2.26)$$

From equation (2.21), community members allocate labor between the two sectors at time t until the value of marginal product in the manufacturing sector is equal to the value of marginal product from the resource sector minus the shadow value of the resource stock and the crowding out effect of non-community members. If the marginal return from labor allocated in the resource sector is greater than the returns in the manufacturing sector, the community member allocates all labor into the resource sector. Equation (2.23) shows the marginal contribution of non-community labor to income at time t . If the contribution of non-community labor to the Lagrangean is negative, the community will close the resource stock. However, if the gain in income from crowding out some community labor is large enough, community members may keep the resource stock open during that period. It is important to reiterate that the necessary condition that allows us to derive this result is the relatively higher harvestability coefficient of community members compared to non-community members.

In order to derive the Nash equilibrium in this dynamic general equilibrium framework, the phase space and the associated regions of the constraints on the control variables are examined. Since there are two control variables, the phase plane in the state and co-state space are derived. To build the phase diagram, we first divide the phase space into regions where the constraints on the control variables bind or not, i.e. $l_{nt} \geq 0$ and $l_{ct} \leq h$. Then, we derive the isoclines within each region of the phase diagram. Lastly, we analyze the stability properties of any steady state solution that are found.

First, we derive the equation that divides the regions where non-community labor is greater than or equal to zero. Let us define the discounted marginal user value of the stock at time t as $\mu_t \equiv \delta\lambda_{t+1}$. Whenever $\eta_t > 0$, non-community

labor is zero, $l_{nt} = 0$. Using equation (2.23) along with our definition for μ_t , we derive a description of the region where non-community labor is zero,

$$\mu_t \geq \frac{p\alpha_c S_t \frac{\partial f((C-1)l_{ct}, l_{ct})}{\partial l_{nt}} + \eta_t}{C\alpha_c S_t \frac{\partial f((C-1)l_{ct}, l_{ct})}{\partial l_{ct}} + N\alpha_n S_t \frac{\partial f(Cl_{ct}, 0)}{\partial l_{nt}}}.$$

Define the right-hand-side of this inequality as $\psi_t(S_t)$. Any value of μ_t greater than or equal to $\psi_t(S_t)$ implies non-community labor is equal to zero. In order to illustrate the region in the phase space where non-community labor is equal to zero as opposed to strictly greater than zero, we draw the function $\psi_t(S_t)$ in state and costate space. Taking the first and second derivative of $\psi_t(S_t)$ with respect to S_t we derive,

$$\frac{\partial \psi_t}{\partial S_t} = -\frac{\eta_t}{S_t^2 \left(C\alpha_c \frac{\partial f((C-1)l_{ct}, l_{ct})}{\partial l_{nt}} + N\alpha_n \frac{\partial f(Cl_{ct}, 0)}{\partial l_{nt}} \right)} \leq 0;$$

$$\frac{\partial^2 \psi_t}{\partial S_t^2} = \frac{2\eta_t}{S_t^3 \left(C\alpha_c \frac{\partial f((C-1)l_{ct}, l_{ct})}{\partial l_{nt}} + N\alpha_n \frac{\partial f(Cl_{ct}, 0)}{\partial l_{nt}} \right)} \geq 0.$$

Here, $\frac{\partial \psi_t}{\partial S_t} \leq 0$ and $\frac{\partial^2 \psi_t}{\partial S_t^2} \geq 0$. Thus, the function $\psi_t(S_t)$ is convex and decreasing in the stock. The region above ψ_t implies that non-community labor is equal to zero. When η_t is equal to zero, non-community labor is positive and this is depicted by the region below ψ_t (see Figure 2.1).

In order to delineate the regions where community labor is at the constraint, h , or less than h , we look at equation (2.21). Whenever $\theta_t > 0$, labor by the representative community member is equal to h . Using equation (2.21) along with our definition for μ_t , we derive a description of the region where community labor is h ,

$$\mu_t \geq \frac{p\alpha_c S_t \frac{\partial f(L_{-ct}, h)}{\partial l_{ct}} - \frac{\partial Y(K, L_{xt})}{\partial L_{xt}} - \theta_t}{C\alpha_c S_t \frac{\partial f(L_{-ct}, h)}{\partial l_{ct}} + N\alpha_n S_t \frac{\partial f(L_{-nt}, l_{nt})}{\partial l_{ct}}}.$$

Define the right hand side of the inequality as $\varpi_t(S_t)$. Any value of μ_t greater than or equal to $\varpi_t(S_t)$ implies community labor is equal to h . To illustrate the region in the phase space where community labor is equal to h as opposed to less than h , we draw the function $\varpi_t(S_t)$ in state and costate space. Taking the first and second derivative of $\varpi_t(S_t)$ with respect to S_t we derive,

$$\begin{aligned} \frac{\partial \varpi_t}{\partial S_t} &= \frac{\frac{\partial Y(K, L_{xt})}{\partial L_{xt}} + \theta_t}{S_t^2 \left(C\alpha_c \frac{\partial f(L_{-ct}, h)}{\partial l_{ct}} + N\alpha_n \frac{\partial f(L_{-nt}, l_{nt})}{\partial l_{ct}} \right)} \geq 0; \\ \frac{\partial^2 \varpi_t}{\partial S_t^2} &= -\frac{\frac{\partial Y(K, L_{xt})}{\partial L_{xt}} + \theta_t}{S_t^3 \left(C\alpha_c \frac{\partial f(L_{-ct}, h)}{\partial l_{ct}} + N\alpha_n \frac{\partial f(L_{-nt}, l_{nt})}{\partial l_{ct}} \right)} \leq 0. \end{aligned}$$

Therefore, the function $\varpi_t(S_t)$ is concave and increasing in S_t . The region above ϖ_t implies community labor is equal to h while the remaining region below ϖ_t shows community labor less than h (Figure 2.1).

By combining both ψ_t and ϖ_t , we are able to delineate the four regions in the phase diagram: (1) an interior solution exists for both controls ($l_{nt} > 0, l_{ct} < h$); (2) an interior solution exists for own labor and the resource sector is fully closed ($l_{nt} = 0, l_{ct} < h$); (3) an interior solution exists for non-community labor but the representative community member devotes all labor into the resource sector ($l_{nt} > 0, l_{ct} = h$); and (4) the representative community member fully specializes in the resource sector and votes to close it off to non-community members ($l_{nt} = 0, l_{ct} = h$) (see Figure 2.1). If there is an abundance of resource stock and marginal user cost is relatively large, the community votes to keep out non-community labor (as shown by the area above ψ_t). Conversely, for relatively lower marginal

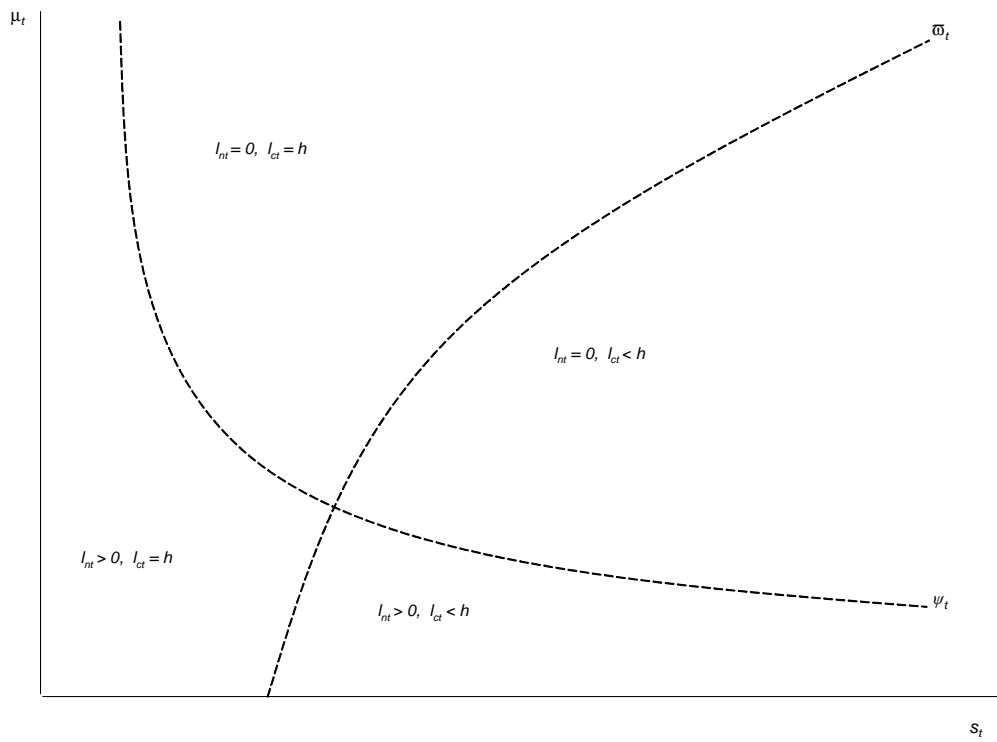


Figure 2.1: Regions in the Phase Diagram

user cost and resource stocks, the community allows entrance into the resource stock (as shown by the area below ψ_t). The derivation of the S and μ isoclines proceeds region by region.

The optimal trajectories for the state and control variables are found as the solution to the following equations based on the maximum principle,

$$(l_{ct}, l_{nt}) = \arg \max \mathcal{L}; \quad (2.27)$$

$$\mu_t - \mu_{t-1} = (1 - \delta)\mu_t - \delta \frac{\partial \max \mathcal{L}}{\partial S_t}; \quad (2.28)$$

$$S_{t+1} - S_t = \frac{\partial \max \mathcal{L}}{\partial \mu_t}; \quad (2.29)$$

$$\lim_{T \rightarrow \infty} \mu_T S_{T+1} = 0. \quad (2.30)$$

We derive the Hessian of the Lagrangean as negative semi-definite, which implies that the determinant of the Hessian is non-negative and the diagonal elements are non-positive. We derive the following comparative statics (see Appendix B.1),

$$\frac{\partial l_{ct}}{\partial \mu_t} \leq 0; \quad \frac{\partial l_{nt}}{\partial \mu_t} \leq 0; \quad \frac{\partial l_{ct}}{\partial S_t} \geq 0; \quad \text{and} \quad \frac{\partial l_{nt}}{\partial S_t} \geq 0. \quad (2.31)$$

From the comparative statics in (2.31), as the shadow value of the resource stock increases, the representative community member allocates less labor and allows less non-community labor in the resource sector. Also, any increase in stock will lead to non-decreasing community and non-community labor, *ceteris*

paribus. These results are needed to obtain the isoclines in each region of the phase plane.

In order to derive the isocline and trajectories, we utilize equations (2.27) to (2.29). We start by deriving the isoclines for the stock and its shadow value when an interior solution exists in both of the control variables (see Appendix B.2 for a complete derivation of the isoclines in each region). The S and μ isoclines can be derived by assuming that the change in S and μ over time is zero, *i.e.* $0 = \frac{\partial \mathcal{L}}{\partial \mu_t}$ and $0 = (1 - \delta)\mu_t - \delta \frac{\partial \mathcal{L}}{\partial S_t}$, respectively. Using the implicit function theorem along with comparative statics above, we derive a positive slope for the S isocline and negative slope for the μ isocline when the optimal control variables are interior solutions. The S and μ isoclines are also positively sloped and negatively sloped, respectively, in the regions where $l_{ct} < h$ and $l_{nt} = 0$; and $l_{ct} = h$ and $l_{nt} > 0$.¹² However, when $l_{ct} = h$ and $l_{nt} = 0$, the S isocline is vertical while the μ isocline remains downward sloping.

The co-state and state isoclines are the steady-state solutions for equations (2.28) and (2.29). The whole system is in a steady state if the change in the optimal value of the Lagrangean due to a change in resource stock equals the discounted current value of the co-state. Using equations (2.28) and (2.29) along with the comparative statics from (2.31), we can illustrate a potential phase diagram as shown in Figure 2.2. The μ -isocline is the long-run demand for the resource stock while the S isocline is the long-run supply of the resource stock. The steady-state values of the resource stock and shadow value are S^{eq} and μ^{eq} , respectively. The unstable regions are: to the left of the S isocline and above the

¹²Since we have assumed that $G'(0) \leq C\alpha_c f(L_{-ct}, l_{ct}) + N\alpha_n f(L_{-nt}, l_{nt})$, the S isocline is monotonically increasing.

μ isocline; and to the right of the S isocline and below the μ isocline. In these regions, the system moves away from the steady state (see Appendix B.2 for the derivation of the direction of motion in each region of the phase plane).

In Figure 2.2, the steady state is in the region where the community utilizes all labor in the resource stock and close the resource stock to non-community members. The heavy arrowed curve represents the converging separatrix. Given a sufficiently large initial stock level, community members close off the resource sector in all time periods but do not initially allocate all labor into the resource sector. The community specializes in the resource sector only when we get close to the steady state equilibrium (see Appendix B.3 that proves the steady state equilibrium is a saddle path).

In general, the optimal trajectory can be increasing from the lower right hand region of the phase plane to the upper left hand region. Alternatively, the optimal dynamic path can move from the upper left hand corner to the lower right hand corner in the phase diagram. We can determine five potential property rights regimes that can occur over time in this trajectory (see Figure 2.3). Let us take trajectory 4 as an example. Given a starting point of z , trajectory 4 follows a potential optimal path where the representative community member initially votes to keep the resource sector closed but after some time, opens the resource sector. Alternatively, there is also the potential to start off at point z' on trajectory 3. Here, the representative community member initially keeps the resource sector open but after some time, closes the resource sector. Sequences of full closure and always opening resource stocks may occur as illustrated in trajectories 1 and 2, respectively. Lastly, semi-cyclical patterns may arise as well where the community votes to keep the resource sector open, then closed and

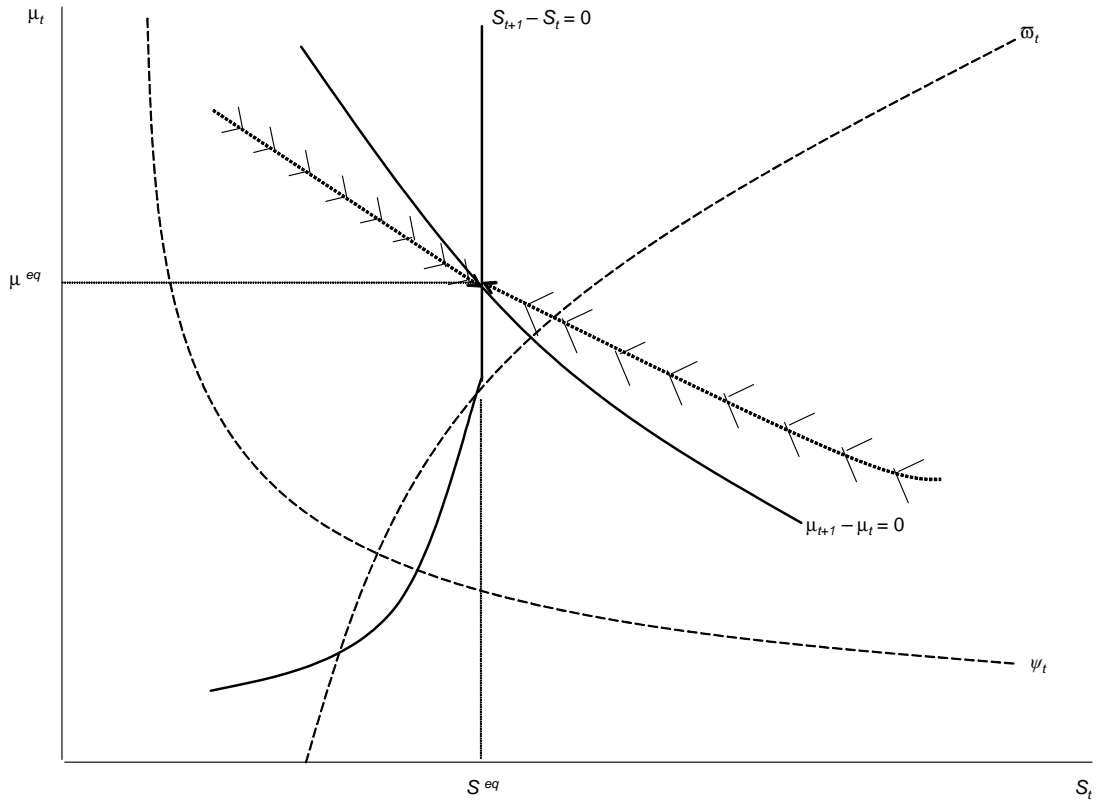


Figure 2.2: Adjustment Path and Steady State Values of Resource Stock and Shadow Price of Stock

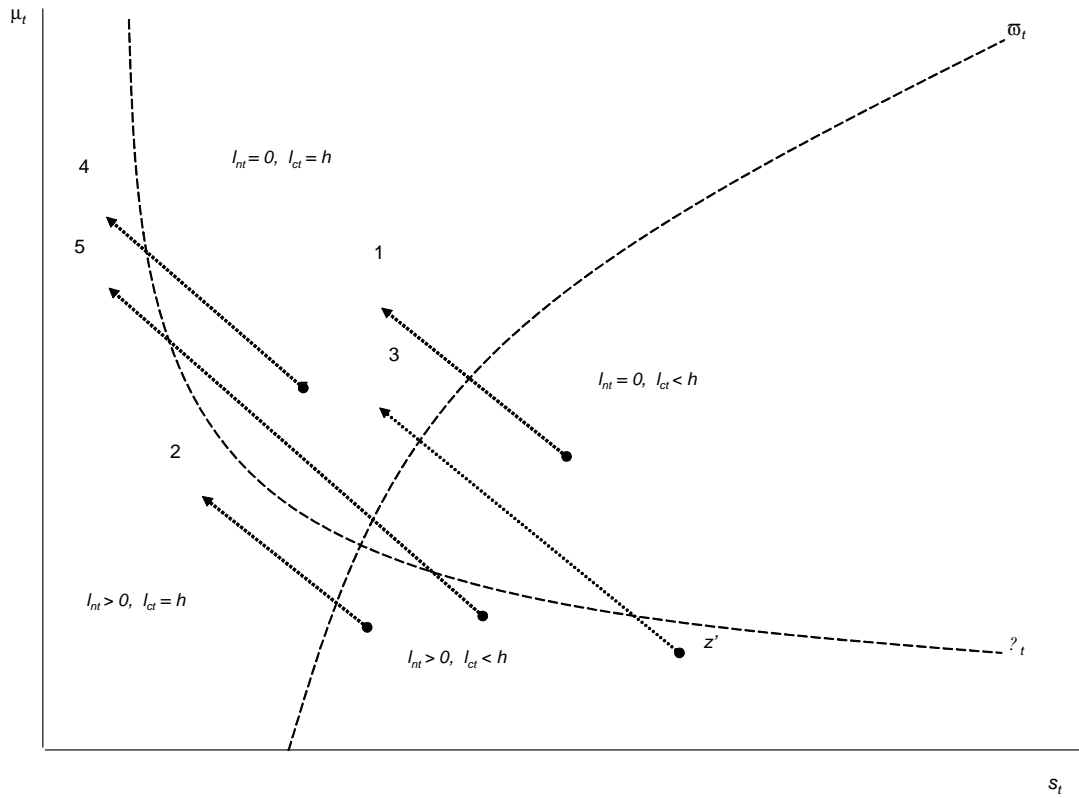


Figure 2.3: Potential Property Rights Regime Patterns in an Infinite Horizon Model

then open.¹³

Results from this model eliminate full cyclical patterns of property rights regime sequences as an optimal management scheme *and* harvesting solution. In the context of fishery management, cyclical harvesting strategies or chattering strategies have been proven to be theoretically optimal (Lewis and Schmalensee, 1979; Clark, 1985). This optimal harvest strategy is characterized by continuous en-

¹³If the optimal saddle path moves from the upper left hand region to the lower right hand region, the same property rights regime sequences can occur in this trajectory.

trance and exit of fishermen. However, a chattering strategy as an optimal harvesting policy is driven by the assumption that the owners of the resource stock have little or no capital costs in vessels, equipment and worker compensation (Liski, et al., 2001). It may not be optimal for community members that have rights over the resource stock to continually change their fishing fleet structure due to the presence of adjustment costs. Furthermore, the property rights regime patterns that eliminate continuous cycling as an optimal management strategy is feasible given the non-cycling pattern of stock population over time. In this model, the assumption of perfect foresight and internalization of the stock effect during the planning horizon eliminates the possibility of cycling of the stock population and, consequently, cycling of the property rights regime pattern.

The phase diagram in Figure 2.2 assumes that the intrinsic growth rate of the stock is less than the change in harvest for a given change in stock. However, if this condition does not hold, the S isocline may become U-shaped. Because of the change in the shape of the S isocline, multiple equilibria may occur. This results in a potential phase diagram as shown in Figure 2.4.¹⁴ There are two equilibria nodes, A and B. Node A has a stable saddle path going through it while node B is an unstable equilibrium. In node A, the steady state stock level is greater than in node B, but the steady state marginal user cost is greater in node B than in node A. The only stable regions occur above the μ isocline and to the right of the S isocline, as well as the area bounded by the two isoclines. Thus, with multiple equilibria, the unstable area is larger compared to a solution with a single equilibrium point.

In this chapter, we derived the different potential property rights regimes

¹⁴The phase regions are suppressed in the diagram for clarity.

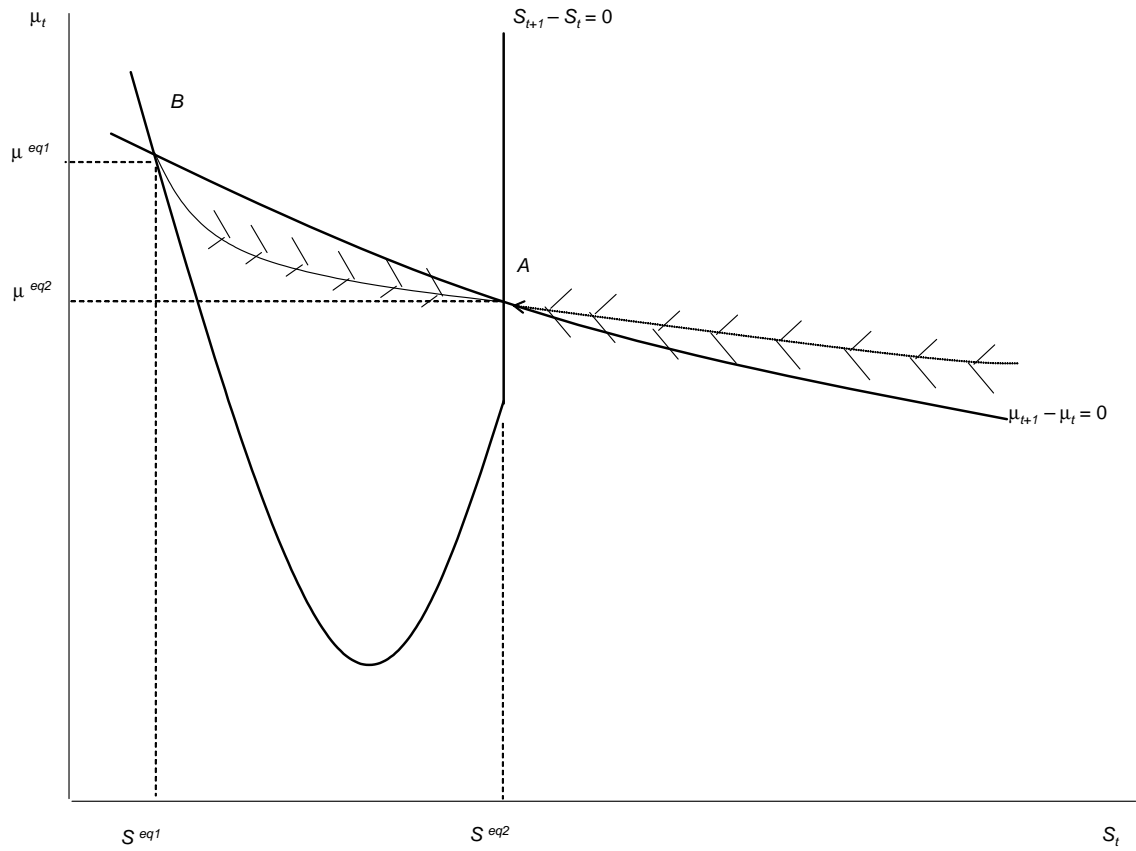


Figure 2.4: Adjustment Path with Multiple Equilibria

governing the resource stock by using a dynamic two-sector general equilibrium model. In a two-period finite horizon model, the community members may vote to keep the resource stock open to some non-community members as long as the marginal gains from opening the stock are greater than the marginal cost. The marginal gains from allowing limited access to non-community members in this model come from the increase in stock by crowding out community members that have a greater impact on the stock when harvesting. Thus, four property rights regimes sequences may occur: full closure during both periods, open in both periods, close in the first period and open in the last period, or open in the first period and close in the last period. The results from this type of mechanism is similar to a tax. If the community planner sets a tax rate for all community members equal to the marginal crowding out effect, the outcome would be similar to our property rights regime mechanism.

In the infinite horizon model, we have shown five property rights regime sequences that may exist. We have eliminated the potential for a cyclical property rights regime as an optimal solution. As long as property rights regimes are well defined and community members internalize the stock effect over time, we will no longer see cyclical patterns of opening and closing the resource stock.

In all three cases, the necessary assumption that allows for the potential to keep the resource sector open is the higher harvestability coefficient in the community relative to the non-community members. When a group of individuals has rights over the use of a particular resource stock, it is not difficult to imagine that they would have better technology and have developed more skills relative to non-owners. However, as skill levels converge and technologies are adapted across individuals, the harvestability coefficient gap may decrease over time and ulti-

mately become insignificant. If this occurs, there will no longer be any incentive to keep the resource sector open since one unit of labor from either the community or non-community in the resource sector diminishes the same amount of stock. Therefore, whenever the harvestability coefficient of non-community members is greater than or equal to that of community members, the stock will always be kept closed.

Another assumption in the model is that wages are exogenous from the viewpoint of an individual player in the economy. However, when unions are formed in the manufacturing sector, their aggregate behavior allows wages to be endogenous. If wages are treated endogenously, opening of the resource stock may also occur in the first round.

The open-loop strategy has been derived in this chapter. In a closed-loop strategy solution, where subjects are allowed to condition their extraction level on the current stock, the optimal harvesting strategy and property rights regime choices will not be affected as long as subjects have perfect foresight. Perfect foresight implies that individuals will know the stock level over time. Thus, with an open-loop strategy, where current stock levels are not observed, or a closed-loop strategy, where current stock levels can be observed, the optimal choices of labor and property rights regime do not differ.

Chapter 3

Trade, Property Rights Regimes and Resource Stocks

Recent protests during the World Trade Organization meetings have highlighted concern over the progress of trade liberalization. An important issue has been the fear of increased environmental degradation, especially in developing countries, due to the reduction in trade barriers. Trade policies can significantly affect natural resource stocks through indirect links, such as endowments of natural resources, technological efficiency, governing institutions, and property rights regimes (Abler, et al., 1999; Antweiler, et al., 2001; Alpay, 2001; Bourgeon and López, 1999; Brander and Taylor, 1997a and 1997b; Chichilnisky, 1994; Copeland and Taylor, 1994).

The model that we have developed implies that the effect of trade on the resource stock is through an indirect and direct channels. The direct channel shows the change in the labor allotted to harvesting the resource stock due to an exogenous change in output price from opening to trade. On the other hand, the indirect effect occurs when the community votes on a particular property rights regime. Once the property rights regime is chosen, the community members reallocate labor between the two sectors accordingly, thus influencing the level of the re-

source stock. In this chapter, the comparative statics in the finite horizon model and comparative dynamics in the infinite horizon model of opening to trade on the resource stock are determined.

3.1 Comparative Statics in Finite Horizon Model

Opening a small economy to trade will result in a change in the relative domestic price towards the prevailing world market price. Countries that have comparative advantage (disadvantage) in the production of the resource-based output will see an increase (decrease) in the relative price of the good. Using the two-period homogeneous community model, we answer the question: how will an improvement in the terms of trade during period 2 (increase in p_1) affect the resource stock for a small open economy during the same period (period 2) and the period after (period 3)? Based on our model, an exogenous change in the terms of trade (p_1) will have an effect on the optimal labor allocation (l_{c0} , l_{c1}) of the representative community member in the resource sector as well as on the amount of non-community labor in both periods (l_{n0} , l_{n1}). An announced change in future price can affect the labor allocation decisions in the current period since individuals may anticipate changing optimal plans formulated in the base period. Once we derive the effect of price on l_{ct} and l_{nt} , we derive the impact of l_{ct} and l_{nt} on stock to get the the total effect of price on stocks.

In obtaining the comparative statics needed to analyze the effect of trade openness on labor allocations, we rely on Topkis (1978) monotonicity theorem: given a system of complements and a vector of complementary exogenous parameters, monotone shifts in the latter imply a monotone shift of the endogenous

variables.¹ Formally, a function $F : R^K \rightarrow R$ is said to be supermodular in z and z' in $R^K \rightarrow R$, we have

$$F(z \vee z') + F(z \wedge z') \geq F(z) + F(z'), \quad (3.1)$$

where $z \vee z'$ is the coordinate-wise maximum of the points z and z' , i.e. $z \vee z' = (\max\{z_1, z'_1\}, \dots, \max\{z_m, z'_m\})$, and $z \wedge z'$ is the coordinate-wise minimum of the points z and z' , i.e. $z \wedge z' = (\min\{z_1, z'_1\}, \dots, \min\{z_m, z'_m\})$. If F is smooth, supermodularity is equivalent to the condition,

$$\frac{\partial^2 F}{\partial z_i \partial z_j} \geq 0 \quad \forall i \neq j. \quad (3.2)$$

Thus, if all the cross-partial derivatives for any smooth function, along with the parameter of interest, are non-negative, then there is an increasing relationship between the parameter and the optimal choice.²

We apply the theorem to our two-period model. The cross partial derivatives of the variables, $\{(-l_{c0}), l_{c1}, (-l_{n0}), (-l_{n1}); p_1\}$, from the objective function are non-negative (see Appendix C.1). Therefore, we derive the following comparative statics,

$$\frac{\partial l_{c0}}{\partial p_1} \leq 0; \frac{\partial l_{c1}}{\partial p_1} \geq 0; \frac{\partial l_{n0}}{\partial p_1} \leq 0 \text{ and } \frac{\partial l_{n1}}{\partial p_1} \leq 0. \quad (3.3)$$

¹Topkis' theorem does not need to impose any assumptions on the concavity of the objection function, interiority of the solution or convexity of the feasible set. See Topkis (1998) for a more detailed examination of supermodularity and complementarity.

²Milgrom and Shannon (1994) developed the general theory of monotone comparative statics. They derived the necessary and sufficient conditions for a solution set of an optimization problem to be monotonic in the parameters of the problem.

An improvement in the terms of trade during period 2 results in an increase in the labor allocated in the resource stock by the representative community member. Given an increase in the profitability of harvesting from the resource stock relative to working in the manufacturing industry, allocating more labor into the resource sector during the second period results in an increase in wealth. However, when an announced increase in the terms of trade occurs in period 2, the representative community member anticipates this price change and tries to preserve more of the resource stock for future harvest by decreasing own labor in period 1.

An improvement in the terms of trade also affects the community's decision to allow non-community labor into the resource sector. As expected, an increase in the relative price from harvesting the resource stock in period 2 results in limiting the entrance of non-community labor in the resource stock in period 2. In period 1, the representative community member chooses to limit the number of non-community entrants as well in order to preserve the resource stock prior to opening to trade. This result is similar to Hotte, et al. (2000), where they show that an increase in terms of trade results in more enforcement of property rights regimes to derive higher returns from harvesting a resource.

To derive the impact of a change in price during period 2 on the available stock in periods 2 and 3, we use the comparative statics from (3.3) along with the transition equation of the stock in (2.6). The stock in period 2 can be written as,

$$S_1 = S_0 + G(S_0) - C\alpha_c S_0 f(L_{-c0}^*, l_{c0}^*) - N\alpha_n S_0 f(L_{-n0}^*, l_{n0}^*) \quad (3.4)$$

where L_{-c0}^* , l_{c0}^* , L_{-n0}^* , and l_{n0}^* are the optimal level of labor allocation in the

resource sector. Taking the derivative of (3.4) with respect to p_1 yields,

$$\frac{\partial S_1}{\partial p_1} = -C\alpha_c S_0 \left(\frac{\partial f(L_{-c0}^*, l_{c0}^*)}{\partial l_{c0}} \frac{\partial l_{c0}}{\partial p_1} + \frac{\partial f(L_{-c0}^*, l_{c0}^*)}{\partial l_{n0}} \frac{\partial l_{n0}}{\partial p_1} \right) - N\alpha_n S_0 \left(\frac{\partial f(L_{-n0}^*, l_{n0}^*)}{\partial l_{c0}} \frac{\partial l_{c0}}{\partial p_1} + \frac{\partial f(L_{-n0}^*, l_{n0}^*)}{\partial l_{n0}} \frac{\partial l_{n0}}{\partial p_1} \right).$$

Rearranging the above equation and imposing the assumption of $C=N$, we derive,

$$\frac{\partial S_1}{\partial p_1} = -CS_0 \left(\alpha_c \frac{\partial f(L_{-c0}^*, l_{c0}^*)}{\partial l_{c0}} + \alpha_n \frac{\partial f(L_{-n0}^*, l_{n0}^*)}{\partial l_{c0}} \right) \frac{\partial l_{c0}}{\partial p_1} - CS_0 \left(\alpha_c \frac{\partial f(L_{-c0}^*, l_{c0}^*)}{\partial l_{n0}} + \alpha_n \frac{\partial f(L_{-n0}^*, l_{n0}^*)}{\partial l_{n0}} \right) \frac{\partial l_{n0}}{\partial p_1}.$$

Whenever the marginal effort from own labor weighted by the harvesting efficiency parameter is greater than the marginal effort from other labor weighted by the harvesting efficiency, i.e. $\alpha_j \frac{\partial f(L_{-j0}^*, l_{j0}^*)}{\partial l_{-j0}} + \alpha_{-j} \frac{\partial f(L_{-j0}^*, l_{j0}^*)}{\partial l_{j0}} > 0$, the effect of an increase in price during period 2 *increases* the stock during the same period. In order to increase the stock level during period 2, it is necessary to decrease labor allocation and entrance of non-community members during the first period.

However, the final impact on the stock after the price effect takes into place is ambiguous in the two-period model. Using (2.6), the stock in period 3 can be written as,

$$S_2 = S_1 + G(S_1) - C\alpha_c S_1 f(L_{-c1}^*, l_{c1}^*) - N\alpha_n S_0 f(L_{-n1}^*, l_{n1}^*). \quad (3.5)$$

Taking the derivative with respect to p_1 yields,

$$\frac{\partial S_2}{\partial p_1} = \frac{\partial S_1}{\partial p_1} + \frac{\partial G(S_1)}{\partial S_1} \frac{\partial S_1}{\partial p_1} - C\alpha_c \frac{\partial S_1}{\partial p_1} \left(\frac{\partial f(L_{-c1}^*, l_{c1}^*)}{\partial l_{c1}} \frac{\partial l_{c1}}{\partial p_1} + \frac{\partial f(L_{-c1}^*, l_{c1}^*)}{\partial l_{n0}} \frac{\partial l_{n0}}{\partial p_1} \right) - N\alpha_n \frac{\partial S_1}{\partial p_1} \left(\frac{\partial f(L_{-n1}^*, l_{n1}^*)}{\partial l_{c1}} \frac{\partial l_{c1}}{\partial p_1} + \frac{\partial f(L_{-n1}^*, l_{n1}^*)}{\partial l_{n1}} \frac{\partial l_{n1}}{\partial p_1} \right).$$

Rearranging the above equation, imposing the assumption of $C=N$, and factoring out $\frac{\partial S_1}{\partial p_1}$, we derive,

$$\begin{aligned} \frac{\partial S_2}{\partial p_1} = & \frac{\partial S_1}{\partial p_1} \left(1 + \frac{\partial G(S_1)}{\partial S_1} - C \left(\alpha_c \frac{\partial f(L_{-c1}^*, l_{c1}^*)}{\partial l_{c1}} + \alpha_n \frac{\partial f(L_{-n1}^*, l_{n1}^*)}{\partial l_{c1}} \right) \frac{\partial l_{c1}}{\partial p_1} - \right. \\ & \left. C \left(\alpha_c \frac{\partial f(L_{-c1}^*, l_{c1}^*)}{\partial l_{n1}} + \alpha_n \frac{\partial f(L_{-n1}^*, l_{n1}^*)}{\partial l_{n1}} \right) \frac{\partial l_{n1}}{\partial p_1} \right). \end{aligned}$$

Three factors affect the impact of stock levels during period 3 when prices increase in period 2. Two factors increase the stock in the third period: the natural growth rate of the stock, $\frac{\partial G(S_1)}{\partial S_1}$, and the decrease in non-community labor during period 2, $\frac{\partial l_{n1}}{\partial p_1} \leq 0$. However, the increased pressure from labor allocations by community members degrade the resource stock, $\frac{\partial l_{c1}}{\partial p_1} \geq 0$. Overall, the remaining stock after the third round may or may not immediately decrease depending on the magnitude of the growth of the stock, property rights regime choice and change in labor allocations by community members. Thus, when we allow for a dynamic resource stock and endogenous property rights regime, opening a country to trade does not necessarily imply an immediate degradation of the resource stock in a two-period model.

3.2 Comparative Dynamics in Infinite Horizon Model

The effect of opening to trade can be analyzed in the dynamic model. We return to the infinite horizon model from Chapter 2.4 to investigate the effect of a price increase, due to opening to trade, on resource stocks. If the economy has comparative advantage in the production from the resource sector, opening to

trade leads to an increase in the relative price of output from that sector. Here, we determine the effect of an increase in p on the long-run equilibrium stock, S^{eq} , and marginal user cost, μ^{eq} . Unlike the previous case where we assumed static output price changes, we are now investigating how long-run equilibrium stock and marginal user cost changes in response to *permanent* price changes that occur in the initial period. To simplify the analysis, we only look at the case where the optimal values are both interior solutions.

To derive the effect of a price increase on steady state stock and marginal user cost of stock, we first examine how the long-run supply and long-run demand curves shift in the phase space. The long-run supply curve is the isocline that traces out $S_{t+1} - S_t = 0$ while the long-run demand curve is the isocline that shows $\mu_{t+1} - \mu_t = 0$. Recall that the steady state solutions to the dynamic problem come from equations (2.28) and (2.29).

Let us first determine how a change in p affects the long-run supply curve. When $S_{t+1} - S_t = 0$, we find that $\frac{\partial \max H}{\partial \mu_t} = 0$. The effect of a shift in the long-run supply curve on the marginal user cost and stock is determined by using the implicit function theorem on $\frac{\partial \max H}{\partial \mu_t} = 0$. Formally (see Appendix C.2.1 for complete derivation),

$$\frac{\partial \mu_t}{\partial p} \Big|_{S_{t+1}-S_t=0} = \frac{-\frac{\partial^2 \max H}{\partial \mu \partial p}}{\frac{\partial^2 \max H}{\partial \mu^2}} \geq 0; \quad (3.6)$$

$$\frac{\partial S_t}{\partial p} \Big|_{S_{t+1}-S_t=0} = \frac{-\frac{\partial^2 \max H}{\partial \mu \partial p}}{\frac{\partial^2 \max H}{\partial \mu \partial S}} \leq 0. \quad (3.7)$$

From (3.6) and (3.7), the long-run supply curve shifts up and to the left. A rise in p increases the amount of labor in the resource sector because of the increase in the value of marginal productivity. This results in a decrease in the long-run

supply curve of the resource stock.

We can also derive the effect of price on the long-run demand curve by using the implicit function theorem on $0 = (1 - \delta)\mu_t - \delta \frac{\partial \max H}{\partial S_t}$. The long-run demand curve shifts down to the left (see Appendix C.2.1 for complete derivation),

$$\frac{\partial u_t}{\partial p}_{u_{t+1}-u_t=0} = \frac{\delta \frac{\partial^2 \max H}{\partial S \partial p}}{(1 - \delta) - \delta \frac{\partial^2 \max H}{\partial \mu \partial S}} \leq 0;$$

$$\frac{\partial S_t}{\partial p}_{u_{t+1}-u_t=0} = \frac{\frac{\partial^2 \max H}{\partial S \partial p}}{\frac{\partial^2 \max H}{\partial S^2}} \leq 0.$$

If an interior solution exists, increasing the output price shifts the long-run supply curve, or S isocline, to the left since more pressure is put on the resource stock. However, the long-run demand curve, or μ isocline, shifts down to the left. The long-run demand for the output in the resource sector decreases due to an increase in the price from the harvested stock. At the same time, the supply of the resource stock decreases because there are incentives to overuse the resource stock and long-run depletion of the stock occurs. Here, the steady state resource stock decreases unambiguously but the marginal user cost may or may not decline. Formally, taking the total derivative of equations (2.28) and (2.29), we obtain,

$$(1 - \delta) \frac{d\mu^{eq}}{dp} - \delta \left(\frac{\partial^2 \max H}{\partial S_t \partial \mu_t} \frac{d\mu^{eq}}{dp} + \frac{\partial^2 \max H}{\partial S_t^2} \frac{dS^{eq}}{dp} + \frac{\partial^2 \max H}{\partial S_t \partial p} \right) = 0 \quad (3.8)$$

$$\frac{\partial^2 \max H}{\partial \mu_t^2} \frac{d\mu^{eq}}{dp} + \frac{\partial^2 \max H}{\partial \mu_t \partial S_t} \frac{dS^{eq}}{dp} + \frac{\partial^2 \max H}{\partial \mu_t \partial p} = 0. \quad (3.9)$$

Using Cramer's Rule, we derive (see Appendix C.2.2 for proof),

$$\frac{dS^{eq}}{dp} = \frac{1}{\Delta} \left(\delta \frac{\partial^2 \max H}{\partial \mu^2} \frac{\partial^2 \max H}{\partial S_t \partial p} + \left((1 - \delta) - \delta \frac{\partial^2 \max H}{\partial \mu_t \partial S_t} \right) \frac{\partial^2 \max H}{\partial \mu_t \partial p} \right) \leq 0; \quad (3.10)$$

$$\frac{du^{eq}}{dp} = \frac{1}{\Delta} \left(\delta \frac{\partial^2 \max H}{\partial \mu_t \partial p} \frac{\partial^2 \max H}{\partial S_t^2} - \frac{\partial^2 \max H}{\partial \mu_t \partial S_t} \frac{\partial^2 \max H}{\partial S_t \partial p} \right) \leq 0;$$

where $\Delta = -\frac{\partial^2 \max H}{\partial \mu_t^2} \frac{\partial^2 \max H}{\partial S_t^2} - \left((1 - \delta) - \delta \frac{\partial^2 \max H}{\partial \mu_t \partial S_t} \right) \frac{\partial^2 \max H}{\partial \mu_t \partial S_t} \geq 0$. The overall impact on the steady-state level of the marginal user cost depends upon the magnitude of the shifts in both the long-run supply and demand curves. Figure 3.1 illustrates a case where the effect of an increase in price due to opening to trade results in an upward shift of the trajectory. Here, the marginal user cost increases, from μ^{eq1} to μ^{eq2} , and the steady-state stock is lower, S^{eq1} to S^{eq2} .³

In the very short run, an increase in the price of the output from the resource sector gives an incentive for all community members to allocate more labor into the resource sector. Instantaneously, production from the resource sector rises along with income of community members. At first, the resource stock will decline due to intensive extraction. However, with more intensive use of the stock, the shadow price of the resource stock increases as each unit of the remaining stock now has more of the variable input, labor, in the production process. This calls for more preservation of the resource stock for future use. Although the effect of the long-run resource stock is unambiguously decreasing, the overall effect on the marginal user cost of the resource stock is unclear. The temporary increase in shadow value of the stock is mitigated by the decrease in demand for the output in the resource stock because of the higher price. The long-run degradation of the resource stock under community based management coincides with the dynamic

³We consider a case where a single steady-state outcome exists in the phase region in which the optimal values of the control variables are interior solutions. The other phase regions are omitted to simplify the diagram.

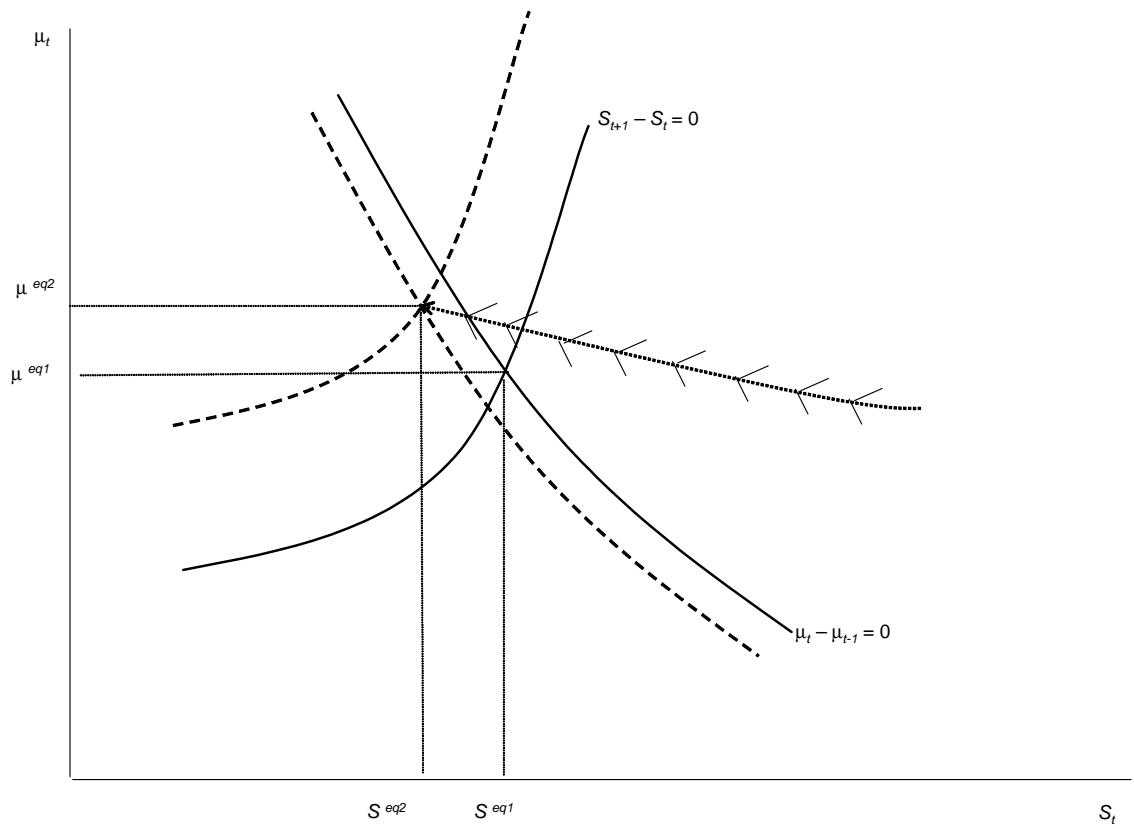


Figure 3.1: Comparative Dynamics in a Change in Relative Price Due to Opening to Trade

results from Brander and Taylor (1997a). However, degradation of the resource stock is an optimal outcome that maximizes long-run welfare and not due to short-sightedness of any planner.

When a single stable separatrix exists, a price increase may cause the optimal trajectory path to jump up as shown in Figure 3.1. The magnitude of the jump of the trajectory determines if the property rights regime governing the resource stock changes or remains the same. In Figure 3.2, we illustrate how a price increase may or may not change the property rights regime. We simplify the phase region by showing only ψ_t , which delineates the phase diagram into regions where the resource stock is closed (above ψ_t) and where it is open (below ψ_t). We start at trajectory 1 where the resource stock is always open. A very small increase in the price may not move the trajectory up at all, thus, resulting in the same property rights regime. However, a larger shift from trajectory 1 to trajectory 2 may lead to the full closure of the resource stock.

In this chapter, we have derived the effects of trade on the resource stock in the finite and infinite horizon model. In the two-period finite horizon model, if it is announced that the country will open to trade in a future period, the resource stock increases prior to trade liberalization. Owners of the resource stock will lessen their current extraction and limit entrance of non-community members. Their actions in the current period build up the stock for future use. When the country opens to trade and the relative price in the resource sector increases, the community will continue to decrease access of the resource stock to non-members and we will see an increase in labor allocations in the resource sector. Increased pressure on the resource stock may or may not result in its degradation after period 2.

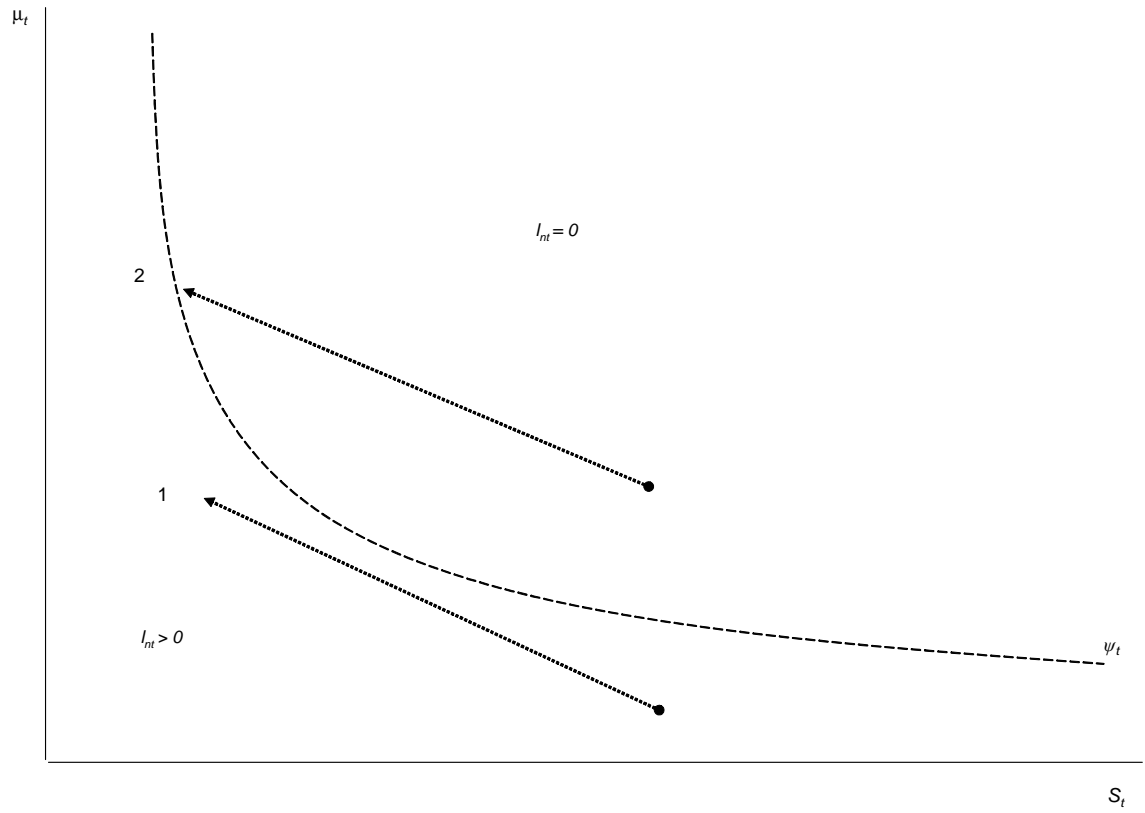


Figure 3.2: Property Rights Regimes and an Increase in Output Price due to Opening to Trade

In the infinite horizon model, a permanent price increase decreases the steady state stock level. However, degrading the stock maximizes welfare for the community as long as it follows the dynamic Nash equilibrium path. If we deviate from this path by extracting resource stocks too quickly, or even too slowly, it will not maximize welfare for the community. Therefore, the result from this section must be interpreted very carefully: welfare is maximized only when the optimal trajectory path that reduces the resource stock is followed.

Chapter 4

Endogenizing the Trade Policy Choice

So far, we have investigated the case where the trade policy decision is exogenously adopted in the economy. However, the decision to open or close the economy to trade is truly endogenous from the point of view of the country. Political influence by different groups within an economy can affect the decision of the government to open to trade. In this chapter, we analyze how interest groups influence the decision of the government to implement the trade policy of the economy. Once we have endogenized the trade policy choice, we link it back to the property rights regime choice governing stock over time.

There are two distinct approaches in modelling the effect of political influence on trade policies: models that emphasize political competition between candidates; and models that view governments as entities seeking to maximize political support (Hillman, 1989). Models of political competition have parties, lobbying groups and voters as entities in the economy. Lobbying groups contribute to a party that supports their trade policy stand in order to maximize welfare. Then, the party uses political contributions from the lobby groups to influence voters' decisions in adopting a particular policy option. Political competition models answer the broader questions regarding trade policy selection, such as what type

of political party will dominate the policy choices in the economy or who will benefit from these policies.

The alternative view is to model the incumbent government as an entity that maximizes political support by choosing optimally the type of trade policy given the welfare of agents in the economy. Political support models have the benefit of answering more specific questions with regard to trade policy choice such as, what is the extent to which a particular industry will be favored or what type of policy instrument will be adopted by the government (Hillman, 1982)? The objective of this chapter is to determine the equilibrium trade protection structure in a small open economy. Specifically, we analyze how lobby groups affect the equilibrium decision of the government to implement the trade policy. We also determine the optimal property rights regime chosen by communities governing the resource stock given the government's decision. A political support framework is used to arrive at the answers.

Grossman and Helpman (1994) developed a political economy model showing how various interest groups can lobby the government to influence policy. In the environmental economic literature, this framework has been used to determine optimal pollution taxes, study the competitive lobbying behavior between polluting industries, and analyze the impact of free trade on environmental regulations (Fredriksson, 1997; Aidt, 1998; Yu, 1999; Gulati, 2003). We adopt the political economy framework by Grossman and Helpman to determine the effect of endogenously opening to trade on the welfare of the entities in our model, as well as on the community members' property rights regime choice in governing the use of a resource stock.

The remaining subsections in this chapter are divided into four parts. Section

4.1 outlines the political economy structure of the model. Section 4.2 determines the conditions by which the optimal trade regime is chosen given the political economy framework. Section 4.3 illustrates the optimal trade instrument selected by the government over time. Lastly, Section 4.4 derives the optimal property rights regime pattern given an endogenous tariff rate.

4.1 Political Economy Structure

There are four main entities in the economy: (1) community members; (2) non-community members; (3) owners of capital; and (4) the government. Among these four entities, only community members (or the owners of the resource stock) and owners of capital control a specific factor in production of a sector in the economy. The non-community members are deemed as entities that have no power or resources to lobby for any particular trade policy. The government selects the trade policy. We assume that only the owners of a specific factor are allowed to collude in order to create lobby groups that influence the government in choosing a trade policy.

Two types of trade policies are analyzed: a dichotomous measure of trade regime and a continuous measure of tariff rates. First, we investigate the type of trade regime that the government adopts, whether it is an autarky, state of the economy where no outside trade exists, or free trade, where trade across countries exist without any barriers. We then move from the extreme case of a dichotomous trade policy choice to the implementation of optimal tariff rates over time. Autarky and free trade can be achieved through the use of tariffs. A tariff rate of zero implies free trade. On the other hand, a tariff rate that creates the same terms of trade within the economy, as well as the international

market, mimics an autarkic regime. Throughout the analysis in this chapter, we determine the level of tariffs that the government selects for the economy given social welfare and lobby contributions.

The owners of capital, owners of the resource stock and non-community members maximize their welfare given the trade policy regime chosen by the government. To simplify our analysis, we use the same notation as the previous chapters but we introduce a definition for the optimal stream of welfare that all entities in the economy obtain from the solution to the general equilibrium analysis. The owners of capital maximize their stream of profits over time by optimally selecting the amount of labor to employ in order to maximize welfare, given the decision of all providers of labor. We can write the maximum stream of welfare of owners of capital, W^K , for a trade policy as follows,

$$W^K(\tau) \equiv \sum_{t=0}^{\infty} V_t^K(\tau, S_t(\tau)) \equiv \max_{L_{xt}} \sum_{t=0}^{\infty} \{Y_x(K, L_{xt}) - w_t L_{xt}\} \delta_K^t, \quad (4.1)$$

where τ is the tariff rate selected by the government, V_t^K is the optimal value derived by the owners of capital at time t and δ_K is the discount factor.

Similarly, owners of the resource stock maximize returns from the stock over time by choosing the amount of labor to allocate in both sectors of the economy and regulating the use of the resource stock for non-community members. The welfare derived by the owners of the resource stock, W^S , for a particular trade policy can be expressed as,

$$\begin{aligned}
W^S(\tau) &\equiv \sum_{t=0}^{\infty} V_t^S(\tau, S_t(\tau)) & (4.2) \\
&\equiv \max_{l_{mt}, l_{nt}} \sum_{t=0}^{\infty} \sum_{m=1}^C (w_t(h - l_{mt}) + p(\tau)\alpha_m S_t f(L_{-mt}, l_{mt})) \delta_m^t \\
\text{s.t. } S_{t+1} - S_t &= G(S_t) - \sum_{m=1}^C (\alpha_m S_t f(L_{-mt}, l_{mt})) - N\alpha_n S_t f(L_{-nt}, l_{nt}).
\end{aligned}$$

where V_t^S is the optimal value derived by the owners of capital at time t and δ_m is the rate of time preference by the m^{th} individual.

Each i^{th} group's net welfare is equal to $\Phi^i = W^i(\tau) - \phi^i(\tau) \quad \forall i = K, S$, where $\phi^i(\tau)$ is the contribution schedule of the i^{th} group. In this particular framework, we disregard the issues of lobby formation and free riding amongst members of a lobby group. Here, we assume that both the owners of the resource stock and the owners of capital overcome free riding and lobby formation problems. Since non-community members do not have lobby power, their contributions are equal to zero.

The social welfare function, W , that designates the aggregate welfare of all groups in the economy is linear in total earnings by all entities in the economy. This can be written as,

$$W(\tau) \equiv \sum_{t=0}^{\infty} V_t(\tau, S_t(\tau)) = W^K(\tau) + W^S(\tau), \quad (4.3)$$

where $V_t(\tau, S_t(\tau))$ is the optimal value derived by society at time t . Note that the trade choice affects social welfare directly through the relative price of the commodities produced in the economy.

The government welfare depends on social welfare as well any contributions made by the existing lobby groups. Formally,

$$G(\tau) = W(\tau) + a(\phi^K(\tau) + \phi^S(\tau)), \quad (4.4)$$

where a is a non-negative value representing the political weight given to the contribution of all lobby groups. A large value of a implies that the government places a greater weight on political contributions. A value of a equal to zero implies that lobbying will have no effect whatsoever on the decision of the government to adopt a particular policy. Here, the government does not have any bias as to the source of the contribution, but only cares about the total amount of contributions. The type of trade policy is determined through a two-stage non-cooperative game as a sub-game perfect outcome. First, the existing lobby group will determine the optimal political contribution schedule in order to maximize the net welfare of the group. In the second stage, the government will choose the optimal trade regime that maximizes its own welfare.

Bernheim and Whinston (1986) and Grossman and Helpman (1994) derive an equilibrium in the trade policy game as a set of policy choices and contribution schedules that are characterized by the following conditions:

Proposition 4.1. (Bernheim and Whinston (1986) and Grossman and Helpman (1994)):

The contribution schedule, $(\{\phi^{io}(\tau^o)\}_{i=K,S}, \tau^o)$, is a sub-game perfect Nash Equilibrium of the trade policy game if and only if:

- (a). $\phi^{io}(\tau^o)$, and τ^o is feasible for all lobby groups i ;
- (b). The trade policy regime, τ^o , maximizes $W(\tau) + a(\phi^K(\tau) + \phi^S(\tau))$;
- (c). The trade policy regime, τ^o , maximizes $W^i(\tau) - \phi^{io}(\tau) + W(\tau) + a(\phi^K(\tau) + \phi^S(\tau))$ for all lobby groups; and
- (d). For all lobby groups, there exists τ' that maximizes the government welfare, $W(\tau) + a \sum_{i=K,S} \phi^i(\tau)$, such that $\phi^i(\tau') = 0$.

Condition (a) states that the contribution by all lobby groups must be feasible, *i.e.*, non-negative and less than the aggregate welfare of the lobby group. Condition (b) stipulates that the government maximizes their own welfare by setting the trade regime optimally given the contribution schedule of the lobby groups. Condition (c) implies that the optimal trade regime choice must maximize the joint welfare of the government and all the lobby groups involved in the political process. Lastly, condition (d) states that for any lobby group, there must exist a trade regime that elicits a contribution of nill from that lobby group, which the government finds as equally attractive as the equilibrium generated from an alternative trade regime.

4.2 Dichotomous Trade Regime Choice

In this subsection, the type of trade regime, which exists when either the owners of the resource stock or owners of capital or both groups can lobby is determined. We also derive the optimal contribution schedules from the lobby groups.

The government decides on the appropriate trade regime that maximizes its welfare. Lobby groups that exist will be able to contribute to influence the decision of the government on whether to choose an autarkic or free trade regime. Contributions are used by the current government for re-election purposes in order to stay in power for the next term. Once the government chooses the particular trade regime that maximizes its welfare, the regime will be adopted immediately. Thus, we can simplify the analysis into a static problem where we look at the maximized stream of welfare that each entity obtains and compare the results

under the two possible trade regimes.

The instrument available for the government to establish either an autarkic or free trade regime is a specific tariff. A specific tariff is a fixed charge per unit of the imported good. At time t , the world price of good i adopted in the economy upon opening to trade, p_i^w , will increase by the tariff, τ , such that the resulting domestic price is equal to $p_i^d = p_i^w + \tau_i$. The presence of an import tariff will affect the terms of trade in the economy. A tariff placed on a good produced in a sector will protect that sector by increasing the domestic price of that good and, conversely, decreasing the relative price of the good in the other sector. For example, if the manufacturing sector in this economy is protected by a specific tariff but the resource sector is not, the resulting domestic price of the output from the manufacturing sector will increase to $p_K^d = p_K^w + \tau_K$. Thus, the relative price of the good produced in the resource sector decreases as the level of tariff in the manufacturing sector increases, $\frac{p_S^d}{p_K^d + \tau_K}$. In this section, we consider only two values for the tariff rate. Under free trade, $\tau_K = 0$ while under autarky, $\tau_K = \overline{\tau}_K$ such that the tariff rate $\overline{\tau}_K$ creates the same terms of trade within the economy as well as in the international market. This has implications in terms of the preference of the lobby groups in the economy as well as their contribution schedules. Throughout the chapter, we consider the case where the government only chooses to implement a tariff in the manufacturing sector. The welfare from the owners of capital is such that $W^K(0) < W^K(\overline{\tau}_K)$ while for the owners of the resource stock, $W^S(0) > W^S(\overline{\tau}_K)$. Furthermore, the contribution schedule for the owners of capital is such that $\phi^K(0) < \phi^K(\overline{\tau}_K)$ while for the owners of the resource stock, $\phi^S(0) > \phi^S(\overline{\tau}_K)$.

The government's decision to select a particular trade regime depends on the

following condition,

$$W(\tau_K^*) + a(\phi^K(\tau_K^*) + \phi^S(\tau_K^*)) \geq W(\tau'_K) + a(\phi^K(\tau'_K) + \phi^S(\tau'_K)). \quad (4.5)$$

where τ_K^* is the optimal trade regime while τ'_K is the non-optimal trade regime. The optimal trade regime in this dichotomous choice setting maximizes the government's welfare derived from both the contributions and social welfare of the economy.

4.2.1 Single Lobby Group

Let us first assume that only the owners of capital can lobby while the owners of the resource stock cannot lobby. We derive the optimal level of contribution when a single lobby group exists given that the government chooses to implement a tariff rate equal to $\overline{\tau}_K$ in the manufacturing sector or not. The net welfare of the owners of capital under the two trade regimes can be summarized below:

$$\Phi^K = \left\{ \begin{array}{ll} W^K(0) - \phi^K(0) & \text{if } W(0) + a\phi^K(0) > W(\overline{\tau}_K) + a\phi^K(\overline{\tau}_K) \\ W^K(\overline{\tau}_K) - \phi^K(\overline{\tau}_K) & \text{if } W(0) + a\phi^K(0) \leq W(\overline{\tau}_K) + a\phi^K(\overline{\tau}_K) \end{array} \right\} \quad (4.6)$$

Under a free trade regime, the level of lobby contribution is such that $\phi^K(0) \geq 0$. The maximum contribution level that the lobby group provides that makes him indifferent between the two trade regimes is equal to the additional gains when moving to a free trade regime from an autarky. Therefore, from (4.6), the lobby group is indifferent between autarky and free trade when, $W^K(0) - \phi^K(0) = W^K(\overline{\tau}_K)$. Rearranging, we find that the maximum contribution level that owners

of capital are willing to give to the government under free trade is $\phi^K(0) = W^K(0) - W^K(\bar{\tau}_K)$. However, we have assumed that $W^K(0) < W^K(\bar{\tau}_K)$. Since the minimum contribution level must be non-negative, we find that $\phi^K(0) = 0$. Thus, in a dichotomous trade regime scenario, the lobbying group will never contribute a strictly positive amount under a trade regime that gives them a lower level of welfare.

Under an autarky regime, the level of lobby contribution must also be non-negative, $\phi^K(\bar{\tau}_K) \geq 0$. The maximum contribution levels that the owners of capital provide is equal to the additional gains when adopting an autarky as opposed to a free trade regime. Therefore, from (4.6), the lobby group is indifferent between free trade and autarky when, $W^K(\bar{\tau}_K) - \phi^K(\bar{\tau}_K) = W^K(0)$. Therefore, the lobby contribution under autarky must lie in the following range: $0 \leq \phi^K(\bar{\tau}_K) \leq W^K(\bar{\tau}_K) - W^K(0)$. Recall that $\phi^K(0) = 0$ and the government will choose a free trade regime when the owners of capital contribute $\phi^K(\bar{\tau}_K) \geq \frac{W(0) - W(\bar{\tau}_K)}{a}$. There are two potential optimal values for $\phi^K(\bar{\tau}_K)$. If social welfare is greater under autarky than free trade, then $W(0) - W(\bar{\tau}_K) < 0$. This implies that owners of capital would contribute an amount equal to zero since negative contributions are not possible. However, when social welfare is greater under free trade than autarky, $W(0) - W(\bar{\tau}_K) > 0$, the owners of capital need to contribute $\phi^K(\bar{\tau}_K) = \frac{W(0) - W(\bar{\tau}_K)}{a}$ to make the government indifferent between the two trade regimes.¹ The amount contributed is equal to the weighted difference in social welfare under the two trade regimes. If the government puts more weight on lobby contributions, the optimal contribution is lower.

We have now determined the optimal lobby contributions in both trade regimes,

¹As long as condition (a) of Proposition 4.1 holds, this is an optimal solution to the problem.

now we derive the condition when the lobby group contributes these amounts. The owners of capital earn more net welfare under autarky when,

$$\Phi^K(0) < \Phi^K(\bar{\tau}_K).$$

Substituting for $\Phi^K(0)$ and $\Phi^K(\bar{\tau}_K)$ along with $\phi^K(0) = 0$ and $\phi^K(\bar{\tau}_K) = \frac{W(0) - W(\bar{\tau}_K)}{a}$, we arrive at the following condition,

$$W^K(0) + \frac{W(0) - W(\bar{\tau}_K)}{a} < W^K(\bar{\tau}_K). \quad (4.7)$$

The sufficient condition for this inequality to hold occurs when social welfare under autarky is greater than under free trade, i.e. $W(0) - W(\bar{\tau}_K) < 0$. In this case, the optimal contribution will be equal to zero. However, if $W(0) - W(\bar{\tau}_K) > 0$ autarky is still preferred as long as $\phi^K(\bar{\tau}_K) = \frac{W(0) - W(\bar{\tau}_K)}{a} < W^K(\bar{\tau}_K) - W^K(0)$. Otherwise, the owners of capital would prefer to have a free trade regime and contribute nothing.

Figure 4.1 depicts the optimal contribution when the aggregate welfare of the lobbyist and the social welfare are maximized under the same trade regime, autarky. Without any contributions, the government will choose autarky to maximize social welfare, thus yielding $W^K(\bar{\tau}_K)$ for the owners of capital. Any positive contribution will decrease net welfare by the amount of the contribution. In fact, if the level of contribution equalled $W^K(0) - W^K(\bar{\tau}_K)$, the net welfare derived by the owners of capital would be equal to the welfare under a free trade regime.

Figure 4.2 depicts the relationship between a contribution of the single lobby group and net welfare when the trade policy preferences of the owners of capital do not coincide with social welfare and it is optimal to contribute a positive amount. For any contribution that falls within the range from zero to $\frac{W(0) - W(\bar{\tau}_K)}{a}$, the

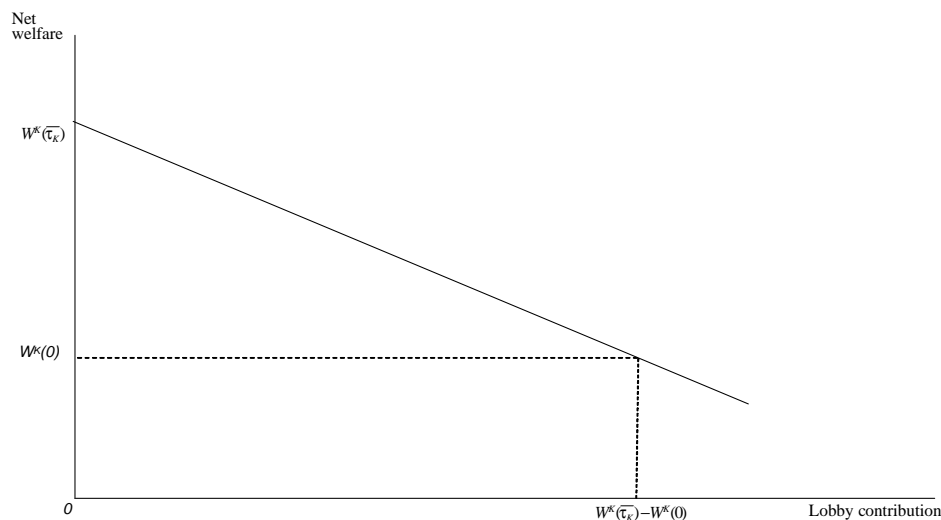


Figure 4.1: Optimal Contribution of Owners of Capital when Social Welfare Change Coincide with Aggregate Welfare

government chooses to adopt a free trade regime resulting in net welfare for the owners of capital equal to $W^K(0) - \phi^K$. However, when the contribution level increases to $\frac{W(0) - W(\bar{\tau}_K)}{a}$, the government chooses the autarkic regime and the owners of capital earn net welfare equal to $W^K(\bar{\tau}_K) - \frac{W(0) - W(\bar{\tau}_K)}{a}$. Note that if the net welfare line W^{K2} is below W^{K1} , the lobby group would rather have a free trade regime and always contribute nothing.

So far, we have disregarded problems associated with lobby formation and lobby contribution between owners of capital and owners of the resource stock. However, given the communal nature of the management of the resource stock, it is more likely that the owners of capital are more efficient in lobbying the government to adopt a particular trade regime than the communal members of a resource stock (López, 2005). This implies that governments may skew the particular trade policy to favor more organized, more connected and elite members of

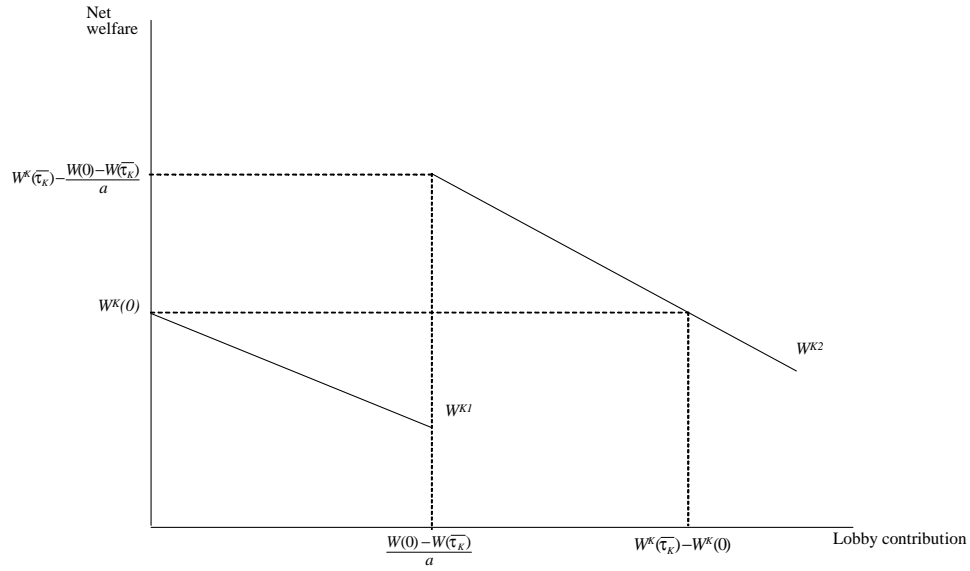


Figure 4.2: Optimal Contribution of Owners of Capital when Social Welfare Change Does Not Coincide with Aggregate Welfare

the economy especially if they put more political weight on lobby contributions. Thus, lobbying may explain why some governments implement trade policies even though it knowingly results in the decrease of welfare of poorer members of society.

4.2.2 Two Lobby Groups

Let us examine the case where there are two opposing lobby groups that exist in the economy. Adopting an autarkic regime increases welfare for the owners of capital ($W^K(0) < W^K(\bar{\tau}_K)$) but free trade regimes increase welfare for the owners of the resource stock ($W^S(0) > W^S(\bar{\tau}_K)$). Furthermore, assume that the two lobbying groups are equally powerful, meaning $W^K(\bar{\tau}_K) - W^K(0) = W^S(0) - W^S(\bar{\tau}_K)$. We determine the optimal contribution levels of each lobby

group along with the trade regime adopted by the government.

The objective of each lobby group is to maximize their own aggregate welfare by optimally selecting their level of contribution given all other lobby groups' level of contribution. From the previous section, we have determined that a lobby group will contribute an amount equal to zero under a trade regime that gives them lower welfare. Thus, the owners of capital contribute zero under free trade while owners of the resource stock contribute zero under autarky, i.e. $\phi^S(\bar{\tau}_K) = \phi^K(0) = 0$. The net welfare returns by the owners of capital and owners of the resource stock are summarized below:

$$\{\Phi^K, \Phi^S\} = \left\{ \begin{array}{ll} W^K(0), W^S(0) - \phi^S(0) & \text{if } W(0) + a\phi^S(0) > W(\bar{\tau}_K) + a\phi^K(\bar{\tau}_K) \\ W^K(\bar{\tau}_K) - \phi^K(\bar{\tau}_K), W^S(\bar{\tau}_K) & \text{if } W(0) + a\phi^S(0) \leq W(\bar{\tau}_K) + a\phi^K(\bar{\tau}_K) \end{array} \right\} \quad (4.8)$$

From the previous section, we know that the optimal lobbying contribution ranges from 0 to additional gains from adopting the trade regime that guarantees the highest welfare. This implies the following: $0 \leq \phi^S(0) \leq W^S(0) - W^S(\bar{\tau}_K)$ and $0 \leq \phi^K(0) \leq W^K(\bar{\tau}_K) - W^K(0)$. If an autarky is established, from (4.8) this implies that, $\phi^K(\bar{\tau}_K) \geq \frac{W(0) - W(\bar{\tau}_K)}{a} + \phi^S(0)$. Since we have assumed that the two lobby groups are equally powerful, the maximum lobby contribution by both the owners of capital and owners of the resource stock is such that $\max \phi^K(\bar{\tau}_K) = \max \phi^S(0)$. We can simplify the optimal condition for an autarky as $0 \geq \frac{W(0) - W(\bar{\tau}_K)}{a}$. To ensure that this inequality holds, social welfare under autarky must be greater than under a free trade regime, else the government would never adopt an autarky which is a contradiction to our earlier statement.²

²Note that the level of contribution by the owners of capital will always be in the feasible

The result also holds true when the owners of capital are more powerful than the owners of the resource stock, i.e. $W^K(\bar{\tau}_K) - W^K(0) > W^S(0) - W^S(\bar{\tau}_K)$.³

The owners of capital will earn more returns from autarky if the following condition holds true:

$$\Phi^K(0) < \Phi^K(\bar{\tau}_K).$$

Imposing the assumption that $W^K(\bar{\tau}_K) - W^K(0) = W^S(0) - W^S(\bar{\tau}_K)$ along with $\phi^K(\bar{\tau}_K) = \frac{W(0) - W(\bar{\tau}_K)}{a} + W^S(0) - W^S(\bar{\tau}_K)$, we arrive at the following condition,

$$-\frac{W(0) - W(\bar{\tau}_K)}{a} < 2(W^K(\bar{\tau}_K) - W^K(0)). \quad (4.9)$$

This condition implies that the owners of capital will only lobby to ensure an autarky if the weighted social welfare change from autarky to free trade is less than two times the welfare gain by the owners of capital.

The opposite holds true when the government adopts a free trade regime. The owners of the resource stock must lobby an amount equal to $\phi^S(0) \geq \frac{W(\bar{\tau}_K) - W(0)}{a} + W^K(\bar{\tau}_K) - W^K(0)$. It must be the case that $0 > \frac{W(\bar{\tau}_K) - W(0)}{a}$ when both lobby groups are equally powerful, which implies that social welfare is higher under free trade than autarky. However, similar to the previous analysis, the owners of the resource stock will only lobby to ensure free trade if the weighted difference in the social welfare between the trade regimes are greater than two

range since $W^K(\bar{\tau}_K) - W^K(0) > \frac{W(0) - W(\bar{\tau}_K)}{a} + W^S(0) - W^S(\bar{\tau}_K)$.

³However, no clear results can be obtained if the owners of the resource stock are more powerful than the owners of capital.

times the difference of the change in welfare of owners of the resource stock. This means, $\Phi^S(0) > \Phi^S(\bar{\tau}_K)$ along with $W^K(\bar{\tau}_K) - W^K(0) = W^S(0) - W^S(\bar{\tau}_K)$ and $\phi^S(0) = \frac{W(\bar{\tau}_K) - W(0)}{a} + W^K(\bar{\tau}_K) - W^K(0)$ results in the following condition,

$$-\frac{W(\bar{\tau}_K) - W(0)}{a} < 2(W^S(0) - W^S(\bar{\tau}_K)). \quad (4.10)$$

Figure 4.3 illustrates the optimal lobbying contribution of owners of the resource stock when an equally powerful lobby group exists and it is beneficial for the lobbying group to contribute a positive amount to ensure his preferred trade regime. Without the presence of the competing lobbyist, the owners of the resource stock would not need to contribute anything since the trade regime preferred by the government to maximize social welfare coincides with their own preferences. However, with a competing lobby group, the move from an autarkic trade regime to a free trade regime is not ensured since the opposing lobby group can contribute a significant amount to keep the autarkic regime. The broken line represents welfare levels that are not guaranteed to be reached; given that the owners of capital can contribute up to $W^K(\bar{\tau}_K) - W^K(0)$ in order to obtain autarky. The owners of the resource stock need to make a positive contribution equal to $\frac{W(\bar{\tau}_K) - W(0)}{a} + W^K(\bar{\tau}_K) - W^K(0)$ to ensure that the economy moves toward the free trade regime. This particular result is similar to the outcome in the Grossman and Helpman (1994) model where they show that each lobby group pays according to their political rival's strength.

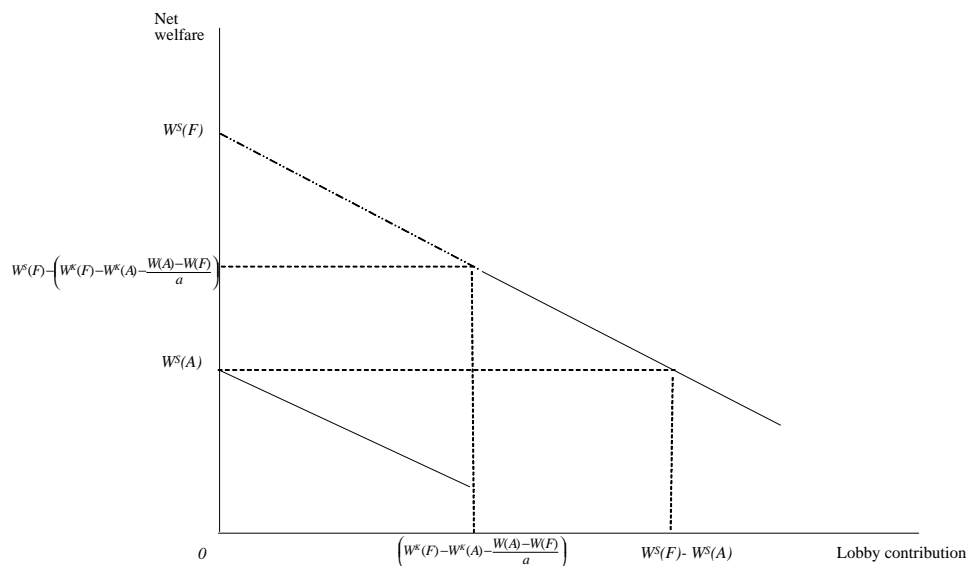


Figure 4.3: Net Welfare for Owners of Resource Stock with Two Competing Lobby Groups in the Economy

4.3 Trade Liberalization Over Time

We now look at how trade liberalization is adopted gradually by investigating the optimal specific tariff placed on the different goods produced in the economy. In this section, we determine the tariff rate that maximizes the government's welfare in the presence of two lobbying groups as well as determine the tariff's effect on community's property rights regime choice and stock over time.

Consider the same model as in the previous section, where the government's objective is to be able to maximize its own welfare by optimally choosing a particular trade policy. However, two important characteristics of the problem are different. First, the trade instrument is a continuous tariff rate that the government can set on the good produced in the manufacturing sector instead of a discrete dichotomous choice between autarky and free trade. We also assume

that the tariff rate is determined during each time period. Unlike the previous case where the trade regime is set for all time during the initial period, we allow a more flexible tariff rate decided by the government during each time period.

Similar to the previous section, we focus on an import tariff in the manufacturing sector. The only difference in notation is that the tariff will now be allowed to vary during each time period. Thus, the resulting domestic price of the output from the manufacturing sector is $p_{K,t}^d = p_{K,t}^w + \tau_t$. The relative price of the good produced in the resource sector decreases as the level of tariff in the manufacturing sector increases, $\frac{p_{S,t}^d}{p_{K,t}^d + \tau_t}$. This has implications in terms of the preference of the lobby groups in the economy as well as their contribution schedules. In this case, if the government only chooses to implement a tariff in the manufacturing sector, the contribution schedule for the owners of capital will be increasing in the specific tariff, $\frac{\partial \phi_t^K(\tau_t)}{\partial \tau_t} > 0$, while it would be decreasing for the owners of the resource stock, $\frac{\partial \phi_t^S(\tau_t)}{\partial \tau_t} < 0$.

When a particular economy has comparative advantage in the production of the output from the resource sector, the country becomes a net exporter in the resource intensive good and a net importer of the capital intensive good. The government chooses the tariff level placed on imported goods that compete with output produced domestically from the manufacturing sector. The government's objective is to maximize social welfare plus the weighted value of contribution over time by optimally selecting a tariff rate in the manufacturing sector during each period. Recall from equation (4.3) we defined the stream of social welfare as $W(\tau_t) \equiv \sum_{t=0}^{\infty} V_t(\tau_t, S_t(\tau_t))$ where $V_t(\tau_t, S_t(\tau_t))$ is the maximum value function of social welfare at time t . To formally express the government's problem, we re-write equation (4.4),

$$\max_{\tau_t} G(\tau_t) = \sum_{t=0}^{\infty} V_t(\tau_t, S_t(\tau_t)) + a \sum_{t=0}^{\infty} (\phi_t^K(\tau_t) + \phi_t^S(\tau_t)). \quad (4.11)$$

Here, the main difference between the original government problem formulation in equation (4.4) and the equation above is that the tariff rates are chosen during each time period. Since the resource stock changes over time as well, we express the effect of tariff directly on the value of social welfare as well as indirectly through the stock over time. The government also derives welfare from the political contributions of both lobby groups in the economy. The larger the weight, a , the greater the preference placed by the government on obtaining these contributions. In this case, we assume that the tariff revenues are redibursed lump sum back into the economy.

The net welfare function of the owners of capital and owners of the resource stock can easily be extended to take into account the time-dependent nature of the problem. The net welfare of the lobby group i is equal to $\Phi^i = \sum_{t=0}^{\infty} V_t^i(\tau_t, S_t(\tau_t)) - \sum_{t=0}^T \phi_t^i(\tau_t)$. Since the stock level changes over time, the tariff level would also have an impact on the resource stock during each time period.

The optimal tariff rate maximizes the joint welfare of the government and each lobby group in the political process (as shown in condition (c) of Proposition 4.1). Formally, we maximize the following joint welfare function,

$$\max_{\tau_t} \sum_{t=0}^{\infty} V_t(\tau_t, S_t(\tau_t)) + a \sum_{t=0}^{\infty} (\phi_t^K(\tau_t) + \phi_t^S(\tau_t)) + \sum_{i \in K, S} \left(\sum_{t=0}^{\infty} V_t^i(\tau_t, S_t(\tau_t)) - \sum_{t=0}^{\infty} \phi_t^i(\tau_t) \right). \quad (4.12)$$

Assuming that contribution functions are differentiable, the optimal tariff that maximizes joint welfare must satisfy the following necessary condition ,

$$\frac{\partial V_t^i(\tau_t)}{\partial \tau_t} - \frac{\partial \phi_t^i(\tau_t)}{\partial \tau_t} + \frac{\partial V_t(\tau_t, S_t(\tau_t))}{\partial \tau_t} + \frac{\partial V_t(\tau_t, S_t(\tau_t))}{\partial S_t} \frac{\partial S_t(\tau_t)}{\partial \tau_t} + a \sum_i \frac{\partial \phi_t^i(\tau_t)}{\partial \tau_t} = 0; \quad (4.13)$$

$$\forall i = K, S.$$

However, the government's maximization implies that the following first-order condition holds,⁴

$$\frac{\partial V_t(\tau_t, S_t(\tau_t))}{\partial \tau_t} + \frac{\partial V_t(\tau_t, S_t(\tau_t))}{\partial S_t} \frac{\partial S_t(\tau_t)}{\partial \tau_t} + a \sum_i \frac{\partial \phi_t^i(\tau_t)}{\partial \tau_t} = 0. \quad (4.14)$$

Here, we find that the government selects the tariff by equating the direct marginal returns from the tariff, $\frac{\partial V_t(\tau_t, S_t(\tau_t))}{\partial \tau_t}$, to the sum of the marginal contributions of all lobby groups, $a \sum_i \frac{\partial \phi_t^i(\tau_t)}{\partial \tau_t}$, plus the indirect impact of tariffs through the stock, $\frac{\partial V_t(\tau_t, S_t(\tau_t))}{\partial S_t} \frac{\partial S_t(\tau_t)}{\partial \tau_t}$. The term $\frac{\partial V_t(\tau_t, S_t(\tau_t))}{\partial S_t}$ is the shadow value or the marginal user cost of the stock. As the stock level decreases, the marginal user cost increases. Given the variability in the marginal user cost of the stock, we can infer that the optimal tariff must also be changing over time.

Combining the equations (4.13) and (4.14), we arrive at the necessary conditions for a locally truthful contribution schedule during each time period,

$$\frac{\partial V_t^i(\tau_t)}{\partial \tau_t} - \frac{\partial \phi_t^i(\tau_t)}{\partial \tau_t} = 0 \quad \forall i = K, S. \quad (4.15)$$

Here, we find that each lobby group sets its contribution schedule so that the marginal returns from lobbying will equal the marginal contribution made to the government during each time period. The shape of the contribution schedules by

⁴This coincides with condition (b) of Proposition 4.1.

each lobby group should reflect their true preferences. The second-order condition for locally truthful contribution is,

$$\frac{\partial^2 V_t^i(\tau_t)}{\partial \tau_t^2} - \frac{\partial^2 \phi_t^i(\tau_t)}{\partial \tau_t^2} \leq 0 \quad \forall \quad i = K, S. \quad (4.16)$$

4.4 Tariff Rates, Property Rights and Labor Allocation

In this subsection, we derive the property rights regime patterns governing the use of the resource stock given an endogenous tariff rate. First, we solve the government's problem of choosing the tariff rate. Then, we look at the problem faced by the owners of capital. Lastly, we combine the two conditions derived from the government's problem and the owner of capital's problem with the first order conditions from the optimization problem of the representative community member to derive the property rights regime patterns governing the resource stock.

Let us assume that the contribution schedule for the owners of capital and the owners of the resource stock follow a quadratic functional, i.e.

$$\phi_t^K(\tau_t) = q_K \frac{(\tau_t)^2}{2} \quad (4.17)$$

$$\phi_t^S(\tau_t) = \bar{\tau}_K - q_S \frac{(\tau_t)^2}{2} \quad (4.18)$$

where $\bar{\tau}_K$ is the tariff rate that creates an autarky, q_K and q_S are slope parameters of the contribution schedule and we assume that $q_K < q_S$. From equation (4.1)

and (4.2), we can re-write the government's problem in (4.12) of deriving the optimal tariff rate during each period in time as,

$$\max_{\tau_t} G(\tau_t) = \sum_{t=0}^{\infty} \left(\sum_{m=1}^C (\alpha_m S_t f(L_{-mt}, l_{mt})) + \left(\frac{p_{K,t}^d + \tau_t}{p_{S,t}^d} \right) Y_x(K, L_{xt}) + a(\phi_t^K(\tau_t) + \phi_t^S(\tau_t)) \right) \delta^t.$$

Here, we have reformulated the problem such that the output price in the resource sector is normalized instead of the output price in the manufacturing sector. The necessary condition that maximizes the government's problem during each time period is the following,

$$\frac{Y_x(K, L_{xt})}{p_t^R} = a(q_S \tau_t - q_K \tau_t).$$

The first-order condition shows that the marginal change in social welfare must equal the marginal change in the weighted contributions derived by the government. The second-order condition that guarantees that the government maximizes its own welfare as long as,

$$-a(q_S - q_K) \leq 0. \tag{4.19}$$

The second-order condition holds since we have assumed $q_S > q_K$. Note here that the optimal tariff rate can be written as,

$$\tau_t^* = \frac{Y_x(K, L_{xt})}{a(q_S - q_K)p_t^R}. \tag{4.20}$$

Since we have assumed that $q_K < q_S$, the optimal tariff rate that the government chooses will be positive as long as the manufacturing sector produces a positive amount.

To incorporate the effect of an endogenous tariff rate in our general equilibrium problem, we solve for the Nash equilibrium in our general equilibrium problem that determines a set of labor allocations, wage rates and tariff rates in the economy. Recall that the manufacturers of capital maximize quasi-rent from capital by equating the prevailing wage rate in the market with the value of marginal product of labor (see Equation 2.19). The community members solve for their optimal wealth over time by determining their labor allocations in both sectors of the economy as well as the number of non-community members allowed into the resource sector (see Equation 2.20). To simplify our analysis, we only consider the case where the choice of labor allocation in the resource sector by the community members has an interior solution ($h > l_{ct} > 0$) but allow for full closure ($l_{nt} = 0$) and partial opening ($l_{nt} > 0$) to non-community members.

The tariff rate per period, τ_t^* , enters into the general equilibrium problem through the relative price. Recall that, $p^* = \frac{p_{S,t}^d}{p_{K,t}^d + \tau_t^*}$. Substituting (4.20) into p^* yields $p^* \equiv \frac{a(q_K - q_S)(p_{S,t}^d)^2}{a(q_K - q_S)p_{S,t}^d p_{K,t}^d + Y_x(K, L_{xt})}$. By substituting w_t using (2.19) and τ_t^* using (4.20) into the first order conditions from the representative community member (2.21-2.26), the conditions that solve for the dynamic Nash equilibrium model are,

$$(p^* - \mu_t C) \alpha_c S_t \frac{\partial f(L_{-ct}, l_{ct})}{\partial l_{ct}} - \mu_t N \alpha_n S_t \frac{\partial f(L_{-nt}, l_{nt})}{\partial l_{ct}} - \frac{\partial Y(K, L_{xt})}{\partial L_{xt}} \leq 0; \quad (4.21)$$

$$(p^* - \mu_t C) \alpha_c S_t \frac{\partial f(L_{-ct}, l_{ct})}{\partial l_{nt}} - \mu_t N \alpha_n S_t \frac{\partial f(L_{-nt}, l_{nt})}{\partial l_{nt}} + \eta_t \leq 0; \quad (4.22)$$

$$l_{nt} \frac{\partial \mathcal{L}}{\partial l_{nt}} = 0;$$

$$\frac{\partial \mathcal{L}}{\partial \eta_t} = l_{nt} \geq 0; \quad l_{nt} \eta_t = 0; \quad (4.23)$$

$$\mu_t - \mu_{t-1} = (1 - \delta)\mu_t - \delta(G'(S_t) - C\alpha_c f(L_{-ct}, l_{ct}) + N\alpha_n f(L_{-nt}, l_{nt})) - p\alpha_c f(L_{-ct}, l_{ct}); \quad (4.24)$$

$$S_{t+1} - S_t = G(S_t) - C\alpha_c S_t f(L_{-ct}, l_{ct}) - N\alpha_n S_t f(L_{-nt}, l_{nt}); \quad (4.25)$$

where $\mu_t \equiv \delta\lambda_{t+1}$. The interpretation of the first order conditions follow that in Chapter 2.4. We have just substituted the optimal relative price equal to the relative price chosen by the government given the optimal tariff rate. Using the same procedure as in Chapter 2.4, we derive the phase diagram illustrating the optimal path of stock and the marginal user cost.

Since there are two control variables, the phase plane in the state and co-state space are derived. However, we can divide the phase plane into two distinct regions depending on the optimal control path: (1) an interior solution exists for both controls ($l_{nt} > 0, l_{ct} < h$); and (2) an interior solution exists for own labor and the resource sector is fully closed ($l_{nt} = 0, l_{ct} < h$).

First, we derive the equation that traces out a contour dividing the regions, where non-community labor is greater than or equal to zero. Whenever $\eta_t > 0$, non-community labor is zero. Using equation (4.22), we derive,

$$\mu_t > \frac{p^* \alpha_c S_t \frac{\partial f((C-1)l_{ct}, l_{ct})}{\partial l_{nt}} + \eta_t}{C\alpha_c S_t \frac{\partial f((C-1)l_{ct}, l_{ct})}{\partial l_{nt}} + N\alpha_n S_t \frac{\partial f(Cl_{ct}, 0)}{\partial l_{nt}}} \equiv \zeta_t$$

where $\zeta_t(S_t)$ delineates two regions in the phase space: where non-community labor is equal to zero or strictly greater than zero. Any value of μ_t greater than

or equal to $\zeta_t(S_t)$ implies non-community labor is equal to zero. In order to illustrate the region in the phase space where non-community labor is equal to zero as opposed to strictly greater than zero, we draw the function $\zeta_t(S_t)$ in state and costate space. Taking the first and second derivative of $\zeta_t(S_t)$ with respect to S_t we derive,

$$\frac{\partial \zeta_t}{\partial S_t} = -\frac{\eta_t}{S_t^2 \left(C\alpha_c \frac{\partial f((C-1)l_{ct}, l_{ct})}{\partial l_{nt}} + N\alpha_n \frac{\partial f(Cl_{ct}, 0)}{\partial l_{nt}} \right)} \leq 0;$$

$$\frac{\partial^2 \zeta_t}{\partial S_t^2} = \frac{2\eta_t}{S_t^3 \left(C\alpha_c \frac{\partial f((C-1)l_{ct}, l_{ct})}{\partial l_{nt}} + N\alpha_n \frac{\partial f(Cl_{ct}, 0)}{\partial l_{nt}} \right)} \geq 0.$$

Here, $\frac{\partial \zeta_t}{\partial S_t} \leq 0$ and $\frac{\partial^2 \zeta_t}{\partial S_t^2} \geq 0$. Thus, the function $\zeta_t(S_t)$ is convex and decreasing in the stock. The region above ζ_t implies that non-community labor is equal to zero. When η_t is equal to zero, non-community labor is positive and this is depicted by the region below ζ_t .

The optimal trajectories for the state and control variables are found as the solution to the following equations based on the maximum principle,

$$(l_{ct}, l_{nt}) = \arg \max \mathcal{L}; \quad (4.26)$$

$$\mu_t - \mu_{t-1} = (1 - \delta)\mu_t - \delta \frac{\partial \max \mathcal{L}}{\partial S_t}; \quad (4.27)$$

$$S_{t+1} - S_t = \frac{\partial \max \mathcal{L}}{\partial \mu_t}; \quad (4.28)$$

$$\lim_{T \rightarrow \infty} \mu_T S_{T+1} = 0. \quad (4.29)$$

We derive the Hessian of the Lagrangean as negative semi-definite, which implies that the determinant of the Hessian is positive and the diagonal elements are non-positive. We derive the the following comparative statics (see Appendix D for complete derivation of results),

$$\frac{\partial l_{ct}}{\partial \mu_t} \leq 0; \frac{\partial l_{nt}}{\partial \mu_t} \leq 0; \frac{\partial l_{ct}}{\partial S_t} \geq 0; \text{ and } \frac{\partial l_{nt}}{\partial S_t} \geq 0. \quad (4.30)$$

From (4.30) we find that as the shadow value of the resource stock increases, the representative community member allocates less labor and allows less non-community labor in the resource sector. Also, any increase in stock will lead to non-decreasing community and non-community labor, *ceteris paribus*. These results are needed to obtain the isoclines in each region of the phase plane.

In order to derive the isocline and trajectories, we utilize equations (4.26) – (4.29). Using the same procedure as in Chapter 2.4, we derive the isocline in both regions in the phase space. The stock, S , and marginal user cost, μ , isoclines, are increasing and decreasing, respectively in both regions in the phase space (see Appendix D for formal proofs).

The co-state and state isoclines are the steady-state solutions for equations (4.27) and (4.28). Using equations (4.27) and (4.28) along with the comparative statics from equation (4.30), we can illustrate a potential phase diagram as shown in Figure 4.4. The μ isocline is the long-run demand for the resource stock while the S isocline is the long-run supply of the resource stock. The long-run equilibrium resource stock and shadow value are S^{eq} and μ^{eq} , respectively. The unstable regions are: to the left of the S isocline and above the μ isocline; and to the right of the S isocline and below the μ isocline. In these regions, the system moves away from the steady state.⁵

In Figure 4.4, the long-run equilibrium is in the region where the community utilizes all labor in the resource stock and close the resource stock to non-community members. The heavy arrowed curve represents the converging separa-

⁵Appendix D derives the direction of motion in each region.

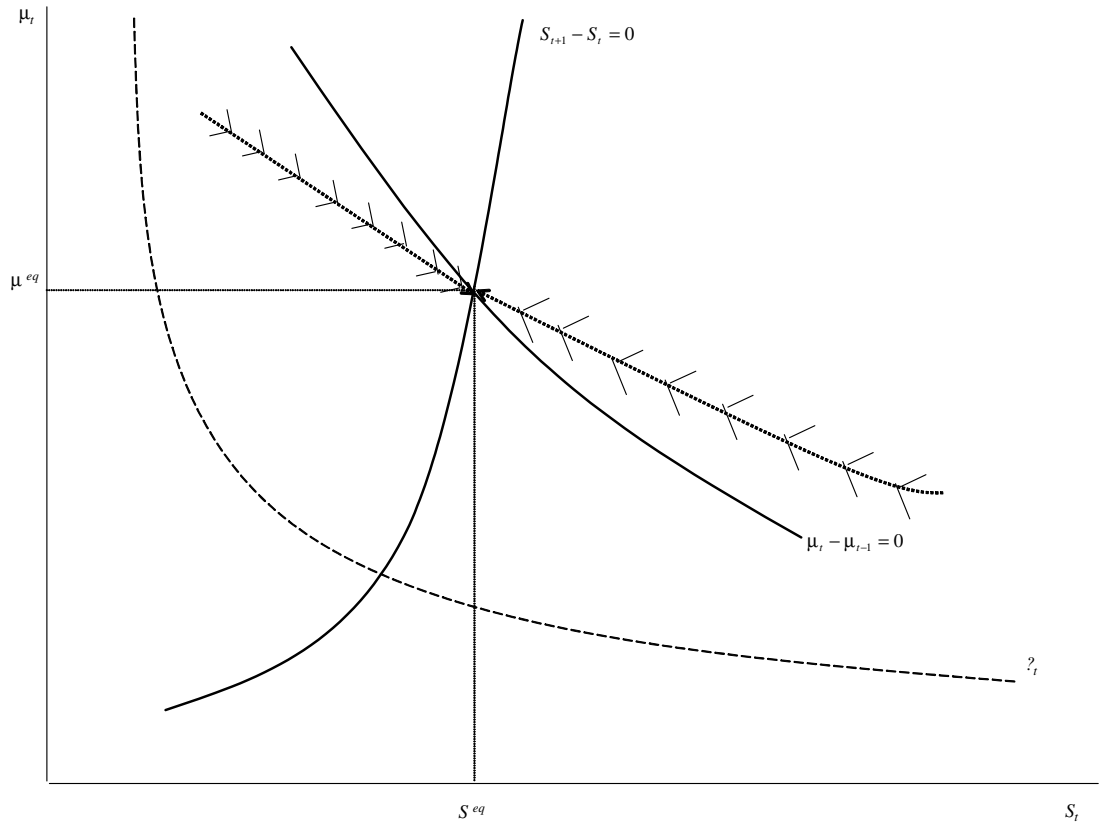


Figure 4.4: Adjustment Path and Steady State Values of Resource Stock and Shadow Price of Stock with an Endogenous Tariff Rate

matrix. Given a sufficiently large initial stock level, community members close off the resource sector in all time periods but do not initially allocate all labor into the resource sector. In general, we find the same five potential property rights regime patterns as in Chapter 2.4.

When we endogenize the tariff choice through lobbying by the government, we do not derive a discrete jump in the trajectory as in the case of exogenous trade regimes. Instead we obtain a smooth optimal trajectory over time. Similar to the baseline infinite horizon model, we continue to find five potential property rights regime patterns when endogenizing the tariff choice.

In this chapter, we analyzed the effects of lobbying on the choice of trade policies by the government. Lobby groups have influence over the trade regime choice of the government as long as the government places considerable weight on the contributions received from lobbyists. If a single lobby group exists, they may be able to contribute enough funds so as to obtain the trade regime they prefer. However, when two equally powerful but opposing lobbying parties exist, the lobby group where trade regime preferences coincide with society's preference will determine the trade regime. Lobby groups also have an impact on the tariff protection rate. We find that the optimal tariff rate changes over time since it is a function of the marginal user cost of the stock. However, endogenizing the tariff choice yields the same property rights regime patterns as in the baseline infinite horizon model. Instead of a discrete jump in the trajectory path when trade regime is chosen exogenously, we follow a smooth trajectory over time.

Chapter 5

Dynamic Common Property Resource

Experiment

The previous sections have suggested theoretical results governing the trade policy-property rights regime evolution-resource stock relationship. This section tests some of the theoretical results derived in the previous chapters. In particular, we test how property rights regimes and labor allocations are determined in a controlled laboratory experiment. We also determine how resource stocks evolve through the selection of labor allocations and property rights regime when there is an announced change in the terms of trade. It would have been also desirable to extend the experimental model to test the long run effects of trade as well as endogenizing the trade choice. Unfortunately, budgetary constraints limited the treatments in the experiment.

One of the earliest experimental studies that examined behavior within common pool resources was conducted by Walker, Gardner and Ostrom (1990). Their study tried to determine if subjects in a common property resource dilemma followed the predicted Nash equilibrium. Subjects were given a choice of investing in market 1, where they earn a fixed return on their investment, or in market

2, where earnings depend on the proportion of their investment in this market relative to total investment. In this scenario, the second market is akin to investing in a static resource stock. Two treatments were considered: high endowment of tokens and low endowment of tokens. Nash equilibrium was found to be a good predictor of aggregate behavior in the low endowment case and in the latter rounds of the high endowment case. However, Nash equilibrium behavior is not a good predictor of individual decisions. Subjects tended to utilize various rules of thumb in determining the amount of tokens to invest in either market.

In the common pool resource experiment by Walker, Gardner and Ostrom (1990), the resource stock was assumed to be static and completely regenerate in the next time period. In reality, the available stock in the next period depends upon the amount of extraction in the current period as well as the regenerative capacity of the stock. Thus, over-harvesting may result in the destruction of the resource stock. Walker and Gardner (1992) investigate how subjects behave if they are faced with a positive probability in terminating the experiment whenever subjects invest in the resource market. Results indicate that when faced with early termination of the experiment, there is still over-investment in the resource market even when a safety buffer on the available resource stock is put in place. This implies that subjects decisions are myopic. Herr, et al. (1997) also conducted a time-dependent common pool resource game. They also find decisions by subjects to be more myopic than dynamic.¹

One reason why over harvesting may occur in a common pool resource frame-

¹Mason and Philipps (1997) conducted a similar time-dependent game with a public resource. They investigated how firms in an oligopoly manage a common resource. However, their main point of emphasis is not the path of the harvesting trajectory but the steady-state solution.

work is because of the lack of any enforceable contracts to curb this behavior. Communication, as a means of enforcing "contracts" amongst group members, was found to have a positive impact on the preservation of the resource stock. Ostrom and Walker (1991) investigated the effectiveness of communication in achieving a cooperative solution to preserve the resource stock. They conducted a static common pool resource experiment but allowed for various types of communication patterns within treatments. Single shot communication during the beginning of the experiment allowed minimal improvement above the non-cooperative equilibrium. If costless repeated communication is allowed, the cooperative equilibrium can be sustained. However, when communication becomes costly, cooperation can still occur between groups but it will take longer. Hackett, et al. (1994) test the robustness of the effect of communication but for heterogeneous individuals. Results indicate that heterogeneous individuals create distributional conflict over the access of the resource stock even with communication.

The existing institutions governing the resource stock have been assumed to be exogenously determined by experimenters in common pool resource games, thus far. However, Vyrastekova and Van Soest (2003) endogenize the cost of enforcement through group voting and show that individuals tend to be more cooperative as long as the majority favors enforcing resource management amongst community members.

The studies presented have indicated that there is a significant impact of two types of externalities related to common property resources: an intratemporal externality, or crowding out effect within times; and an intertemporal externality, or stock effect across time. Also, communication does seem to have a significant

effect on individuals' decisions. Lastly, voting can affect how individuals govern the use of the resource stock. This particular experiment tries to combine these elements by analyzing how community members determine the type of property rights regime governing the resource stock through a majority voting rule, in the presence of a crowding out and stock effect. Thus, we design a *dynamic common property* resource game. Dynamic implies that all the treatments will have the stock evolving over time. Furthermore, common property implies that a group of individuals own the stock and they will be allowed to choose the type of property rights regime governing its use. The remaining sections of this chapter are divided into the following: Section 5.1 outlines the hypotheses that will be tested in the experiment. The experimental design is presented in Section 5.2. Section 5.3 summarizes the design conditions and parameters used to simulate the baseline results for the laboratory experiment. Section 5.4 shows the descriptive results from the experiment and Section 5.5 concludes the chapter with a formal analysis of the experimental data.

5.1 Hypotheses

The experiment tested selected hypotheses derived from the theoretical model. One of the central objectives of this dissertation is to link the effect of opening to trade on resource stock levels through an endogenous property rights regime mechanism. This particular experiment tries to determine this impact as well as derive the optimal property rights regime patterns governing the resource stock. We test two categories of hypotheses. First, we outline game-theoretic hypotheses regarding extraction levels and choice of property rights regimes in a two-sector general equilibrium model. Next, we test behavioral hypothesis with regard to

the effect of opening to trade (as proxied by a change in the relative price of goods produced in the economy) on the resource stock through changes in labor allocation and property rights regime choices.

First, the game-theoretic hypothesis with regard to extraction behavior is defined as follows:

Hypothesis 1. Dynamic Nash equilibrium hypothesis governing the extraction of a dynamic resource stock. Owners of a resource stock behave as rational, wealth maximizing individuals and expect all other members of their community to behave in the same manner over time. Thus, when all community members are homogeneous, they choose extraction levels that satisfy equations (2.8) to (2.11) as well as take into consideration the stock evolution from equation (2.6). However, when community members are heterogeneous, they choose extraction levels that satisfy equations (2.14) to (2.17) while considering the stock equation.

As an alternative to this hypothesis, we compare the results of the analysis for the case of myopic Nash equilibrium behavior. Here, individuals maximize earnings for each individual period without taking into consideration the stock effect over time. This implies that we follow the same equations stated in hypothesis 1 but now, the marginal user cost of the stock is equal to zero. Here, individuals no longer take into consideration the future consequences of their actions on the resource stock.

The game-theoretic hypothesis of property rights regime choice is the following:

Hypothesis 2. Dynamic Nash equilibrium hypothesis governing the optimal property rights regime pattern voted by the community over time. The property

rights regime chosen by the community will depend on the preference of the median community member. The median community member will vote on a property rights regime sequence that maximizes his wealth over time given the expected choices of all other community members. Thus, the representative community member or median voter chooses the property rights regime that satisfies equations (2.8) to (2.11) or (2.14) to (2.17), respectively.

As an alternative to this hypothesis, we look at the myopic Nash equilibrium behavior of the community where they always choose a common property resource management scheme that closes the resource stock to non-community members.

It must be noted that the choice of property rights regimes and labor allocation by the community are jointly determined. This implies that we will test if both labor allocations and property rights regime choice follow a dynamic Nash equilibrium path or the alternative myopic Nash path. It will not make sense to individually test each choice separately because the choice variables jointly determine the earnings of subjects.

Next, we specify the behavioral result expected from the experiment:

Hypothesis 3. Effect of price change on stock levels in a Finite Model. An announced price increase in the future results in the community members trying to build the stock up by optimally selecting their labor use in both sectors in the economy and adjusting the property rights regime that govern the use of the resource stock. More specifically, we would find that the stock levels are higher before opening to trade as shown in the comparative statics $\frac{\partial S_1}{\partial p_1} \geq 0$ (chapter 3.1).

If subjects do internalize some of the stock effect over time, we will likely follow a dynamic equilibrium path that seeks to maximize wealth over time and not only earnings round by round. Clusters that adjust labor allocation and property rights regime choices to build stocks in anticipation of the future price increases may show some inclination of following a dynamic path. However, following the *optimal* dynamic path is another matter altogether.

5.2 Experimental Design

The experimental design is intended to capture the elements from the two-sector general equilibrium model introduced in Chapter 2. Community and non-community members allocating labor into the two sectors of the economy are replaced by subjects who earn cash benefits from the experiment by accumulating currency dollars using a parameterized version of equations (2.7) and (2.13). The general design of the experiment follows a common property resource game where subjects allocate their labor hours into different market types. Market 1 is used to mimic the earnings from the resource sector in the model; while market 2 is used to capture earnings from the manufacturing sector. There are some elements in this experiment that differ significantly from the usual common pool resource game. First, most common pool resource experiments in the literature are static repeated games. Though this has the advantage of analytical and theoretical simplicity, it hinders us from understanding any of the dynamic elements that may influence behavior. Second, the institutions in almost all common pool resource games are exogenously given and fixed throughout the experiment. However, in this game, we will allow for an endogenously determined institution

governing the use of the resource stock. Lastly, the two sectors in the economy are connected by an endogenous wage rate instead of an exogenous wage rate usually used in the literature.

The experiment was conducted at the University of Maryland using a fully computerized program that captures the basic elements of the two-sector dynamic general equilibrium model. Subjects were recruited from a pool of graduate and undergraduate students who have a background in economics and have had prior experience in participating in experiments. Prior to volunteering, subjects were not informed of any specific details related to the game's content. They were only told of the average duration of the game (1.5 hours), and that earnings will be based on their decisions during the experiment.

Each experimental session was conducted in the following manner. To ensure that all 24 terminals in the computer laboratory are used, more than 24 subjects were recruited during each session. If the session is already full, those that were not able to participate are given a \$5 attendance fee as well as a guaranteed slot for a future session. All participants are logged on to their computer with a messenger program and two windows open, a practice window and a window for the actual experiment.² At the beginning of each section, the instructions are read aloud while the projector screen provides visual assistance (see Appendix E.1 for sample instructions). A practice session is played before the actual experiment is conducted. After the experiment, a post survey questionnaire is handed out to all subjects, after which they are paid for their participation.

During an experimental session, each subject participates in two treatments.

²Beside each terminal is a hard copy of all the instructions and a copy of the student newspaper, which is used to fill the time during waiting periods between rounds.

The sequence of the experiment during each session is summarized in Figure 5.1. Subjects were randomly placed into a six-person cluster containing two groups. The first group in the cluster comprised of five individuals representing the community, who had *de facto* rights over the use of a stock. The second group in the cluster contained one individual representing five non-community members that did not have any rights to the use of the resource stock. Each subject stayed in these groups throughout the experiment. Instructions were simultaneously read to all subjects, after which a two-round practice was conducted. Group 1 individuals acted first in each round, while group 2 members waited. Once all group 1 members finish, group 2 members respond while group 1 waited. After all group 2 members are finished with their decision, the results are displayed in front of all participants in a summary table and the next round starts again. Throughout the entire session, subjects were allowed to view their earnings and their past decisions. However, since we simulated an open loop solution, the stock levels over time were not shown to subjects in their history box. This continues until the last round. Before paying off the participants, they are required to answer a post survey questionnaire.³

³It must be noted that the main focus and source of data that is used to test the hypotheses come from group 1 members (subjects representing the community). It would have been possible to use the computer as representatives of non-community members. We have chosen to include live subjects as representatives of the non-community members because group 1 members may react differently when faced with a computer acting as a group 2 member. Having live subjects to interact with may elicit more truthful responses from subjects as opposed to computerized responses. It would be interesting to re-run the experiment in the future with computer responses in group 2 and test whether individuals behave differently than if there are human subjects.

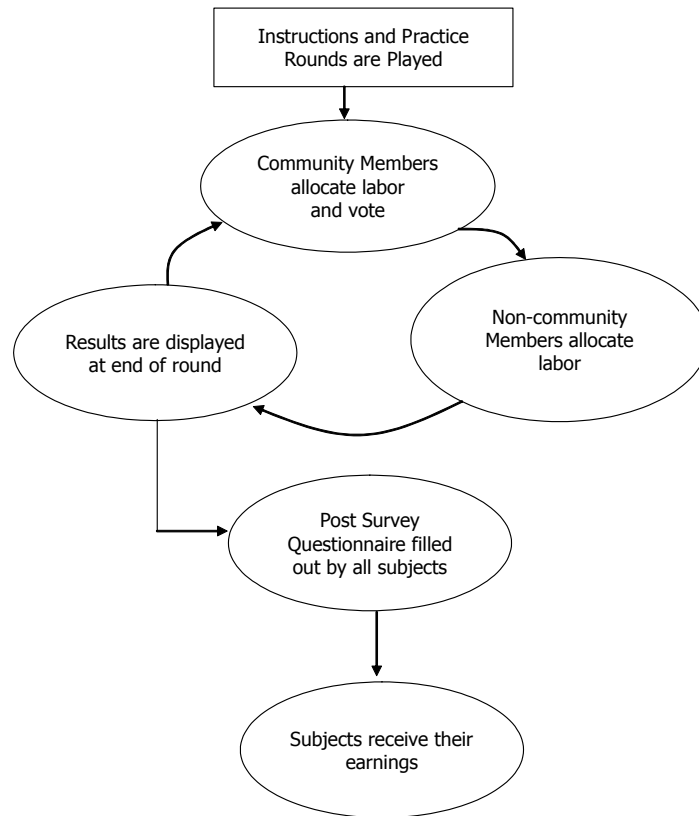


Figure 5.1: Sequence in the Experiment

Subjects earned "currency dollars" by allocating labor in two types of markets. In market 1, subjects received income as a proportion of the number of labor hours allocated into this market relative to total labor hours. In market 2, income was dependent upon the prevailing wage rate. The decisions of the subjects were framed such that they allocated 10 units of their total labor hours into these two markets. Thus, subjects can allocate their labor units into the manufacturing sector (market 2) and earn a wage rate equal to the marginal value product of labor in that sector. Alternatively, they can also allocate labor into the resource sector (market 1) and earn an amount equal to the value of harvest. In the manufacturing sector, the wage is determined by how many people enter into the sector. The more participants allocate labor into the sector, the lower the contribution of each participant into the production of output, therefore decreasing the wage rate. Thus, wage varies during each round depending upon the total number of labor hours allocated into the sector. In the resource sector, total earnings depend upon the amount of stock, harvest of other participants and the relative price of harvested resource. The amount of available stock depends upon the growth of the stock, initial stock level as well as total allocated labor by all individuals. In all the treatments, subjects were informed that the initial stock level would start low, however, it could potentially grow over time as long as less labor is allocated in market 1.

Group 1 members allocate their labor between the two markets and chose to keep the resource stock open or closed to non-community members by voting. If they decide to keep the resource stock open, a secondary voting question regarding the maximum allowed number of labor hours per group 2 member is answered. Here, group 1 members vote on the amount of labor hours per individual they

allow into the resource sector from, 0 to 10. The majority voted by individuals was multiplied by 5 to obtain the total “permits” available for the group 2 member. Once the amount of permits are chosen, group 2 members then choose the amount of labor they allocate into the two sectors given the constraint on allowable labor hours in the resource sector.⁴

Group 1 members are allowed to communicate amongst each other via the MSN messenger system but their individual decisions were kept private. Before the first round of a treatment, all group 1 members were given 5 minutes to chat via messenger to familiarize themselves with the program. In the subsequent rounds, they are no longer given any time to explicitly communicate but they were allowed to chat throughout the duration of the treatment. Allowing for communication helps to sustain any agreements formulated by the group (see Ostrom and Walker, 1991).

There are four different treatments. In the first treatment, all community members have the same harvesting efficiency (homogeneous). In another treatment, community members have varying harvesting efficiencies (heterogeneous). These cases serve as the base treatments. A set of treatments where trade effects (output price changes) are tested is also conducted with homogeneous and heterogeneous community members. All participants know *a priori* that the price of harvested output will increase on the fifth round. In this way, we are able to test how property rights regime patterns and labor allocations are affected in the presence of an announced increase in terms of trade in the resource sector. Each treatment consists of 10 rounds. Four sessions were conducted containing two treatments each. The first treatment contained homogeneous community

⁴See Appendix E.2 for sample viewing screen faced by group 1 and 2 members.

Treatment Types	Homogeneous Community Members	Heterogeneous Community Members
Base	Treatment 1	Treatment 2
Output Price Change	Treatment 3	Treatment 4

Note: Four sessions were conducted containing two treatments each.

Table 5.1: Experimental Design

members and in the second treatment, harvesting efficiencies varied. The first two sessions did not have any price change while the last two sessions had price changes. To test for any ordering effects, two sessions were conducted by interchanging the order of the two treatments. Table 5.1 summarizes the treatments of the experiment.

After the main experiment, a post survey questionnaire was conducted to collect background information from subjects regarding their prior experience with experiments and socio-economic profile. Subjects were given a participation fee along with the additional income they earn during each session. In the experiment, all earnings were in the form of currency dollars. The exchange rate for each currency dollar to real dollar was approximately 0.40. On average each participant earned \$21.86.

5.3 Design Conditions and Parameterization of the Model

5.3.1 Functions and Parameters

The set of parameters used in a particular session determines the design condition in the laboratory experiment. In each session, there are either homogeneous or

heterogeneous community members in each group 1 cluster and either the price stays the same during the whole period or it changes over time. Given these possibilities, there are four design conditions used in the experiment: homogeneous or heterogeneous community members with prices constant or changing. Table 5.2 presents the functional form and parameters used to represent the maximization problems in equations (2.7) and (2.13) in the laboratory experiment. In each session, subjects participate in two treatments lasting ten rounds each. The only difference between the two treatments in each session is the harvesting efficiency in group 1. In some cases, the harvesting efficiencies are the same, 0.0004, or they differ with values ranging from 0.0003 to 0.0005. We try to minimize any ordering effects by conducting only two treatments in each session where harvesting efficiencies are different.⁵ We test for the effect of an announced price change starting at the fifth round from 5 to 8.5 units. In all, there are two sessions each where, either the price does not change at all in two treatments of ten rounds each, or where the price changes during the fifth round of each treatment.

In market 2 or the manufacturing sector, the owners of capital maximize their returns to capital over time by hiring labor. The sector-specific capital in the manufacturing sector is normalized to 1. The production function in the manufacturing sector for the j^{th} cluster is specified to be quadratic in total labor hired by the owners of capital. Thus, the objective function faced by the owners of capital in the j^{th} cluster is written as,

⁵We formally test the presence of any ordering effects in the succeeding subsections by running a similar session but the order of homogeneous or heterogeneous harvesting efficiency treatments are interchanged.

Specification	Experimental Session
Number of subjects in a cluster	5
Number of Group 1 in one cluster	4
Number of Group 2 in one cluster	1
Maximum number of labor hours per subject	10
Production function in the manufacturing sector $(aLx-bLx^2)$	a = 6.75 b = 0.0325
Production function in the resource sector $p H S_t (cLr-dLr^2)(l/Lr)$	c = 50 d = 0.001
Harvesting efficiency (H) Harvesting efficiency for Group 2 subjects Harvesting efficiencies for Group 1 subjects ¹	0.00025 0.0003 0.00035 0.0004 0.00045 0.0005
Relative price ² (p)	5
Growth of stock over time ³	e =0.59
$G(S_t)=eS_{t-1}(1-(S_{t-1}/f))$	f = 80

¹ The harvesting efficiency when all community members are homogeneous is equal to 0.0004.

² In the treatments with a change in price, price increases from 5 to 8.5 during the fifth round.

³ The initial stock is equal to 10.

Table 5.2: Parameters of the Laboratory Experiment

$$\max_{Lx_{jt}} Y(Lx_{jt}) = aLx_{jt} - bLx_{jt}^2 - w_{jt}Lx_{jt},$$

where a and b are parameters of the production function. The optimal condition that solves the problem of the owners of capital shows that the marginal product of labor must equal the wage rate. From this, the variable wage of the j^{th} cluster during each time period t is derived to be,

$$w_{jt} = a - 2bLx_{jt}.$$

Wage is positive as long as $\frac{a}{2b} \geq Lx_{jt}$ and this assumption is satisfied given the parameters chosen in the model. From the parameters of the model, wage can be as low as 0.25 or reach a maximum of 6.75 currency dollars per labor hour. For each additional unit of labor allocated into the resource sector, the marginal decrease in wage is equal to 0.065 units.

The production function for entrants into the resource sector follows the general functional form as specified in equation (2.3). The product of the harvesting efficiency, current stock and the effort function determine the level of harvest in the resource sector. The effort function for the i^{th} individual in the j^{th} cluster is quadratic in the total number of labor in the resource sector. Also, the individual returns from labor in the resource sector is a proportion of own labor to the total labor in this sector. The harvest from the resource sector for the i^{th} individual in the j^{th} cluster is expressed as,

$$H_{ij}(S_{jt}, L_{jt}, l_{ijt}) = \alpha_i S_{jt} (cL_{jt} - dL_{jt}^2) \frac{l_{ijt}}{L_{jt}},$$

where c and d are parameters in the effort function and L_{jt} is the summation of

all community labor and non-community labor in the resource sector.⁶ Whenever the amount of labor in the resource sector is equal to zero, the harvest is zero as well. As the stock level increases over time, the marginal harvest from a unit of labor increases.

The net growth function, $G_j(S_{jt})$, takes a logisitic functional form, $G_j(S_{jt}) = eS_{jt} \left(1 - \frac{S_{jt}}{f}\right)$ where e is the intrinsic growth rate of the stock and f is the natural carrying capacity. Without any harvest, the steady-state equilibrium occurs when stock is equal to zero or when the carrying capacity, f , is reached. Furthermore, the maximum sustainable yield of the stock is equal to $\frac{f}{2}$. Given the logistic functional form, the stock in the next period is calculated according to the following equation,

$$S_{jt+1} = eS_{jt} \left(1 - \frac{S_{jt}}{f}\right) + S_{jt} - \sum_{i=1}^{N+C} \alpha_i S_{jt} (cL_{jt} - dL_{jt}^2) \frac{l_{ijt}}{L_{jt}}.$$

It must also be noted that in each cluster, there are two groups. In group 1, there are a total of five individuals representing members of the community while there is 1 member in group 2 representing five homogeneous non-community members. Even though there are effectively 10 subjects in a representative economy, this study does recognize that the assumption that subjects take wage as given may not be strictly fulfilled. However, given that the marginal change in wage is relatively small, *i.e.* about 0.06 currency dollars per unit of labor hour, a single subject in the representative economy is not likely to realize that their

⁶The value of harvest is equal to H_{ij} multiplied by the relative price. The relative price in some treatments will stay the same during the whole treatment. In other treatments, there is an announced permanent price change starting from the fifth round where the price increases from 5 to 8.5.

individual labor choice has a significant impact on wage.⁷

The objective of the subjects in the experiment is to maximize their earnings over time by optimally allocating labor in the two markets in the experiment.

This can be written as,⁸

$$\begin{aligned} \max_{l_{jt}, l_{-jt}} W_j &= \sum_{t=0}^{10} \left(w_{jt}(h - l_{ijt}) + p_t \alpha_i S_{jt} (cL_{jt} - dL_{jt}^2) \frac{l_{ijt}}{L_{jt}} \right) \\ \text{s.t. } S_{jt+1} &= eS_{jt} \left(1 - \frac{S_{jt}}{f} \right) + S_{jt} - \sum_{i=1}^{10} \alpha_i S_{jt} (cL_{jt} - dL_{jt}^2) \frac{l_{ijt}}{L_{jt}}. \end{aligned} \quad (5.1)$$

The first order conditions that solve this dynamic problem are the following,

$$\frac{\partial W_j}{\partial l_{ijt}} = p_t \alpha_i S_{jt} (c - d(1 + L_{jt})) + p_{t+1} \alpha_i \frac{\partial S_{jt+1}}{\partial l_{ijt}} (c - dL_{jt+1}) l_{ijt+1} - w_{jt} \leq 0; \quad (h - l_{ijt}) \frac{\partial W_j}{\partial l_{ijt}} = 0; \quad (5.2)$$

$$\frac{\partial W_j}{\partial l_{-ijt}} = -p_t \alpha_i S_{jt} d 5 l_{ijt} + p_{t+1} \alpha_i \frac{\partial S_{jt+1}}{\partial l_{-ijt}} (c - dL_{jt+1}) l_{ijt+1} \leq 0; \quad (h - l_{-ijt}) \frac{\partial W_j}{\partial l_{-ijt}} = 0. \quad (5.3)$$

⁷Ideally, with a larger budget, the results from an experiment with five group 1 members would be compared with results from a similar group with more subjects in order to test the assumption that individuals act as though the wage is given when there are five group 1 members only.

⁸We assume for the experiment that the discount factor is equal to 1. This implies that the earnings during each round is equally weighted. This particular assumption simplifies the problem for the subjects without compromising the main results of the theoretical model. It must be noted that, although the discount rate in the experiment does not change, the subjects may have their own internal discount factor. Camerer *et al.* (2004) review a number of studies to determine the extent to which internal discount factors impact laboratory experiments.

These first order conditions are used to determine the optimal dynamic Nash equilibrium path.

5.3.2 Simulated Results

In order to solve for the open loop Nash equilibrium solutions, the General Algebraic Modeling System (GAMS) was used to derive simulated results under the assumptions of heterogeneous and homogeneous community members (see Appendix E.3 for the commands used). The algorithm used to solve for the numerical solution is known as the Branch and Bound process which was first proposed by Land and Doig (1960). The basic idea of the algorithm is to find the minimum or maximum value of a function given the domain or feasible region of a variable. The process utilizes two tools: the first tool finds a way to cover the feasible region by dividing it into feasible subregions (branching) and the second tool is a fast way of finding the upper and lower bounds of a function in the subregion (bounding). For example, to find the maximum value of a function $f(x)$, the domain of x will be subdivided into a number of regions. If the upper bound of the function in the first subregion is less than the upper bound of the function in the second subregion, then the first subregion can be discarded. If it is greater than the second subregion, the upper bound value from the first subregion will be stored and compared with the next subregion. This process continues until the highest upper bound among all the subregions has been found.⁹

Two different types of solutions are simulated - the dynamic Nash equilibrium path and the myopic Nash equilibrium path. The dynamic Nash equilibrium path represents the optimal open-loop strategy of individuals when subjects formulate

⁹Brusco and Stahl (2005) summarize the method and applications of the algorithm.

a strategy that maximizes their own welfare during the entire duration of the game given that all other individuals also maximize their own welfare. Here, we are solving out the problems in equations (2.7) and (2.13) for the homogeneous and heterogeneous cases, respectively, over 10 periods. As an alternative hypothesis, the myopic Nash equilibrium path is simulated. The myopic Nash path implies that the stock effect is not taken into consideration during each period.

Tables 5.3 and 5.4 illustrate the dynamic versus myopic Nash equilibrium paths with and without price changes for the case where all community members are homogeneous. In the dynamic case, the optimal voting strategy is to keep the resource sector open during the first four periods and then to close it off during the remaining periods. Optimal labor allocation in the resource sector is equal to zero during the first four rounds but, afterwards, ranges from 3 to 5. When an announced price increase is known during the fifth round, community members anticipate the increase in returns to harvesting in the future by limiting non-community entrance from the first four rounds to now only three rounds. However, after the price increase, harvest steadily increases. A comparison of the stock differences between the two treatments show that the stock is conserved when an announced price change occurs in the future.

With myopic individuals, the optimal management solution is to keep the resource stock closed during each period. This is because they do not internalize any of the potential benefits of temporarily allowing non-community members into the resource sector. Community members would simply equate the value of marginal product of labor in both sectors of the economy without taking into consideration the stock effect over time. Furthermore, any price increase starting at the fifth round would result in an intensification of labor in the resource sector

Time	Baseline				With price change during round 5			
	Stock	Labor in Market 1	Hours of Group 2 labor allowed in Market 1	Earnings	Stock	Labor in Market 1	Hours of Group 2 labor allowed in Market 1	Earnings
1	10	0	1.2	6.2	10	0	1.2	6.2
2	14.4	0	2	9	14.4	0	2	9
3	19.6	0	3	12.3	19.6	0	3	12.3
4	24.7	0	4	15.4	24.7	0.4	0	4.6
5	28.6	3	0	17.1	33.8	2.9	0	25.4
6	30.9	3.2	0	18.8	35.4	3.1	0	27.5
7	32.1	3.5	0	20.2	35.9	3.3	0	29.2
8	32.3	3.8	0	21.6	35.7	3.6	0	31.1
9	31.3	4.1	0	22.2	34.4	3.6	0	30.3
10	29.7	4.9	0	24.1	33.5	7.6	0	51.7
Sum				166.8				227.3

Table 5.3: Dynamic Nash Equilibrium Paths for Homogeneous Community Members

Time	Baseline				With price change during round 5			
	Stock	Labor in Market 1	Hours of Group 2 labor allowed in Market 1	Earnings	Stock	Labor in Market 1	Hours of Group 2 labor allowed in Market 1	Earnings
1	10	1.2	0	6.7	10	1.2	0	6.7
2	14	1.9	0	9.8	14	1.9	0	9.8
3	18.1	2.7	0	13.2	18.1	2.7	0	13.2
4	21.5	3.4	0	16.1	21.5	3.4	0	16.1
5	23.5	3.8	0	18	23.5	6.9	0	35.4
6	24.5	3.9	0	18.9	17.1	4.8	0	23.3
7	24.9	4	0	19.3	16.8	4.7	0	22.9
8	25	4	0	19.4	16.7	4.7	0	22.7
9	25.1	4	0	19.5	16.7	4.7	0	22.7
10	25.1	4.1	0	19.5	16.7	4.7	0	22.7
<i>Sum</i>				160.3				195.4

Table 5.4: Myopic Nash Equilibrium Paths for Homogeneous Community Members

leading to a decline in the stock over time.

Tables 5.5 and 5.6 summarize the simulated results for heterogeneous community members. We derive similar results as the homogeneous community member case - the optimal property rights regime pattern is to keep the resource stock open for several rounds and then closed afterwards. However, in both treatments with and without the announced price change, the optimal solution is to keep the resource sector open to non-community members during the first three periods. This is because any adjustment made to preserve the stock comes during the round prior to the price increase. Since the fourth round already calls for closure of the resource stock in the base case, we would not expect any change in the property rights regime sequence in the case where an announced price change

Time	Baseline				With price change during round 5			
	Stock	Average Labor in Market 1	Hours of Group 2 labor allowed in Market 1	Average Earnings	Stock	Average Labor in Market 1	Hours of Group 2 labor allowed in Market 1	Average Earnings
1	10	0	1.2	6.2	10	0	1.2	6.2
2	14.4	0	2	9	14.4	0	2	9
3	19.6	0	3	12.3	19.6	0	3	12.3
4	24.7	3.1	0	14.8	24.7	1.4	0	8.5
5	28.6	3.4	0	16.7	32.2	3.4	0	23.6
6	31.7	3.6	0	18.3	34.9	3.6	0	26.5
7	33.8	3.8	0	19.6	36.3	3.9	0	28.5
8	34.9	4	0	20.5	36.6	4.1	0	30
9	35.3	4.1	0	21.1	36.2	4.6	0	34.7
10	35.2	6	0	32.6	33	10	0	56
<i>Sum</i>				<i>171</i>				<i>235.5</i>

Table 5.5: Dynamic Nash Equilibrium Paths for Heterogeneous Community Members

occurs. In order to increase the stock during the fifth round, less labor is put in the resource sector during the fourth round. However, once the price increase starts to take into affect, more labor is allocated after the fifth round.

Myopic behavior in the heterogeneous community treatment is also similar to the homogeneous case. The median member always prefers to keep the resource stock closed since the subject does not internalize the benefits of keeping the stock open. Furthermore, once a price increase occurs, rapid decline in the stock ensues. Appendix E.4 show the individual Nash equilibrium choices over time.

Time	Baseline				With price change during round 5			
	Stock	Average Labor in Market 1	Hours of Group 2 labor allowed in Market 1	Average Earnings	Stock	Average Labor in Market 1	Hours of Group 2 labor allowed in Market 1	Average Earnings
1	10	1.2	0	7	10	1.2	0	7
2	13.7	1.9	0	10.2	13.7	1.9	0	10.2
3	17.2	2.5	0	13.4	17.2	2.5	0	13.4
4	19.8	3	0	15.9	19.8	3	0	15.9
5	21.4	3.3	0	17.4	21.4	6.2	0	33.7
6	22	3.5	0	18.1	15.8	4.4	0	23.2
7	22.3	3.5	0	18.4	15.2	4.2	0	22.1
8	22.4	3.5	0	18.5	14.9	4.1	0	21.7
9	22.5	3.5	0	18.6	14.8	4.1	0	21.5
10	22.5	3.5	0	18.6	14.8	4.1	0	21.5
Sum				156.1				190.1

Table 5.6: Myopic Nash Equilibrium Paths for Heterogeneous Community Members

5.4 Descriptive Results

5.4.1 Background of Subjects

A total of 96 subjects were recruited for the whole experiment where 24 subjects volunteered per session.¹⁰ Out of the 24 subjects in each session, 20 were randomly selected as group 1 members (representatives in the community), while the remaining 4 represent group 2 members. Table 5.7 summarizes the characteristics of the subjects in group 1. Most of the subjects participated in at least one experiment prior to this experiment and also had an economics background. At least a quarter of the respondents were graduate students.

5.4.2 Labor Allocation, Stock Dynamics, Property Rights Regime Choices and Wages

The results of the experiment are summarized in Figures 5.2 to 5.17. Figures 5.2 and 5.3 compare the average total labor hour allocation in the resource sector observed from the experiment for each round with the myopic and dynamic Nash equilibrium paths. Both the dynamic Nash and myopic Nash equilibrium paths start at a low point and steadily increase. However, the observed average total labor allocation is significantly larger than the myopic and dynamic Nash equilibria in both the homogeneous and heterogeneous community cases. When all community members are homogeneous, there is a decreasing trend in

¹⁰Sample selection bias is a potential problem in any laboratory experiment. However, given the limitations of the study, we are not able to go into a detailed analysis regarding sample selection problems that may occur. See Eckel and Grossman (2000) and Bellemare and Kroger (2003) for ways of dealing with selection bias.

Characteristics	Frequency	Percentage
Education		
Sophomore	34	42.5
Junior	11	13.75
Senior	17	21.25
Graduate Student	18	22.5
Sex		
Female	42	53.85
Male	36	46.15
Economics Major		
No	29	39.19
Yes	45	60.81
Experimental		
0	27	33.75
1	37	46.25
2	11	13.75
3	2	2.5
4	3	3.75

Table 5.7: Background Information of Subjects from Group 1

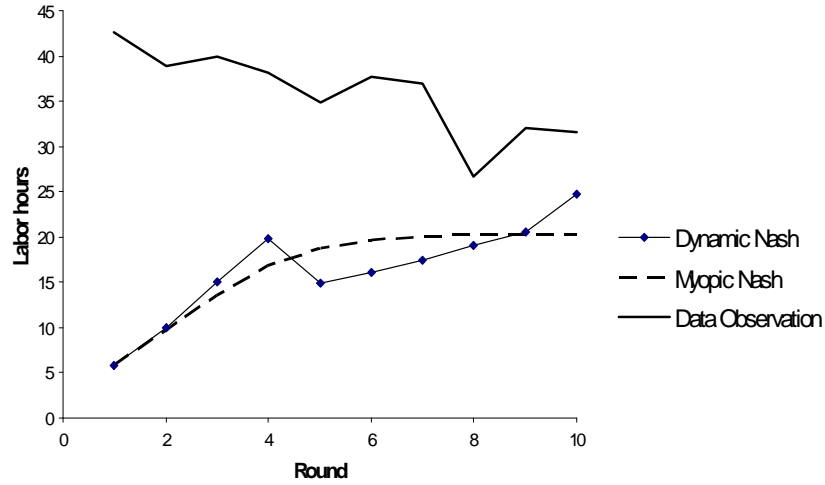


Figure 5.2: Average Total Labor in Market 1 with Homogeneous Community Members - Base Treatment

observed labor allocations over time. However, with heterogeneous community members, there is more variability in total labor allocation and no discernible trend of average observed labor allocations over time. It is interesting to note that during the start of the rounds, the initial total labor allocations seem to be significantly larger than the optimal starting levels in the trajectory, but the gap between average observed labor allocations and predicted labor allocations seems to diminish over time.

In treatments where a price change is introduced, we see a consistent pattern in the data (see Figures 5.4 and 5.5). The average total number of labor hours allocated in the resource sector is lowered prior to the fifth round. Presumably, this is due to the anticipation of earning more income by building up the stock when the price is higher during rounds 5 to 10. The drop in labor prior to

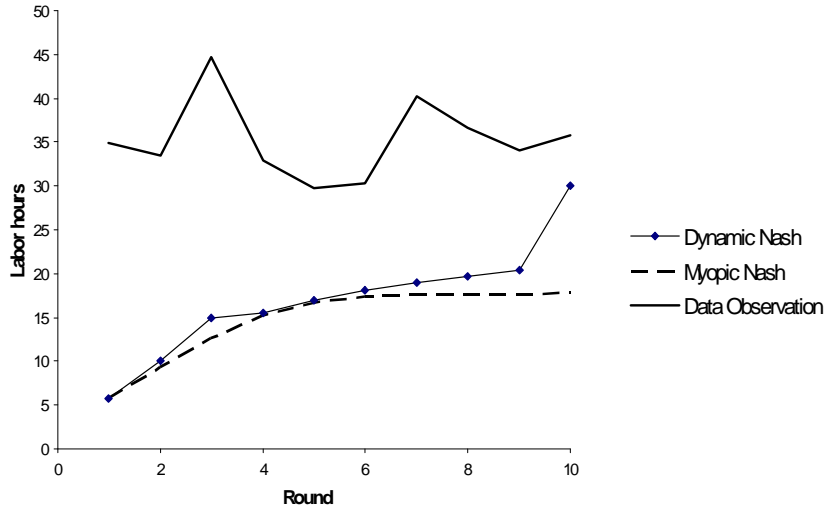


Figure 5.3: Average Total Labor in Market 1 with Heterogeneous Community Members - Base Treatment

the price increase in the fifth round is immediately followed by a spike in total labor hours during the fifth round. Afterwards, we see a relative decrease in labor allocations. For the case of heterogeneous community members, the drop in labor after the fifth round is relatively smooth. In both homogeneous and heterogeneous treatments, there is still persistent over-investment of labor in the resource sector relative to both the dynamic and myopic Nash equilibrium paths.

The total labor allocation in Figures 5.2 to 5.5 represent labor hours in the resource sector from both the community and non-community members. In general, majority of the clusters tend to keep the resource stock open, not only during the first few periods but throughout the ten rounds. Table 5.8 shows the average percentage of clusters in each treatment that have voted to keep the resource stock open to non-community members. In the homogeneous community

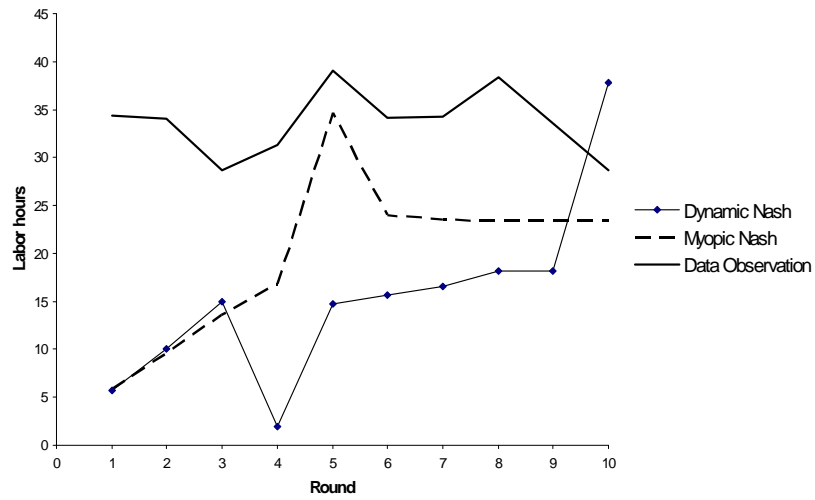


Figure 5.4: Average Total Labor in Market 1 with Homogeneous Community Members - Price Change Treatment

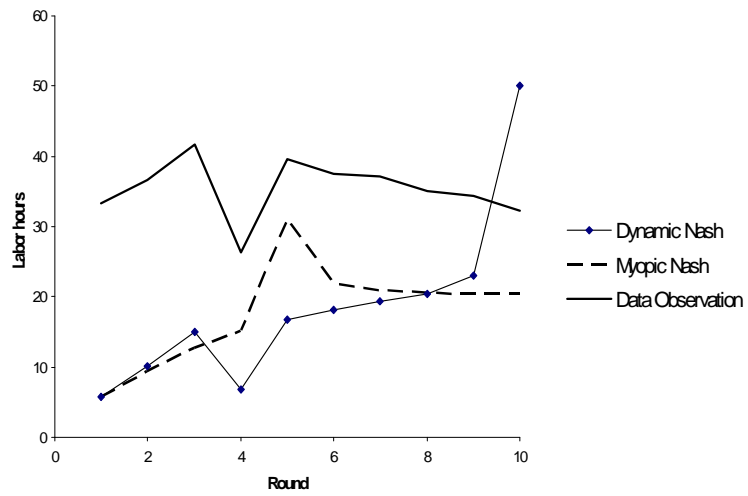


Figure 5.5: Average Total Labor in Market 1 with Heterogeneous Community Members - Price Change Treatment

Period	Homogeneous Community Members		Heterogeneous Community Members	
	Baseline	With Price Change	Baseline	With Price Change
1	100	75	100	87.5
2	100	75	87.5	87.5
3	75	87.5	100	100
4	87.5	87.5	100	62.5
5	87.5	87.5	87.5	87.5
6	87.5	87.5	87.5	100
7	75	87.5	100	87.5
8	62.5	100	87.5	87.5
9	75	75	87.5	100
10	87.5	87.5	100	100

Table 5.8: Percentage of Clusters that Vote to Keep the Resource Stock Open

baseline treatment, there is more tendency to keep the resource stock open during the initial rounds. However, over time, we see that a smaller percentage of clusters vote to keep the resource stock open. When an announced price change occurs in the homogeneous community treatment, the clusters in general seem to try to build the stock prior to the fifth round by lessening non-community entrance into the resource stock. However, more entrance into the resource sector is allowed over time. In the heterogeneous community treatments, there appears to be more variability in the percentage of clusters that keep the resource stock open or closed. However, when an announced price change occurs in the fifth round, we find a decrease in the percentage of clusters that allow non-community entrance prior to the price increase.

The previous illustrations have depicted the overall labor allocation in the resource sector. However, we are more interested in looking at the allocation decisions by owners of the resource stock over the ten rounds in each treatment.

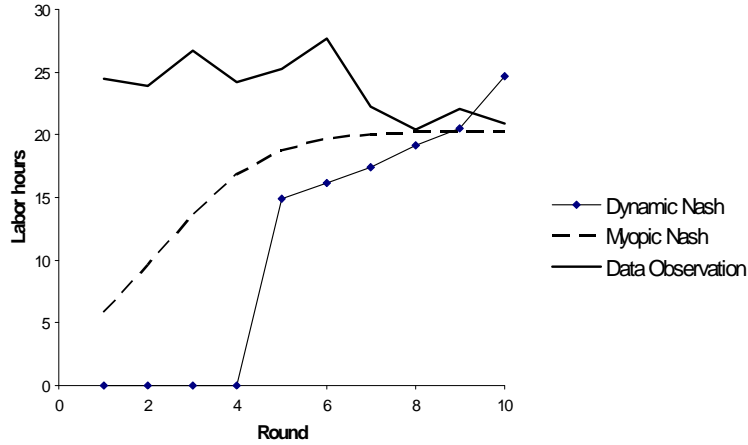


Figure 5.6: Average Group 1 Labor in Market 1 with Homogeneous Community Members - Base Treatment

Figures 5.6 and 5.7 look at how all community members (group 1) allocate their labor in the baseline treatment. Overall, there is still over-allocation of labor in the resource sector relative to the optimal Nash equilibrium paths, especially during the initial periods. In both cases when community members are homogeneous or heterogeneous, the level of labor allocated in the resource sector is larger than even the myopic Nash equilibrium outcome. Over time, however, there seems to be a declining trend in the level of labor allocation by community members. In both homogeneous and heterogeneous community member treatments, the labor allocations over time seem to be converging to the myopic Nash equilibrium trajectory.

When there is an announced price change in the future, we find a decrease in labor allocation prior to the fifth round (see Figures 5.8 and 5.9). However, after the fifth round, the observed average labor allocations of group 1 members

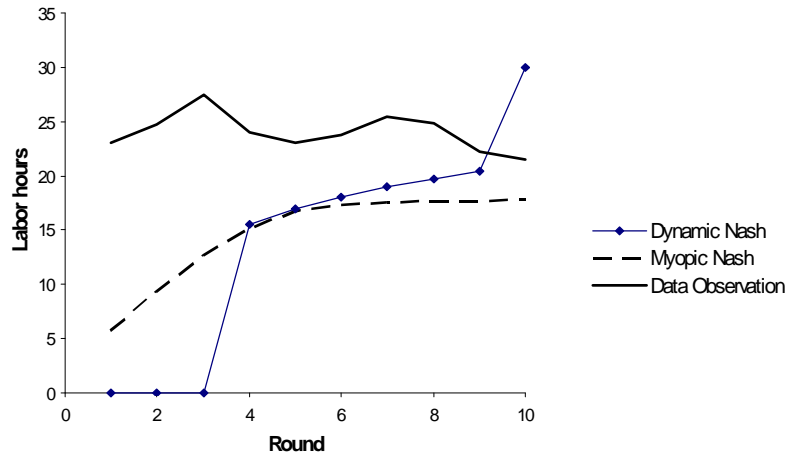


Figure 5.7: Average Group 1 Labor in Market 1 with Heterogeneous Community Members - Base Treatment

are lower than the predicted labor investment during most rounds. The average labor allocated by community members after the fifth round is considerably less than the myopic Nash equilibrium path but slightly more than the dynamic Nash equilibrium path. The disparity in the increase may be due to the over-allocation of labor by subjects during the initial rounds. Too much labor allocated in the resource sector during the first few rounds may have resulted in a relatively more significant decline in stock levels. Thus, less stock is preserved prior to the fifth round when the price increase occurs. In order to verify this supposition, we now turn to the stock patterns over time.

The optimal stock evolution in both the dynamic and myopic Nash equilibrium cases show that the stock rises over time given the optimal labor allocation and property rights regime strategy (see Figures 5.10 to 5.11). However, in order to arrive at this result, subjects would have had to lessen the pressure on the

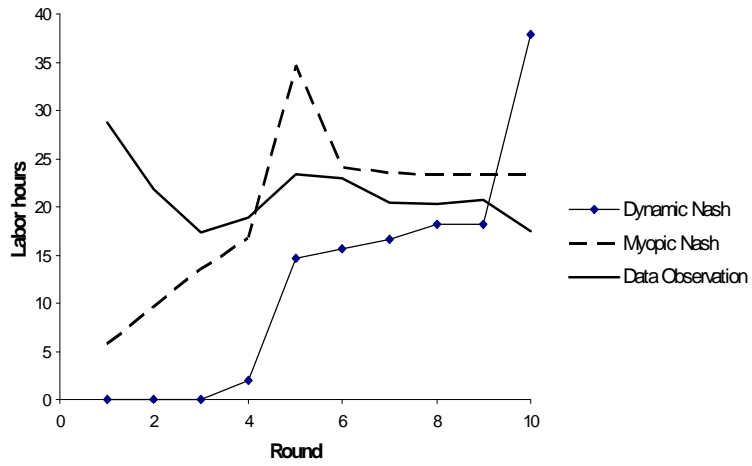


Figure 5.8: Average Group 1 Labor in Market 1 with Homogeneous Community Members - Price Change Treatment

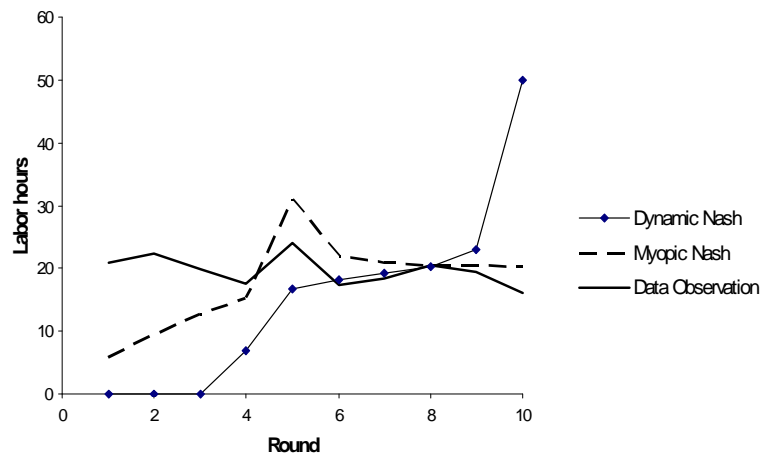


Figure 5.9: Average Group 1 Labor in Market 1 with Heterogeneous Community Members - Price Change Treatment

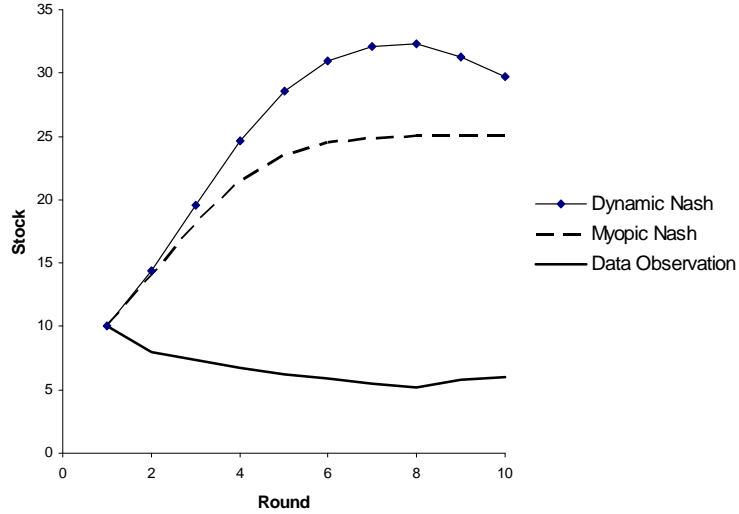


Figure 5.10: Average Stock Over Time with Homogeneous Community Members - Base Treatment

stock, especially during the first 3 rounds, in order to build it up. Given the over-allocation of labor by subjects during the first few rounds, there is a general downward trend in the average stock levels over time in both baseline treatments.

The optimal stock levels increase in the dynamic and myopic Nash equilibrium paths in the treatments with an announced price change. When subjects are introduced with a price increase during the fifth round, the average stock level across the clusters slightly increases (Figure 5.12 and 5.13). However, the increase in stock is short lived. The sudden increase in labor allocation into the resource sector during the fifth round dissipates the rise in the stock. This seems to indicate that the initial levels of labor are critical in order to arrive at the optimal trajectory. In a dynamic setting, choosing the wrong starting point may lead one to the wrong trajectory path.

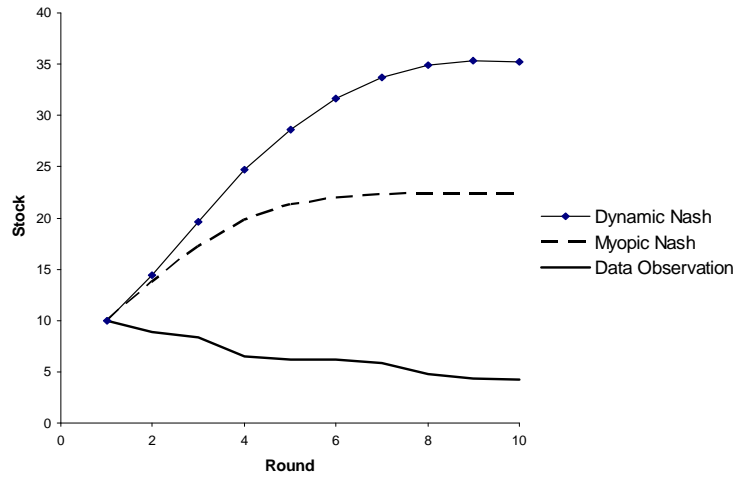


Figure 5.11: Average Stock Over Time with Heterogeneous Community Members
 - Base Treatment

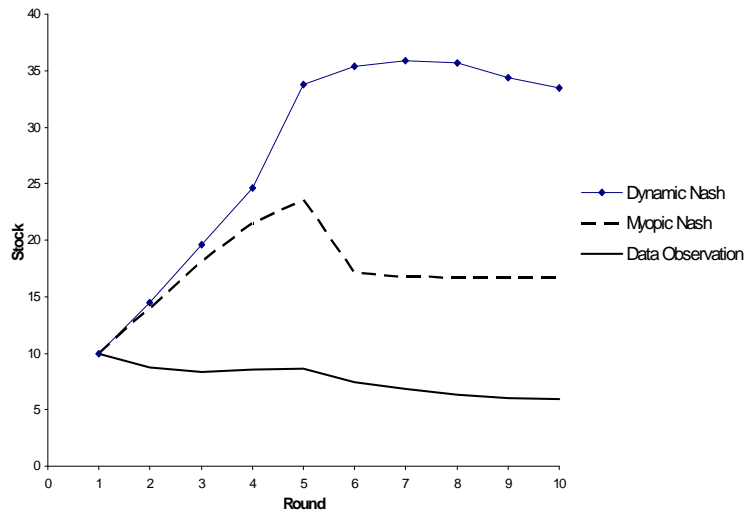


Figure 5.12: Average Stock Over Time with Homogeneous Community Members
 - Price Change Treatment

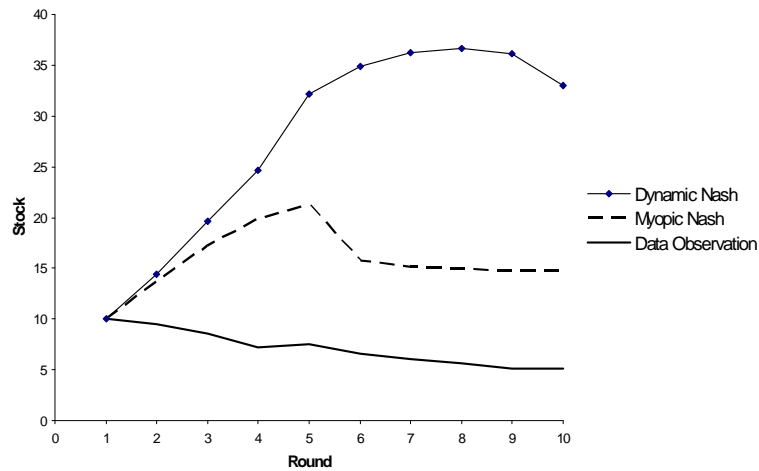


Figure 5.13: Average Stock Over Time with Heterogeneous Community Members
- Price Change Treatment

The four illustrations below show how wages change in each round in the four treatments of the experiment (see Figures 5.14 to 5.17). Wage changes over time reflect the opportunity cost of investing labor hours in the resource sector. In the base treatments without any price change, wages are significantly larger than either the dynamic or myopic Nash equilibrium levels. This indicates that subjects are over-harvesting the stock in the resource sector. When an announced price change is in place, the optimal wage rate is still higher than the Nash equilibrium paths. However, they seem to track more closely with the myopic Nash equilibrium path. Wages decline prior to the fifth round since more labor is allocated in the manufacturing sector. Once the price increase is in effect, wage increases as well because more labor is allocated in the resource sector.

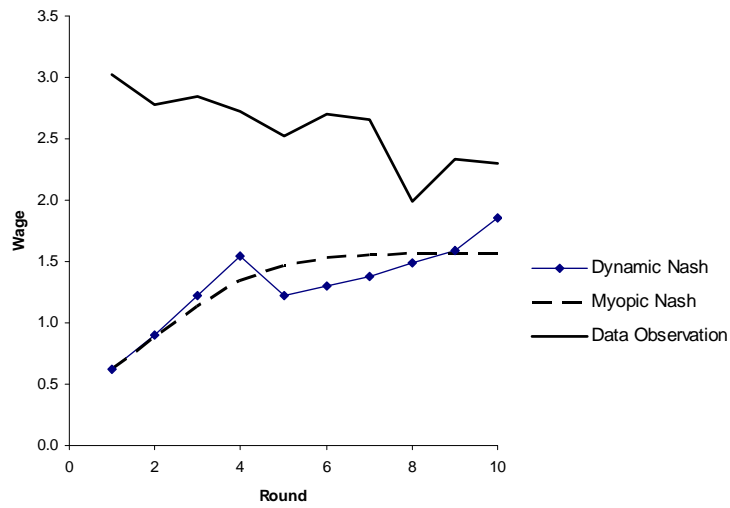


Figure 5.14: Average Wage Over Time with Homogeneous Community Members
- Base Treatment

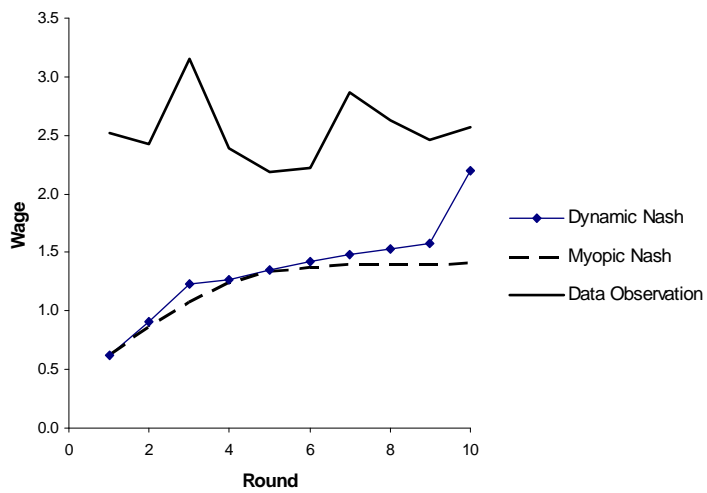


Figure 5.15: Average Wage Over Time with Heterogeneous Community Members
- Base Treatment

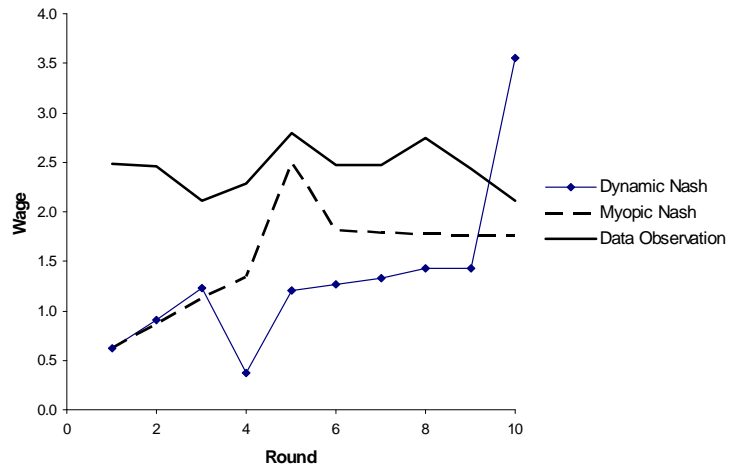


Figure 5.16: Average Wage Over Time with Homogeneous Community Members
- Price Change Treatment

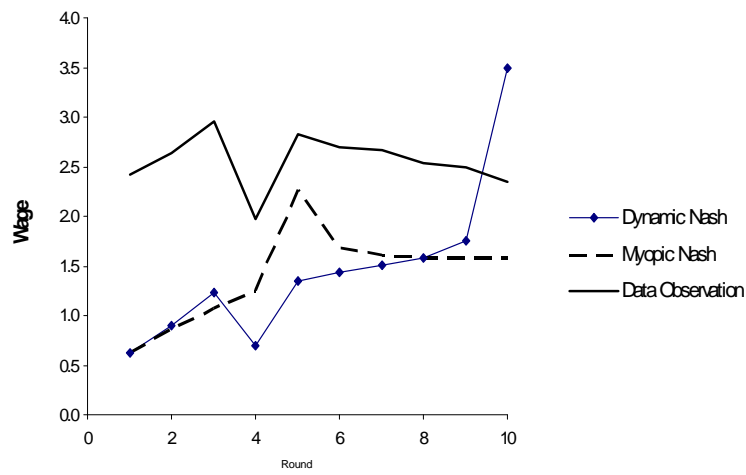


Figure 5.17: Average Wage Over Time with Heterogeneous Community Members
- Price Change Treatment

5.5 Analysis of the Data

Statistical analysis in this subsection is divided into two parts: (1) joint determination of the behavioral rule of labor allocation and property rights regimes choice in group 1 (representing community members); and (2) testing the short-run effects of trade on stock.

5.5.1 Labor Allocation and Property Rights Regime Choice

There are two important components that influence the stock level of a common pool resource over time: labor allocations in the resource sector; and the institutions governing the use of the resource. Figures 5.6 to 5.9 displays the trend of labor allocation in the resource sector by members of group 1. Based on the figures, we find that the overall mean labor allocations by members in the community follow the relatively more myopic Nash equilibrium path. More specifically, the labor allocation path diverges from the optimal dynamic path when faced with an announced price increase during the fifth round. Another important component determining stock over time is the type of property rights regime selected by the community over time. Two measures of property rights regimes were collected from subjects in group 1. The first voting question asked individuals if they preferred to keep the stock open to group 2 individuals or not. Thus, we obtained a dichotomous measure of property rights regime types: limited open access and common property resource management.¹¹ Recall that

¹¹The second voting question asked group 1 members to vote how many labor hours they would allow group 2 into the resource sector. However, we focus our data analysis on the results from the first voting question. A dichotomous choice is analyzed in this case to arrive at incentive-compatible decisions for community members. Gibbard (1973) and Satterthwaite

Table 5.8 summarizes the percentage of clusters that keep the resource stock open during each round. The trend lends qualitative proof that in terms of choosing the property rights regime governing the resource stock, community members consider some of the future impact on their wealth since there is a tendency to initially keep the resource stock open.

To formally test the initial hypotheses that labor allocations and property rights regime choice follow a dynamic Nash equilibrium path, we derive the joint mean squared deviations of labor allocation and property rights regime choice for all rounds and compare it with the two competing Nash equilibrium paths.¹² Table 5.9 summarizes the results from the analysis. Each value in the table displays the mean squared deviation of the observed data from the equilibrium path for a single treatment for a set of rounds.¹³ Thus, each row in the table compares the mean squared deviation of observed labor allocations and property rights regime choice from the dynamic Nash versus the myopic Nash equilibrium path. The smaller mean squared deviation is indicated by an asterisk "*". For all four treatment groups, all but one of the rows show that the mean squared

(1975) proved that if three or more choices are voted upon, the resulting outcome is not incentive compatible. From the baseline model, this implies that an optimal value of non-community labor in the resource sector equal to (greater than) zero implies preference for closing (opening) the resource stock.

¹²For the heterogeneous community member case, we compare the subjects' labor allocations with the optimal Nash equilibrium found in Appendix E.4.

¹³The joint mean squared deviation is $\frac{\sum_t \sum_i (l_{ijt} - l_{ijt}^N)^2}{n} + \frac{\sum_t \sum_j (p_{jtt} - p_{jtt}^N)^2}{n}$ where p_{jtt} is the observed property rights regime by the j^{th} cluster; l_{ijt} is the observed labor hour by the i^{th} individual at time t in the resource sector; p_{jtt}^N is the optimal Nash property rights choice by the j^{th} cluster at time t ; l_{ijt}^N is the optimal Nash labor hour by the i^{th} individual at time t and n is the total number of observations.

Treatment	Solution Paths	
	Dynamic Nash	Myopic Nash
Homogeneous Community Members		
Baseline		
Rounds 1-10	17.80	10.70*
Rounds 1-5	27.49	14.11*
Rounds 6-10	8.12	7.28*
Price Change		
Rounds 1-10	19.85	13.71*
Rounds 1-5	25.52	16.89*
Rounds 6-10	14.16	10.70*
Heterogeneous Community Members		
Baseline		
Rounds 1-10	37.23	23.37*
Rounds 1-5	33.54	24.35*
Rounds 6-10	40.96	22.20*
Price Change		
Rounds 1-10	34.24	30.01*
Rounds 1-5	25.83*	28.91
Rounds 6-10	42.65	31.12*

* Denotes the Solution Path that Minimizes the Mean Squared Deviation.

Note: Each entry in the table represents the mean squared deviation of the labor hours of community members from the corresponding solution path.

Mean squared deviation is equal to $\frac{1}{n} \sum_t (l_{ijt} - l_{ijt}^N)^2 / n + \frac{1}{n} \sum_t \sum_j (p_{jt} - p_{jt}^N)^2 / n$

where p_{jt} is the observed property rights regime by the j^{th} cluster; l_{ijt} is the observed labor hour by the i^{th} individual at time t in the resource sector;

p_{jt}^N is the optimal Nash property rights choice by the j^{th} cluster at time t ;

l_{it}^N is the optimal Nash labor hour by the i^{th} individual at time t and n is the total number of observations.

Table 5.9: Mean Squared Deviation of Labor Hours and Property Rights Regime Choice by Community Members

deviation is smallest under the myopic Nash equilibrium path. This seems to indicate that the null hypotheses stating that subjects follow a dynamic Nash equilibrium path cannot be accepted. This particular result coincides with the finding from Herr, et al. (1997) where subjects tend to decide myopically when extracting from a dynamic resource stock.

The average payoffs over the different treatments are summarized in Table 5.10. The average payoffs are lower than the dynamic Nash equilibrium pay-

	Treatments			
	Homogeneous Community Members		Heterogeneous Community Members	
	Baseline	Price Change	Baseline	Price Change
Average Payoffs (standard deviation)	7.4 (2.51)	6.7 (1.44)	7.57 (2.66)	7.05 (1.94)
Myopic Nash Equilibrium Payoff	7.54	7.23	7.34	7.03
Dynamic Nash Equilibrium Payoff	7.84	8.41	8.04	8.71
Ratio of Average Payoff to Myopic Nash Equilibrium Payoff	0.98	0.93	1.03	1
Ratio of Average Payoff to Dynamic Nash Equilibrium Payoff	0.94	0.8	0.94	0.81

Table 5.10: Average Payoff of Subjects Relative to Optimal Solution

off, with the ratio of payoffs ranging from 80% to 94%. However, payoffs are relatively closer to the myopic Nash equilibrium path payoff, with the ratio of payoffs ranging from 93% to 103%. These payoffs further support the alternative hypothesis that individuals follow the myopic Nash equilibrium path closer than the dynamic Nash equilibrium path.¹⁴

Two potential reasons can be cited to explain such a phenomenon in this particular experiment. First, subjects may have been led to a non-optimal dynamic trajectory due to their initial labor allocations during the beginning of

¹⁴It must be noted that a flat-payoff problem may exist, i.e. subjects may not have enough incentive to derive the optimal path given the parameters of the model. Parameters were chosen to create enough of a difference between *total earnings* when choosing either the Myopic or the Dynamic Nash equilibrium paths. However, the differences in actual dollar earnings in *each round* between the two potential equilibrium paths may not have been large enough for some subjects to spend time deriving the optimal result. This implies that caution must be taken when interpreting some of the disaggregated round by round results of the model.

the round. Subjects may have understood the importance of planning over the whole ten periods and tried to maximize wealth. However, because of the wrong choices during the first few rounds, they may have started on the "non-optimal" dynamic trajectory path. The initial choices in the first round are crucial in order to arrive at the optimal dynamic trajectory path.

Another reason may be due to the assumption of perfect foresight throughout the planning horizon in the theoretical model. The experiment was designed to try to satisfy this particular assumption: a calculator was provided to show how earnings are accumulated during each round; instructions were constructed to show that there are benefits of preserving the resource for future use; and a practice session was conducted to give subjects the opportunity to plan out their extraction path for the ten rounds. However, even with these items in the experiment, they may not have been a sufficient proxy for perfect foresight.

It must be noted that a t-test across sessions and treatments were conducted to test for any ordering effects (Appendix E.5). The labor allocations for sessions 1 and 2 were compared with each other as well as sessions 3 and 4 holding community efficiency constant. The mean labor allocations did not show any significant differences in the treatments of homogeneous community members with an announced price change and heterogeneous community members with no price change. However, it must be noted that there does seem to be some significant differences in labor allocations in a few rounds when subjects are homogeneous and there are no price changes and, to a lesser extent, the treatment where individuals are heterogeneous and a price change is announced.

5.5.2 Effect of Trade on Stock

In order to determine the effect of an announced price increase on the stock, the stock levels in the treatments without any price change are compared to the treatment with the price change. Hypothesis 3 indicates that an announced price change will lead to the community trying to build the resource stock up but will lead to lower stock levels in the future. Using a t-test that compares the mean stock level of the two treatments, we do find a significant positive difference of stocks in the treatment with an announced price change (Table 5.11). During the fourth and fifth rounds, the clusters in the homogeneous sessions responded to the price change by building the stock up. However, community members allocated more labor over time resulting in a decrease in stock levels over time. During the last round, we do find that the mean stock level is lower with the price change than the baseline case, albeit a statistically insignificant amount. In the heterogeneous community member case, however, stocks did not increase as much as in the homogeneous community treatment. However, we did find that during the fifth round, there was a slightly significant increase in stock compared to the base case.¹⁵

Most of the stock build up could be attributed to the decrease in labor allocations prior to the price increase. Table 5.12 summarizes a t-test of the mean differences of labor allocation and percentage of votes favoring to keep the resource stock open. During the third and fourth rounds in both the heterogeneous community member and homogeneous community member treatments, there is a significant decrease in labor allocations resulting in the increase of the stock. The

¹⁵The t-test for ordering effects do not show any statistically significant differences in stock levels across sessions, as shown in Appendix E.5.

Treatment	Baseline	Price Change	T-Stat
Homogeneous Community Members			
1	10.00	10.00	-
2	8.00	8.72	0.78*
3	7.32	8.38	0.63
4	6.75	8.50	1.02**
5	6.24	8.61	1.30***
6	5.90	7.44	0.79*
7	5.48	6.88	0.74*
8	5.14	6.29	0.72*
9	5.79	5.99	0.11
10	5.96	5.91	-0.03
Heterogeneous Community Members			
1	10.00	10.00	-
2	8.93	9.52	0.59
3	8.38	8.54	0.1
4	6.53	7.23	0.42
5	6.21	7.57	0.87*
6	6.13	6.55	0.26
7	5.87	6.01	0.09
8	4.73	5.62	0.55
9	4.37	5.14	0.52
10	4.25	5.15	0.54

Note: *** 15% level of significance; ** 20% level of significance;
* 25% level of significance.

Table 5.11: Differences in Average Stock Levels Across Treatments

property rights regime mechanism was also used in order to preserve the stock until after the price increase, but to a lesser extent. During the fourth round in the heterogeneous community member case, we find that there was a significant decrease in the percentage of clusters that vote to keep the resource stock open. Therefore, we do find some support for hypothesis 3.

The evidence supports some of hypothesis 3 wherein subjects do internalize some of the stock effect over time. This seems to indicate that subjects do follow a dynamic path, albeit non-optimal. The crucial role of selecting the correct initial levels of labor allocation and property rights regime choice during the first few rounds heavily influence the trajectory path in a dynamic framework.

In this chapter, we tested three hypotheses derived from the theoretical model using a laboratory experiment. The experimental design is a variation of the static common pool resource game. We develop a dynamic common property resource game where subjects allocate their labor hours between two sectors in the economy given a dynamic resource stock evolving over time. Results from the experiment show that labor allocation and property rights regime decisions do not follow the optimal dynamic path. It is closer to the myopic Nash equilibrium path. However, an alternative explanation may be attributed to subjects choosing a "non-optimal" dynamic equilibrium path instead. Subjects tended to start at initial labor allocations away from the optimal starting point that would lead them to the optimal dynamic Nash equilibrium. This may have led to choices in labor allocation and property rights regimes that were along a non-optimal dynamic path. We find that resource stocks temporarily increase prior to the price change. Stocks rise through lessening of labor and, to a lesser extent, by implementing a common property resource management scheme. Internalization

Treatment	Labor Allocation in Group 1			Property Rights Regime		
	Baseline	Price Change	T-Stat	Baseline	Price Change	T-Stat
Homogeneous Community Members						
1	24.50	28.74	-1.42*	100.0	75.0	1.53**
2	23.94	21.88	0.74	100.0	75.0	1.53**
3	26.75	17.36	3.67***	75.0	87.5	-0.61
4	24.15	18.84	1.96***	87.5	87.5	0
5	25.25	23.44	0.56	87.5	87.5	0
6	27.69	22.91	1.50**	87.5	87.5	0
7	22.28	20.46	0.63	75.0	87.5	-0.61
8	20.45	20.29	0.06	62.5	100.0	-2.05***
9	22.09	20.73	0.44	75.0	75.0	0
10	20.94	17.41	1.38*	87.5	87.5	0
Heterogeneous Community Members						
1	23.00	20.85	0.64	100.0	87.5	1
2	24.76	22.34	0.8	87.5	87.5	0
3	27.50	19.78	2.44***	100.0	100.0	0
4	24.05	17.64	2.04***	100.0	62.5	2.05***
5	23.00	23.95	-0.26	87.5	87.5	0
6	23.75	17.36	1.75**	87.5	100.0	-1
7	25.39	18.41	2.06***	100.0	87.5	1
8	24.80	20.48	1.12*	87.5	87.5	0
9	22.23	19.41	0.84	87.5	100.0	-1
10	21.46	16.05	1.52**	100.0	100.0	0

Note: *** 5% level of significance; ** 10% level of significance; *15% level of significance.

Table 5.12: Differences in Property Rights Regime and Labor Allocation Across Treatments

of some of the stock effect over time indicates that the non-optimal dynamic path explanation is plausible.

In the experimental design, an open-loop strategy was simulated. However, if the assumption of perfect foresight did not hold, then subjects may have tried to play a closed-loop Nash equilibrium strategy. The current stock levels were never shown to the subjects but they may have tried to infer the value of the stock by comparing their round by round earnings between market 1 and market 2. It would be interesting to determine the type of strategy played in time-dependent laboratory experiments, whether open-loop or closed-loop strategies, in future researches.

Chapter 6

Conclusion

International clamor regarding the potential degradation of the environment in developing countries due to opening to trade has been an important issue that has moved from the streets into academic studies. This dissertation links the effect of opening to trade on resource stocks in developing countries. The primary mechanism by which we link trade impacts on resource stocks is through the endogenous property rights regime choice. The type of property rights regime governing the resource stock, be it complete open access, common property resource management or private property management, has a significant impact on how the resource stock evolves over time. The model developed in this study tries to explain how communities that have communal ownership of a resource stock select the property rights regime governing the use of their resource stock via a voting mechanism. Then, the impact of opening to trade is linked to the choice of the property rights regime and, ultimately, stock changes over time.

We found that under some plausible assumptions, community members would vote to allow non-community members into the resource sector. A necessary but not sufficient condition for this to occur is when the harvestability coefficient of all community members is greater than the harvestability coefficient of non-

community members. Different property rights regime patterns are derived in both finite and infinite horizon models. Opening to trade, when the country has comparative advantage in the production of resource intensive goods, does result in a decrease in the long-run equilibrium stock. This particular impact of trade on the environment is similar to what previous studies have reported. In this study, as long as property rights regimes are endogenous, we find that degrading the resource stock can be an optimal solution! Thus, one of the messages of this study is that as long as a country follows the optimal trajectory that degrades the resource stock when opening to trade, then this is actually welfare maximizing. It must be emphasized that one must follow the optimal trajectory path to maximize welfare. If it is degraded too fast or even too slowly, then the country would not be welfare maximizing.

We were able to test some of the basic theoretical results of the model using a laboratory experiment. A dynamic common property resource game with two sectors in the economy was designed and implemented. Results from the experiment did show that subjects tried to preserve some of the stock for future extraction when they know that the terms of trade in the resource sector would improve in the future. Adjustments were made in labor allocation and property rights regime choice before the price increase was implemented in order to preserve the stock. After which, the stock was degraded again. Experimental results seem to indicate that subjects did follow a dynamic path, but not the optimal one. The initial choices of the subjects greatly influenced the path which they take in the future. Without instruments or more tools given to subjects in determining the optimal starting point that yields the maximum their stream of welfare, subjects will most likely follow a non-optimal dynamic path. Once communities follow a

non-optimal dynamic path, they will have difficulty moving away from it without any external shock. From a policy standpoint, supporting institutions must be put in place to aid communities governing a resource stock to achieve an optimal trajectory path.

Further research would extend this dissertation in the theoretical, experimental and empirical directions. Theoretically, this model can be extended to understand bargaining between owners of the resource stock and non-owners. In some developing countries, small communities may have the rights over the use of a resource such as a mine or forest but do not have enough technological efficiency to harvest from the resource optimally. Large companies who have capital and resources usually enter and negotiate with community members. The theoretical model can be extended to allow for Nash bargaining between the two entities in order to determine conditions under which the resource is fully exploited or never used at all. Furthermore, theoretical extensions can also be made with regard to the evolution of property rights regimes. So far, we have not allowed any other form of instruments, such as taxes or permits within the community, to directly regulate open access within the community. It would be interesting to extend this aspect of endogenous property rights regime choice through voting to obtain more policy recommendations with regard to resource stock governance both by the community and the government.

The basic experimental setup can be extended to allow for testing the role of communication in enforcing property rights regime choice. In the basic setup, all treatments allowed for communication. It would be interesting to compare the results of all four treatments when communication does not exist or when communication is costly. Furthermore, negotiations between group 1 and group

2 members were non-existent. It would also be interesting to see what would happen if negotiations were possible.

The basic theoretical results also provide a conceptual foundation for empirical analysis. In order to empirically measure the impact of opening to trade on a resource stock, it is important to measure the link between trade and property rights regime. It is more likely than not that the indirect trade effects through the endogenous property rights regime channel is as significant as the direct trade impact on resource stocks, especially in developing countries.

Appendix A

Numerical Example in Finite Horizon Model

A.1 Second Order Conditions in Homogeneous Community Member Case

Recall that the Hessian in the two-period model is (2.12),

$$H = \begin{bmatrix} \frac{\partial^2 W_j}{\partial l_{c0}^2} & \frac{\partial^2 W_j}{\partial l_{c0} \partial l_{c1}} & \frac{\partial^2 W_j}{\partial l_{c0} \partial l_{n0}} & \frac{\partial^2 W_j}{\partial l_{c0} \partial l_{n1}} \\ \frac{\partial^2 W_j}{\partial l_{c1} \partial l_{c0}} & \frac{\partial^2 W_j}{\partial l_{c1}^2} & \frac{\partial^2 W_j}{\partial l_{c1} \partial l_{n0}} & \frac{\partial^2 W_j}{\partial l_{c1} \partial l_{n1}} \\ \frac{\partial^2 W_j}{\partial l_{n0} \partial l_{c0}} & \frac{\partial^2 W_j}{\partial l_{n0} \partial l_{c1}} & \frac{\partial^2 W_j}{\partial l_{n0}^2} & \frac{\partial^2 W_j}{\partial l_{n0} \partial l_{n1}} \\ \frac{\partial^2 W_j}{\partial l_{n1} \partial l_{c0}} & \frac{\partial^2 W_j}{\partial l_{n1} \partial l_{c1}} & \frac{\partial^2 W_j}{\partial l_{n1} \partial l_{n0}} & \frac{\partial^2 W_j}{\partial l_{n1}^2} \end{bmatrix}.$$

The elements in the Hessian matrix are as follows,

$$\frac{\partial^2 W_j}{\partial l_{c0}^2} = (p_0 - \mu_1 C) \alpha_c S_0 \frac{\partial^2 f(L_{-c0}, l_{c0})}{\partial l_{c0}^2} - \mu_1 N \alpha_n S_0 \frac{\partial^2 f(L_{-n0}, l_{n0})}{\partial l_{c0}^2} - \frac{\partial^2 Y_x}{\partial L_{x0} \partial l_{c0}}; \quad (\text{A.1})$$

$$\frac{\partial^2 W_j}{\partial l_{c1} \partial l_{c0}} = \frac{\partial^2 W_j}{\partial l_{c0} \partial l_{c1}} = -p_1 \alpha_c \frac{\partial f(L_{-c1}, l_{c1})}{\partial l_{c1}} \delta S_0 \left(C \alpha_c \frac{\partial f(L_{-c0}, l_{c0})}{\partial l_{c0}} + N \alpha_n \frac{\partial f(L_{-n0}, l_{n0})}{\partial l_{c0}} \right); \quad (\text{A.2})$$

$$\frac{\partial^2 W_j}{\partial l_{c0} \partial l_{n0}} = (p_0 - \mu_1 C) \alpha_c S_0 \frac{\partial^2 f(L_{-c0}, l_{c0})}{\partial l_{c0} \partial l_{n0}} - \mu_1 N \alpha_n S_0 \frac{\partial^2 f(L_{-n0}, l_{n0})}{\partial l_{c0} \partial l_{n0}} - \frac{\partial^2 Y_x}{\partial L_{x0} \partial l_{n0}}; \quad (\text{A.3})$$

$$\frac{\partial^2 W_j}{\partial l_{c0} \partial l_{n1}} = -p_1 \alpha_c \frac{\partial f(L_{-c1}, l_{c1})}{\partial l_{n1}} \delta S_0 \left(C \alpha_c \frac{\partial f(L_{-c0}, l_{c0})}{\partial l_{c0}} + N \alpha_n \frac{\partial f(L_{-n0}, l_{n0})}{\partial l_{c0}} \right); \quad (\text{A.4})$$

$$\frac{\partial^2 W_j}{\partial l_{c1}^2} = p_1 \alpha_c S_1 \frac{\partial^2 f(L_{-c1}, l_{c1})}{\partial l_{c1}^2} \delta - \frac{\partial^2 Y_x}{\partial L_{x1} \partial l_{c1}} \quad (\text{A.5})$$

$$\frac{\partial^2 W_j}{\partial l_{c1} \partial l_{n0}} = p_1 \alpha_c \frac{\partial S_1}{\partial l_{n0}} \frac{\partial f(L_{-c1}, l_{c1})}{\partial l_{c1}} \delta; \quad (\text{A.6})$$

$$\frac{\partial^2 W_j}{\partial l_{c1} \partial l_{n1}} = p_1 \alpha_c S_1 \frac{\partial^2 f(L_{-c1}, l_{c1})}{\partial l_{c1} \partial l_{n1}} \delta - \frac{\partial^2 Y_x}{\partial L_{x1} \partial l_{n1}} \quad (\text{A.7})$$

$$\frac{\partial^2 W_j}{\partial l_{n0}^2} = (p_0 - \mu_1 C) \alpha_c S_0 \frac{\partial^2 f(L_{-c0}, l_{c0})}{\partial l_{n0}^2} - \mu_1 N \alpha_n S_0 \frac{\partial^2 f(L_{-n0}, l_{n0})}{\partial l_{n0}^2}; \quad (\text{A.8})$$

$$\frac{\partial^2 W_j}{\partial l_{n0} \partial l_{c0}} = (p_0 - \mu_1 C) \alpha_c S_0 \frac{\partial^2 f(L_{-c0}, l_{c0})}{\partial l_{c0} \partial l_{n0}} - \mu_1 N \alpha_n S_0 \frac{\partial^2 f(L_{-n0}, l_{n0})}{\partial l_{c0} \partial l_{n0}}; \quad (\text{A.9})$$

$$\frac{\partial^2 W_j}{\partial l_{n0} \partial l_{c1}} = -p_1 \alpha_c \frac{\partial f(L_{-c1}, l_{c1})}{\partial l_{c1}} \delta S_0 \left(C \alpha_c \frac{\partial f(L_{-c0}, l_{c0})}{\partial l_{n0}} + N \alpha_n \frac{\partial f(L_{-n0}, l_{n0})}{\partial l_{n0}} \right); \quad (\text{A.10})$$

$$\frac{\partial^2 W_j}{\partial l_{n1} \partial l_{n0}} = \frac{\partial^2 W_j}{\partial l_{n0} \partial l_{n1}} = -p_1 \alpha_c \frac{\partial f(L_{-c1}, l_{c1})}{\partial l_{n1}} \delta S_0 \left(C \alpha_c \frac{\partial f(L_{-c0}, l_{c0})}{\partial l_{n0}} + N \alpha_n \frac{\partial f(L_{-n0}, l_{n0})}{\partial l_{n0}} \right); \quad (\text{A.11})$$

$$\frac{\partial^2 W_j}{\partial l_{n1}^2} = p_1 \alpha_c S_1 N \frac{\partial^2 f(L_{-c1}, l_{c1})}{\partial l_{n1}^2} \delta; \quad (\text{A.12})$$

$$\frac{\partial^2 W_j}{\partial l_{n1} \partial l_{c0}} = p_1 \alpha_c \frac{\partial S_1}{\partial l_{c0}} N \frac{\partial f(L_{-c1}, l_{c1})}{\partial l_{n1}} \delta; \quad (\text{A.13})$$

$$\frac{\partial^2 W_j}{\partial l_{n1} \partial l_{c1}} = p_1 \alpha_c S_1 \frac{\partial^2 f(L_{-c1}, l_{c1})}{\partial l_{n1} \partial l_{c1}} \delta; \quad (\text{A.14})$$

where: $\mu_1 \equiv p_1 \alpha_c f(L_{-c1}, l_{c1}) \delta$. Note that due to the general equilibrium nature of the model, the cross partial derivatives between l_{nt} and l_{ct} are not symmetric.

The Hessian evaluated at the optimal values, $l_{c0} = 0.409$, $l_{c1} = 2.988$, $l_{n0} = 1.685$, and $l_{n1} = 0$, is

$$H = \begin{bmatrix} -54.91 & -7.81 & -9.88 & 9.88 \\ -7.81 & -9.50 & -65.02 & -55.01 \\ -4.13 & 2.02 & -1.73 & 1.73 \\ 1.73 & 0.10 & 0.50 & -1.50 \end{bmatrix}. \quad (\text{A.15})$$

From the Hessian, the determinants of the principal minors, are

$$\det |H| = \begin{vmatrix} -54.91 & -7.81 & -9.88 & 9.88 \\ -7.81 & -9.50 & -65.02 & -55.01 \\ -4.13 & 2.02 & -1.73 & 1.73 \\ 1.73 & 0.10 & 1.73 & -1.50 \end{vmatrix} = 461.0 > 0.$$

$$\det |H^2| = \begin{vmatrix} -54.91 & -7.81 & -9.88 \\ -7.81 & -9.50 & -65.02 \\ -4.13 & 2.02 & -1.73 \end{vmatrix} = -9572.9 < 0.$$

$$\det |H^1| = \begin{vmatrix} -54.91 & -7.81 \\ -7.81 & -9.50 \end{vmatrix} = 21308.9 > 0.$$

A.2 Second Order Conditions in Heterogeneous Community Member Case

From (2.18), the Hessian in the numerical example with three community members is,

$$H_c = \begin{bmatrix} \frac{\partial^2 W_j}{\partial l_{c1,0}^2} & \frac{\partial^2 W_j}{\partial l_{c1,0} \partial l_{c1,1}} & \frac{\partial^2 W_j}{\partial l_{c1,0} \partial l_{c2,0}} & \frac{\partial^2 W_j}{\partial l_{c1,0} \partial l_{c2,1}} & \frac{\partial^2 W_j}{\partial l_{c1,0} \partial l_{c3,0}} & \frac{\partial^2 W_j}{\partial l_{c1,0} \partial l_{c3,1}} & \frac{\partial^2 W_j}{\partial l_{c1,0} \partial l_{n0}} & \frac{\partial^2 W_j}{\partial l_{c1,0} \partial l_{n1}} \\ \frac{\partial^2 W_j}{\partial l_{c1,1} \partial l_{c1,0}} & \frac{\partial^2 W_j}{\partial l_{c1,1}^2} & \frac{\partial^2 W_j}{\partial l_{c1,1} \partial l_{c2,0}} & \frac{\partial^2 W_j}{\partial l_{c1,1} \partial l_{c2,1}} & \frac{\partial^2 W_j}{\partial l_{c1,1} \partial l_{c3,0}} & \frac{\partial^2 W_j}{\partial l_{c1,1} \partial l_{c3,1}} & \frac{\partial^2 W_j}{\partial l_{c1,1} \partial l_{n0}} & \frac{\partial^2 W_j}{\partial l_{c1,1} \partial l_{n1}} \\ \frac{\partial^2 W_j}{\partial l_{c2,0} \partial l_{c1,0}} & \frac{\partial^2 W_j}{\partial l_{c2,0} \partial l_{c1,1}} & \frac{\partial^2 W_j}{\partial l_{c2,0}^2} & \frac{\partial^2 W_j}{\partial l_{c1,1} \partial l_{c2,1}} & \frac{\partial^2 W_j}{\partial l_{c2,0} \partial l_{c3,0}} & \frac{\partial^2 W_j}{\partial l_{c2,0} \partial l_{c3,1}} & \frac{\partial^2 W_j}{\partial l_{c2,0} \partial l_{n0}} & \frac{\partial^2 W_j}{\partial l_{c2,0} \partial l_{n1}} \\ \frac{\partial^2 W_j}{\partial l_{c2,1} \partial l_{c1,0}} & \frac{\partial^2 W_j}{\partial l_{c2,1} \partial l_{c1,1}} & \frac{\partial^2 W_j}{\partial l_{c2,1} \partial l_{c2,0}} & \frac{\partial^2 W_j}{\partial l_{c2,1}^2} & \frac{\partial^2 W_j}{\partial l_{c2,1} \partial l_{c3,0}} & \frac{\partial^2 W_j}{\partial l_{c2,1} \partial l_{c3,1}} & \frac{\partial^2 W_j}{\partial l_{c2,1} \partial l_{n0}} & \frac{\partial^2 W_j}{\partial l_{c2,1} \partial l_{n1}} \\ \frac{\partial^2 W_j}{\partial l_{c3,0} \partial l_{c1,0}} & \frac{\partial^2 W_j}{\partial l_{c3,0} \partial l_{c1,1}} & \frac{\partial^2 W_j}{\partial l_{c3,0} \partial l_{c2,0}} & \frac{\partial^2 W_j}{\partial l_{c3,0} \partial l_{c2,1}} & \frac{\partial^2 W_j}{\partial l_{c3,0}^2} & \frac{\partial^2 W_j}{\partial l_{c3,0} \partial l_{c3,1}} & \frac{\partial^2 W_j}{\partial l_{c3,0} \partial l_{n0}} & \frac{\partial^2 W_j}{\partial l_{c3,0} \partial l_{n1}} \\ \frac{\partial^2 W_j}{\partial l_{c3,1} \partial l_{c1,0}} & \frac{\partial^2 W_j}{\partial l_{c3,1} \partial l_{c1,1}} & \frac{\partial^2 W_j}{\partial l_{c3,1} \partial l_{c2,0}} & \frac{\partial^2 W_j}{\partial l_{c3,1} \partial l_{c2,1}} & \frac{\partial^2 W_j}{\partial l_{c3,1} \partial l_{c3,0}} & \frac{\partial^2 W_j}{\partial l_{c3,1}^2} & \frac{\partial^2 W_j}{\partial l_{c3,1} \partial l_{n0}} & \frac{\partial^2 W_j}{\partial l_{c3,1} \partial l_{n1}} \\ \frac{\partial^2 W_j}{\partial l_{n0} \partial l_{c1,0}} & \frac{\partial^2 W_j}{\partial l_{n0} \partial l_{c1,1}} & \frac{\partial^2 W_j}{\partial l_{n0} \partial l_{c2,0}} & \frac{\partial^2 W_j}{\partial l_{n0} \partial l_{c2,1}} & \frac{\partial^2 W_j}{\partial l_{n0} \partial l_{c3,0}} & \frac{\partial^2 W_j}{\partial l_{n0} \partial l_{c3,1}} & \frac{\partial^2 W_j}{\partial l_{n0}^2} & \frac{\partial^2 W_j}{\partial l_{n0} \partial l_{n1}} \\ \frac{\partial^2 W_j}{\partial l_{n1} \partial l_{c1,0}} & \frac{\partial^2 W_j}{\partial l_{n1} \partial l_{c1,1}} & \frac{\partial^2 W_j}{\partial l_{n1} \partial l_{c2,0}} & \frac{\partial^2 W_j}{\partial l_{n1} \partial l_{c2,1}} & \frac{\partial^2 W_j}{\partial l_{n1} \partial l_{c3,0}} & \frac{\partial^2 W_j}{\partial l_{n1} \partial l_{c3,1}} & \frac{\partial^2 W_j}{\partial l_{n1} \partial l_{n0}} & \frac{\partial^2 W_j}{\partial l_{n1}^2} \end{bmatrix}.$$

The Hessian evaluated at the optimal values from Table (2.1) is,

$$H_c = \begin{bmatrix} -23.35 & -1.04 & -13.07 & 0.54 & -13.05 & 0.54 & -32.52 & 1.63 \\ -1.04 & -17.11 & -20.48 & -7.61 & -21.43 & -7.61 & -5.91 & -14.83 \\ -13.15 & -2.04 & -23.24 & 0.53 & -13.14 & 0.53 & -32.78 & 1.59 \\ -25.66 & -13.07 & 0.53 & -22.37 & -26.24 & -13.07 & -7.24 & -31.21 \\ -12.70 & -4.46 & -12.72 & 1.16 & -23.19 & 1.16 & -31.45 & 3.49 \\ -19.26 & -5.40 & -18.83 & -5.40 & 1.16 & -15.09 & -5.44 & -8.22 \\ 4.81 & -0.79 & 5.36 & 0.20 & 5.38 & 0.20 & 5.05 & 0.61 \\ 0.54 & -0.36 & 0.53 & 0.58 & 0.55 & 0.58 & 0.61 & -1.76 \end{bmatrix}.$$

The determinants of the principal minors are,

$$\det |H_c| = \begin{vmatrix} -23.35 & -1.04 & -13.07 & 0.54 & -13.05 & 0.54 & -32.52 & 1.63 \\ -1.04 & -17.11 & -20.48 & -7.61 & -21.43 & -7.61 & -5.91 & -14.83 \\ -13.15 & -2.04 & -23.24 & 0.53 & -13.14 & 0.53 & -32.78 & 1.59 \\ -25.66 & -13.07 & 0.53 & -22.37 & -26.24 & -13.07 & -7.24 & -31.21 \\ -12.70 & -4.46 & -12.72 & 1.16 & -23.19 & 1.16 & -31.45 & 3.49 \\ -19.26 & -5.40 & -18.83 & -5.40 & 1.16 & -15.09 & -5.44 & -8.22 \\ 4.81 & -0.79 & 5.36 & 0.20 & 5.38 & 0.20 & 5.05 & 0.61 \\ 0.54 & -0.36 & 0.53 & 0.58 & 0.55 & 0.58 & 0.61 & -1.76 \end{vmatrix} = 3.57 \times 10^8$$

$$\det |H_c^6| = \begin{vmatrix} -23.35 & -1.04 & -13.07 & 0.54 & -13.05 & 0.54 & -32.52 \\ -1.04 & -17.11 & -20.48 & -7.61 & -21.43 & -7.61 & -5.91 \\ -13.15 & -2.04 & -23.24 & 0.53 & -13.14 & 0.53 & -32.78 \\ -25.66 & -13.07 & 0.53 & -22.37 & -26.24 & -13.07 & -7.24 \\ -12.70 & -4.46 & -12.72 & 1.16 & -23.19 & 1.16 & -31.45 \\ -19.26 & -5.40 & -18.83 & -5.40 & 1.16 & -15.09 & -5.44 \\ 4.81 & -0.79 & 5.36 & 0.20 & 5.38 & 0.20 & 5.05 \end{vmatrix} = -1.72 \cdot 10^8 < 0.$$

$$\det |H_c^5| = \begin{vmatrix} -23.35 & -1.04 & -13.07 & 0.54 & -13.05 & 0.54 \\ -1.04 & -17.11 & -20.48 & -7.61 & -21.43 & -7.61 \\ -13.15 & -2.04 & -23.24 & 0.53 & -13.14 & 0.53 \\ -25.66 & -13.07 & 0.53 & -22.37 & -26.24 & -13.07 \\ -12.70 & -4.46 & -12.72 & 1.16 & -23.19 & 1.16 \\ -19.26 & -5.40 & -18.83 & -5.40 & 1.16 & -15.09 \end{vmatrix} = 1.02 \cdot 10^7 > 0.$$

$$\det |H_c^4| = \begin{vmatrix} -23.35 & -1.04 & -13.07 & 0.54 & -13.05 \\ -1.04 & -17.11 & -20.48 & -7.61 & -21.43 \\ -13.15 & -2.04 & -23.24 & 0.53 & -13.14 \\ -25.66 & -13.07 & 0.53 & -22.37 & -26.24 \\ -12.70 & -4.46 & -12.72 & 1.16 & -23.19 \end{vmatrix} = -1.07 \cdot 10^6 < 0.$$

$$\det |H_c^3| = \begin{vmatrix} -23.35 & -1.04 & -13.07 & 0.54 \\ -1.04 & -17.11 & -20.48 & -7.61 \\ -13.15 & -2.04 & -23.24 & 0.53 \\ -25.66 & -13.07 & 0.53 & -22.37 \end{vmatrix} = 89609.5 > 0.$$

$$\det |H_c^2| = \begin{vmatrix} -23.35 & -1.04 & -13.07 \\ -1.04 & -17.11 & -20.48 \\ -13.15 & -2.04 & -23.24 \end{vmatrix} = -5649.9 < 0.$$

$$\det |H_c^1| = \begin{vmatrix} -23.35 & -1.04 \\ -1.04 & -17.11 \end{vmatrix} = 398.5 > 0.$$

Appendix B

Deriving the Phase Diagram

In order to derive the phase diagram in the infinite horizon model with homogeneous community members, we proceed in the following manner. First, we obtain the relevant comparative statics needed to derive the isoclines. Next, we use the comparative statics to derive the isoclines in the four regions of the phase diagram. Lastly, we characterize the steady state equilibrium point.

B.1 Deriving the comparative statics

Using the definition $\mu_t \equiv \delta\lambda_{t+1}$, the Hessian matrix of the Lagrangean is negative semi-definite as shown as below,

$$\frac{\partial^2 \mathcal{L}}{\partial l_{ct}^2} = (p - \mu_t C) \alpha_c S_t \frac{\partial^2 f(L_{-ct}, l_{ct})}{\partial l_{ct}^2} - \mu_t N \alpha_n S_t \frac{\partial^2 f(L_{-nt}, l_{nt})}{\partial l_{ct}^2} - \frac{\partial^2 Y(K, L_{xt})}{\partial L_{xt} \partial l_{ct}} \leq 0; \quad (\text{B.1})$$

Rearranging the equation and assuming that $c=N$, $p\alpha_c S_t \frac{\partial^2 f(L_{-ct}, l_{ct})}{\partial l_{ct}^2} - \mu_t C S_t \left(\alpha_c \frac{\partial^2 f(L_{-ct}, l_{ct})}{\partial l_{ct}^2} + \alpha_n \frac{\partial^2 f(L_{-nt}, l_{nt})}{\partial l_{ct}^2} \right) - \frac{\partial^2 Y(K, L_{xt})}{\partial L_{xt} \partial l_{ct}}$. Since we have assumed that $\alpha_c \frac{\partial^2 f(L_{-ct}, l_{ct})}{\partial l_{ct}^2} + \alpha_n \frac{\partial^2 f(L_{-nt}, l_{nt})}{\partial l_{ct}^2} > 0$ and $\frac{\partial^2 f(L_{-ct}, l_{ct})}{\partial l_{ct}^2} < 0$, we find that $\frac{\partial^2 \mathcal{L}}{\partial l_{ct}^2} \leq 0$.

$$\frac{\partial^2 \mathcal{L}}{\partial l_{nt}^2} = (p - \mu_t C) \alpha_c S_t \frac{\partial^2 f(L_{-ct}, l_{ct})}{\partial l_{nt}^2} - \mu_t N \alpha_n S_t \frac{\partial^2 f(L_{-nt}, l_{nt})}{\partial l_{nt}^2} \leq 0; \quad (\text{B.2})$$

By rearranging the equation above and assuming C=N, we derive $p \alpha_c S_t \frac{\partial^2 f(L_{-ct}, l_{ct})}{\partial l_{nt}^2} - \mu_t C S_t \left(\alpha_c \frac{\partial^2 f(L_{-ct}, l_{ct})}{\partial l_{nt}^2} + \alpha_n \frac{\partial^2 f(L_{-nt}, l_{nt})}{\partial l_{nt}^2} \right)$. Since we have assumed that $\alpha_c \frac{\partial^2 f(L_{-ct}, l_{ct})}{\partial l_{ct}^2} + \alpha_n \frac{\partial^2 f(L_{-nt}, l_{nt})}{\partial l_{ct}^2} > 0$, we find that $\frac{\partial^2 \mathcal{L}}{\partial l_{nt}^2} \leq 0$.

$$\frac{\partial^2 \mathcal{L}}{\partial l_{nt} \partial l_{ct}} = (p - \mu_t C) \alpha_c S_t \frac{\partial f(L_{-ct}, l_{ct})}{\partial l_{nt} \partial l_{ct}} - \mu_t N \alpha_n S_t \frac{\partial f(L_{-ct}, l_{ct})}{\partial l_{ct} \partial l_{nt}} \geq 0 \quad (\text{B.3})$$

Rearranging the above equation along with C=N, we find, $(p - \mu_t C(\alpha_c + \alpha_n)) S_t \frac{\partial f(L_{-ct}, l_{ct})}{\partial l_{nt} \partial l_{ct}}$. This is non-negative as long as $(p - \mu_t C(\alpha_c + \alpha_n)) \geq 0$.

$$\frac{\partial^2 \mathcal{L}}{\partial l_{ct} \partial l_{nt}} = (p - \mu_t C) \alpha_c S_t \frac{\partial^2 f(L_{-ct}, l_{ct})}{\partial l_{ct} \partial l_{nt}} - \mu_t N \alpha_n S_t \frac{\partial^2 f(L_{-nt}, l_{nt})}{\partial l_{ct} \partial l_{nt}} - \frac{\partial^2 Y(K, L_{xt})}{\partial L_{xt} \partial l_{nt}} \geq 0; \quad (\text{B.4})$$

This particular result also holds as shown above.

$$\det |H| = \frac{\partial^2 \mathcal{L}}{\partial l_{ct}^2} \frac{\partial^2 \mathcal{L}}{\partial l_{nt}^2} - \frac{\partial \mathcal{L}}{\partial l_{ct} \partial l_{nt}} \frac{\partial^2 \mathcal{L}}{\partial l_{nt} \partial l_{ct}} \geq 0. \quad (\text{B.5})$$

Furthermore, the cross partial derivatives of the first order conditions with respect to S_t and μ_t ,

$$\frac{\partial^2 \mathcal{L}}{\partial l_{ct} \partial S_t} = (p - \mu_t C) \alpha_c \frac{\partial f(L_{-ct}, l_{ct})}{\partial l_{ct}} - \mu_t N \alpha_n \frac{\partial f(L_{-nt}, l_{nt})}{\partial l_{ct}} \leq 0; \quad (\text{B.6})$$

Removing S_t from the first order conditions yield the same sign.

$$\frac{\partial^2 \mathcal{L}}{\partial l_{nt} \partial S_t} = (p - \mu_t C) \alpha_c \frac{\partial f(L_{-ct}, l_{ct})}{\partial l_{nt}} - \mu_t N \alpha_n \frac{\partial f(L_{-nt}, l_{nt})}{\partial l_{nt}} \leq 0; \quad (\text{B.7})$$

Removing S_t from the first order conditions yield the same sign.

$$\frac{\partial^2 \mathcal{L}}{\partial l_{ct} \partial \mu_t} = C \alpha_c S_t \frac{\partial f(L_{-ct}, l_{ct})}{\partial l_{ct}} + N \alpha_n S_t \frac{\partial f(L_{-nt}, l_{nt})}{\partial l_{ct}} \geq 0; \quad (\text{B.8})$$

Rearranging the equation and assuming C=N yields, $C S_t \left(\alpha_c \frac{\partial f(L_{-ct}, l_{ct})}{\partial l_{ct}} + \alpha_n \frac{\partial f(L_{-nt}, l_{nt})}{\partial l_{ct}} \right)$.

But we have already assumed $\alpha_c \frac{\partial f(L_{-ct}, l_{ct})}{\partial l_{ct}} + \alpha_n \frac{\partial f(L_{-nt}, l_{nt})}{\partial l_{ct}} > 0$, thus this is positive.

$$\frac{\partial^2 \mathcal{L}}{\partial l_{nt} \partial \mu_t} = C \alpha_c S_t \frac{\partial f(L_{-ct}, l_{ct})}{\partial l_{nt}} + N \alpha_n S_t \frac{\partial f(L_{-nt}, l_{nt})}{\partial l_{nt}} \geq 0. \quad (\text{B.9})$$

Rearranging the equation and assuming C=N yields, $C S_t \left(\alpha_c \frac{\partial f(L_{-ct}, l_{ct})}{\partial l_{nt}} + \alpha_n \frac{\partial f(L_{-nt}, l_{nt})}{\partial l_{nt}} \right)$.

But we have already assumed $\alpha_c \frac{\partial f(L_{-ct}, l_{ct})}{\partial l_{ct}} + \alpha_n \frac{\partial f(L_{-nt}, l_{nt})}{\partial l_{ct}} > 0$, thus this is positive.

The comparative statics for S_t can be derived using the following formulation,

$$\begin{bmatrix} \frac{\partial^2 \mathcal{L}}{\partial l_{ct}^2} & \frac{\partial^2 \mathcal{L}}{\partial l_{nt} \partial l_{ct}} \\ \frac{\partial \mathcal{L}}{\partial l_{ct} \partial l_{nt}} & \frac{\partial^2 \mathcal{L}}{\partial l_{nt}^2} \end{bmatrix} \begin{bmatrix} \frac{\partial l_{ct}}{\partial S_t} \\ \frac{\partial l_{nt}}{\partial S_t} \end{bmatrix} = \begin{bmatrix} \frac{\partial^2 \mathcal{L}}{\partial l_{ct} \partial S_t} \\ \frac{\partial^2 \mathcal{L}}{\partial l_{nt} \partial S_t} \end{bmatrix}.$$

Using Cramer's rule, we derive the following comparative statics,

$$\frac{\partial l_{ct}}{\partial S_t} = \frac{\frac{\partial^2 \mathcal{L}}{\partial l_{ct} \partial S_t} \frac{\partial^2 \mathcal{L}}{\partial l_{nt}^2} - \frac{\partial^2 \mathcal{L}}{\partial l_{nt} \partial S_t} \frac{\partial^2 \mathcal{L}}{\partial l_{nt} \partial l_{ct}}}{\det |H|} \geq 0 \quad (\text{B.10})$$

$$\frac{\partial l_{nt}}{\partial S_t} = \frac{\frac{\partial^2 \mathcal{L}}{\partial l_{nt} \partial S_t} \frac{\partial^2 \mathcal{L}}{\partial l_{ct}^2} - \frac{\partial^2 \mathcal{L}}{\partial l_{ct} \partial S_t} \frac{\partial^2 \mathcal{L}}{\partial l_{ct} \partial l_{nt}}}{\det |H|} \geq 0. \quad (\text{B.11})$$

Similarly, the comparative statics for μ_t can be derived using the following formulation,

$$\begin{bmatrix} \frac{\partial^2 \mathcal{L}}{\partial l_{ct}^2} & \frac{\partial^2 \mathcal{L}}{\partial l_{nt} \partial l_{ct}} \\ \frac{\partial \mathcal{L}}{\partial l_{ct} \partial l_{nt}} & \frac{\partial^2 \mathcal{L}}{\partial l_{nt}^2} \end{bmatrix} \begin{bmatrix} \frac{\partial l_{ct}}{\partial \mu_t} \\ \frac{\partial l_{nt}}{\partial \mu_t} \end{bmatrix} = \begin{bmatrix} \frac{\partial^2 \mathcal{L}}{\partial l_{ct} \partial \mu_t} \\ \frac{\partial^2 \mathcal{L}}{\partial l_{nt} \partial \mu_t} \end{bmatrix}.$$

Using Cramer's rule, we derive the following comparative statics,

$$\frac{\partial l_{ct}}{\partial \mu_t} = \frac{\frac{\partial^2 \mathcal{L}}{\partial l_{ct} \partial \mu_t} \frac{\partial^2 \mathcal{L}}{\partial l_{nt}^2} - \frac{\partial^2 \mathcal{L}}{\partial l_{nt} \partial \mu_t} \frac{\partial^2 \mathcal{L}}{\partial l_{nt} \partial l_{ct}}}{\det |H|} \leq 0 \quad (\text{B.12})$$

$$\frac{\partial l_{nt}}{\partial \mu_t} = \frac{\frac{\partial^2 \mathcal{L}}{\partial l_{nt} \partial \mu_t} \frac{\partial^2 \mathcal{L}}{\partial l_{ct}^2} - \frac{\partial^2 \mathcal{L}}{\partial l_{ct} \partial \mu_t} \frac{\partial^2 \mathcal{L}}{\partial l_{ct} \partial l_{nt}}}{\det |H|} \leq 0 \quad (\text{B.13})$$

Therefore, we derive that $\frac{\partial l_{ct}}{\partial S_t} \geq 0$; $\frac{\partial l_{nt}}{\partial S_t} \geq 0$; $\frac{\partial l_{ct}}{\partial \mu_t} \leq 0$; and $\frac{\partial l_{nt}}{\partial \mu_t} \leq 0$. We will use the comparative statics to derive the isoclines in each region of the phase diagram.

B.2 Deriving Isoclines in Each Region of the Phase Space

Region 1. An interior solution exists for both controls ($l_{nt} > 0$, $l_{ct} < h$)

The isoclines for S and μ can be derived using the equations, $0 = \frac{\partial \max H}{\partial \mu_t}$ and $0 = (1 - \delta)\mu_t - \delta \frac{\partial \max H}{\partial S_t}$, respectively. Using the implicit function theorem, we can derive the slopes of the S isocline and μ isocline. The slope of the S isocline is the following,

$$\frac{\partial \mu_t}{\partial S_t}_{S_{t+1}-S_t=0} = - \frac{\frac{\partial^2 \max H}{\partial \mu_t \partial S_t}}{\frac{\partial^2 \max H}{\partial \mu_t^2}}. \quad (\text{B.14})$$

Here,

$$\begin{aligned} \frac{\partial^2 \max H}{\partial \mu_t \partial S_t} &= \frac{\partial G(S_t)}{\partial S_t} - C\alpha_c \left(f(L_{-ct}, l_{ct}) + S_t \frac{\partial f(L_{-ct}, l_{ct})}{\partial l_{ct}} \frac{\partial l_{ct}}{\partial S_t} + S_t \frac{\partial f(L_{-ct}, l_{ct})}{\partial l_{nt}} \frac{\partial l_{nt}}{\partial S_t} \right) \\ &\quad - N\alpha_n \left(f(L_{-nt}, l_{nt}) + S_t \frac{\partial f(L_{-nt}, l_{nt})}{\partial l_{ct}} \frac{\partial l_{ct}}{\partial S_t} + S_t \frac{\partial f(L_{-nt}, l_{nt})}{\partial l_{nt}} \frac{\partial l_{nt}}{\partial S_t} \right) \end{aligned} \quad (\text{B.15})$$

The terms in the parentheses are positive. Thus the last two terms are negative. The growth rate of the stock from the maximum sustainable yield up to maximum stock level (or carrying capacity) is negative, i.e. $\frac{\partial G(S_t)}{\partial S_t} \leq 0$. However, from stock levels 0 to the stock at the maximum sustainable yield, $\frac{\partial G(S_t)}{\partial S_t} > 0$. We have assumed that $\frac{\partial G(0)}{\partial S_t} \leq C\alpha_c f(L_{-ct}, l_{ct}) + N\alpha_n f(L_{-nt}, l_{nt})$. The intrinsic growth rate, $\frac{\partial G(0)}{\partial S_t}$, is the maximum growth rate of the stock. An increase in stock decreases the growth rate but increases the harvest from the stock. Thus, for all stock levels from 0 to the stock at the maximum sustainable yield, the sign of $\frac{\partial^2 \max H}{\partial \mu_t \partial S_t}$ is always non-positive. Thus, $\frac{\partial^2 \max H}{\partial \mu_t \partial S_t} \leq 0$.

Here,

$$\begin{aligned} \frac{\partial^2 \max H}{\partial \mu_t^2} &= -C\alpha_c S_t \left(\frac{\partial f(L_{-ct}, l_{ct})}{\partial l_{ct}} \frac{\partial l_{ct}}{\partial \mu_t} + \frac{\partial f(L_{-ct}, l_{ct})}{\partial l_{nt}} \frac{\partial l_{nt}}{\partial \mu_t} \right) \\ &\quad - N\alpha_n S_t \left(\frac{\partial f(L_{-nt}, l_{nt})}{\partial l_{ct}} \frac{\partial l_{ct}}{\partial \mu_t} + \frac{\partial f(L_{-nt}, l_{nt})}{\partial l_{nt}} \frac{\partial l_{nt}}{\partial \mu_t} \right). \end{aligned} \quad (\text{B.16})$$

Re-arranging the equation and assuming $C=N$ yields $-CS_t \left(\alpha_c \frac{\partial f(L_{-ct}, l_{ct})}{\partial l_{ct}} + \alpha_n \frac{\partial f(L_{-nt}, l_{nt})}{\partial l_{ct}} \right) \frac{\partial l_{ct}}{\partial \mu_t} - CS_t \left(\alpha_c \frac{\partial f(L_{-ct}, l_{ct})}{\partial l_{nt}} + \alpha_n \frac{\partial f(L_{-nt}, l_{nt})}{\partial l_{nt}} \right) \frac{\partial l_{nt}}{\partial \mu_t}$. Since we have assumed that $\left| \alpha_j \frac{\partial f(L_{-jt}, l_{jt})}{\partial l_{jt}} \right| > \left| \alpha_{-j} \frac{\partial f(L_{-jt}, l_{-jt})}{\partial l_{jt}} \right|$ and $\frac{\partial l_{ct}}{\partial \mu_t} \leq 0$ and $\frac{\partial l_{nt}}{\partial \mu_t} \leq 0$ we derive $\frac{\partial^2 \max H}{\partial \mu_t^2} \geq 0$. Therefore, $\frac{\partial \mu_t}{\partial S_t} \Big|_{S_{t+1}-S_t=0} \geq 0$.

The slope of the μ isocline is derived using implicit function theorem on equation $0 = (1 - \delta)\mu_t - \delta \frac{\partial \max H}{\partial S_t}$,

$$\frac{\partial \mu_t}{\partial S_t} \Big|_{\mu_{t+1} - \mu_t = 0} = \frac{\delta \frac{\partial^2 \max H}{\partial S_t^2}}{(1 - \delta) - \frac{\partial^2 \max H}{\partial S_t \partial \mu_t}}. \quad (\text{B.17})$$

Here,

$$\begin{aligned} \frac{\partial^2 \max H}{\partial S_t^2} &= \delta \left(\frac{\partial^2 G(S_t)}{\partial S_t^2} - C\alpha_c \frac{\partial f(L_{-ct}, l_{ct})}{\partial l_{ct}} \frac{\partial l_{ct}}{\partial S_t} - N\alpha_n \frac{\partial f(L_{-nt}, l_{nt})}{\partial l_{nt}} \frac{\partial l_{nt}}{\partial S_t} \right) \\ &\quad - p\alpha_c \left(\frac{\partial f(L_{-ct}, l_{ct})}{\partial l_{ct}} \frac{\partial l_{ct}}{\partial S_t} + \frac{\partial f(L_{-nt}, l_{nt})}{\partial l_{nt}} \frac{\partial l_{nt}}{\partial S_t} \right) \end{aligned} \quad (\text{B.18})$$

Since we have assumed that $\left| \frac{\partial f(L_{-jt}, l_{jt})}{\partial l_{jt}} \right| > \left| \frac{\partial f(L_{-jt}, l_{jt})}{\partial l_{-jt}} \right|$ and $\alpha_c \frac{\partial f(L_{-ct}, l_{ct})}{\partial l_{ct}} + \alpha_n \frac{\partial f(L_{-nt}, l_{nt})}{\partial l_{nt}} > 0$, the sign of $\frac{\partial^2 \max H}{\partial S_t^2} \leq 0$. We have already determined that $\frac{\partial^2 \max H}{\partial \mu_t \partial S_t} = \frac{\partial^2 \max H}{\partial S_t \partial \mu_t} \geq 0$. Therefore $\frac{\partial \mu_t}{\partial S_t} \Big|_{\mu_{t+1} - \mu_t = 0} \leq 0$.

Therefore, the S and μ isoclines are upward sloping and downward sloping, respectively, when we are in the region of the phase diagram where interior solutions exist for both control variables.

In order to derive the equation of motion on each side of the isocline, we take the derivative of the transition equation with respect to stock as well as the derivative of the equation of motion for the user cost with respect to the user cost.

Taking the derivative of the stock with respect to the transition equation yields,

$$\frac{\partial(S_{t+1} - S_t)}{\partial S_t} = G'(S_t) - C\alpha_c f(L_{-ct}, l_{ct}) - N\alpha_n \alpha_c f(L_{-nt}, l_{nt}) < 0. \quad (\text{B.19})$$

Therefore, $S_{t+1} - S_t < 0$ to the right of the S isocline and the change in stock is strictly positive to the left of the S isocline. Taking the derivative of the μ isoclines with respect to μ yields,

$$\frac{\partial(\mu_{t+1} - \mu_t)}{\partial\mu_t} = (1 - \delta) > 0. \quad (\text{B.20})$$

Therefore, $\mu_{t+1} - \mu_t > 0$ to the right of the μ isocline and the change in user cost is strictly negative to the left of the μ isocline.

Region 2. An interior solution exists for own labor and the resource sector is fully closed ($l_{nt} = 0, l_{ct} < h$).

The isoclines for S_t and μ_t can be derived using the same equations earlier, $0 = \frac{\partial \max H}{\partial \mu_t}$ and $0 = (1 - \delta)\mu_t - \delta \frac{\partial \max H}{\partial S_t}$, respectively, but now evaluated at $l_{nt} = 0$. Using the implicit function theorem, we can derive the slopes of the S isocline and μ isocline. The slope of the S isocline is the following,

$$\frac{\partial\mu_t}{\partial S_t}_{S_{t+1}-S_t=0} = -\frac{\frac{\partial^2 \max H}{\partial \mu_t \partial S_t}}{\frac{\partial^2 \max H}{\partial \mu_t^2}}. \quad (\text{B.21})$$

Here,

$$\begin{aligned} \frac{\partial^2 \max H}{\partial \mu_t \partial S_t} &= \frac{\partial G(S_t)}{\partial S_t} - C\alpha_c \left(f(L_{-ct}, l_{ct}) + S_t \frac{\partial f(L_{-ct}, l_{ct})}{\partial l_{ct}} \frac{\partial l_{ct}}{\partial S_t} + S_t \frac{\partial f(L_{-ct}, 0)}{\partial l_{nt}} \frac{\partial l_{nt}}{\partial S_t} \right) \\ &\quad - N\alpha_n \left(S_t \frac{\partial f(L_{-nt}, 0)}{\partial l_{ct}} \frac{\partial l_{ct}}{\partial S_t} + S_t \frac{\partial f(L_{-nt}, 0)}{\partial l_{nt}} \frac{\partial l_{nt}}{\partial S_t} \right) \end{aligned} \quad (\text{B.22})$$

Similar to the previous proof, we find $\frac{\partial^2 \max H}{\partial \mu_t \partial S_t} \leq 0$.

$$\begin{aligned} \frac{\partial^2 \max H}{\partial \mu_t^2} &= -C\alpha_c S_t - C\alpha_c S_t \left(\frac{\partial f(L_{-ct}, l_{ct})}{\partial l_{ct}} \frac{\partial l_{ct}}{\partial \mu_t} + \frac{\partial f(L_{-ct}, l_{ct})}{\partial l_{nt}} \frac{\partial l_{nt}}{\partial \mu_t} \right) \\ &\quad - N\alpha_n S_t \left(\frac{\partial f(L_{-nt}, 0)}{\partial l_{ct}} \frac{\partial l_{ct}}{\partial \mu_t} + \frac{\partial f(L_{-nt}, 0)}{\partial l_{nt}} \frac{\partial l_{nt}}{\partial \mu_t} \right) \end{aligned} \quad (\text{B.23})$$

As shown in the previous section, $\frac{\partial^2 \max H}{\partial \mu_t^2} \geq 0$. Thus, $\frac{\partial \mu_t}{\partial S_t}_{S_{t+1}-S_t=0} \geq 0$.

The slope of the μ isocline is the following,

$$\frac{\partial \mu_t}{\partial S_t \mu_{t+1} - \mu_t = 0} = \frac{\delta \frac{\partial^2 \max H}{\partial S_t^2}}{(1 - \delta) - \frac{\partial^2 \max H}{\partial S_t \partial \mu_t}}. \quad (\text{B.24})$$

Here,

$$\begin{aligned} \frac{\partial^2 \max H}{\partial S_t^2} = & \delta \left(\frac{\partial^2 G(S_t)}{\partial S_t^2} - C\alpha_c \frac{\partial f(L_{-ct}, l_{ct})}{\partial l_{ct}} \frac{\partial l_{ct}}{\partial S_t} - N\alpha_n \frac{\partial f(L_{-nt}, 0)}{\partial l_{nt}} \frac{\partial l_{nt}}{\partial S_t} \right) \\ & - p\alpha_c \left(\frac{\partial f(L_{-ct}, l_{ct})}{\partial l_{ct}} \frac{\partial l_{ct}}{\partial S_t} + \frac{\partial f(L_{-nt}, 0)}{\partial l_{nt}} \frac{\partial l_{nt}}{\partial S_t} \right) \end{aligned} \quad (\text{B.25})$$

The sign of $\frac{\partial^2 \max H}{\partial S_t^2} \leq 0$. Since $\frac{\partial^2 \max H}{\partial S_t \partial \mu_t} \leq 0$, we derive $\frac{\partial \mu_t}{\partial S_t \mu_{t+1} - \mu_t = 0} \leq 0$.

Therefore, the S and μ isoclines are upward sloping and downward sloping, respectively, when we are in the region of the phase diagram where $l_{nt} = 0$ and $l_{ct} < h$.

In order to derive the equation of motion on each side of the isocline, we take the derivative of the transition equation with respect to stock as well as the derivative of the equation of motion for the user cost with respect to the user cost evaluated at $l_{nt} = 0$.

Taking the derivative of the stock with respect to the transition equation yields,

$$\frac{\partial(S_{t+1} - S_t)}{\partial S_t} = G'(S_t) - C\alpha_c f(L_{-ct}, l_{ct}) < 0. \quad (\text{B.26})$$

Since we have assumed that the growth rate is less than the marginal harvest, $S_{t+1} - S_t < 0$ to the right of the S isocline and the change in stock is strictly positive to the left of the S isocline. Taking the derivative of the μ isoclines with respect to μ yields,

$$\frac{\partial(\mu_{t+1} - \mu_t)}{\partial \mu_t} = (1 - \delta) > 0. \quad (\text{B.27})$$

Therefore, $\mu_{t+1} - \mu_t > 0$ to the right of the μ isocline and the change in user cost is strictly negative to the left of the μ isocline.

Region 3. An interior solution exists for non-community labor and the representative community member devotes all labor into the resource sector ($l_{nt} > 0, l_{ct} = h$)

The isoclines for S_t and μ_t can be derived using the same equations earlier, $0 = \frac{\partial \max H}{\partial \mu_t}$ and $0 = (1 - \delta)\mu_t - \delta \frac{\partial \max H}{\partial S_t}$, respectively, but now evaluated at $l_{ct} = h$. Using the implicit function theorem, we can derive the slopes of the S isocline and μ isocline. The slope of the S isocline is the following,

$$\frac{\partial \mu_t}{\partial S_t}_{S_{t+1}-S_t=0} = -\frac{\frac{\partial^2 \max H}{\partial \mu_t \partial S_t}}{\frac{\partial^2 \max H}{\partial \mu_t^2}}. \quad (\text{B.28})$$

Here,

$$\begin{aligned} \frac{\partial^2 \max H}{\partial \mu_t \partial S_t} = & \frac{\partial G(S_t)}{\partial S_t} - C\alpha_c \left(f(L_{-ct}, h) + S_t \frac{\partial f(L_{-ct}, h)}{\partial l_{ct}} \frac{\partial l_{ct}}{\partial S_t} + S_t \frac{\partial f(L_{-ct}, l_{ct})}{\partial l_{nt}} \frac{\partial l_{nt}}{\partial S_t} \right) \\ & - N\alpha_n \left(f(L_{-nt}, l_{nt}) + S_t \frac{\partial f(L_{-nt}, l_{nt})}{\partial l_{ct}} \frac{\partial l_{ct}}{\partial S_t} + S_t \frac{\partial f(L_{-nt}, l_{nt})}{\partial l_{nt}} \frac{\partial l_{nt}}{\partial S_t} \right) \end{aligned} \quad (\text{B.29})$$

Similar to previous sections, we prove that $\frac{\partial^2 \max H}{\partial \mu_t \partial S_t} \leq 0$.

$$\begin{aligned} \frac{\partial^2 \max H}{\partial \mu_t^2} = & -C\alpha_c S_t - C\alpha_c S_t \left(\frac{\partial f(L_{-ct}, h)}{\partial l_{ct}} \frac{\partial l_{ct}}{\partial \mu_t} + \frac{\partial f(L_{-ct}, h)}{\partial l_{nt}} \frac{\partial l_{nt}}{\partial \mu_t} \right) \\ & - N\alpha_n S_t \left(\frac{\partial f(L_{-nt}, l_{nt})}{\partial l_{ct}} \frac{\partial l_{ct}}{\partial \mu_t} + \frac{\partial f(L_{-nt}, l_{nt})}{\partial l_{nt}} \frac{\partial l_{nt}}{\partial \mu_t} \right) \end{aligned} \quad (\text{B.30})$$

As shown in the previous section, $\frac{\partial^2 \max H}{\partial \mu_t^2} \geq 0$. Thus, $\frac{\partial \mu_t}{\partial S_t}_{S_{t+1}-S_t=0} \geq 0$.

The slope of the μ isocline is the following,

$$\frac{\partial \mu_t}{\partial S_t}_{\mu_{t+1}-\mu_t=0} = \frac{\delta \frac{\partial^2 \max H}{\partial S_t^2}}{(1 - \delta) - \frac{\partial^2 \max H}{\partial S_t \partial \mu_t}}. \quad (\text{B.31})$$

Here,

$$\begin{aligned} \frac{\partial^2 \max H}{\partial S_t^2} = & \delta \left(\frac{\partial^2 G(S_t)}{\partial S_t^2} - C\alpha_c \frac{\partial f(L_{-ct}, h)}{\partial l_{ct}} \frac{\partial l_{ct}}{\partial S_t} - N\alpha_n \frac{\partial f(L_{-nt}, l_{nt})}{\partial l_{nt}} \frac{\partial l_{nt}}{\partial S_t} \right) \\ & - p\alpha_c \left(\frac{\partial f(L_{-ct}, h)}{\partial l_{ct}} \frac{\partial l_{ct}}{\partial S_t} + \frac{\partial f(L_{-nt}, l_{nt})}{\partial l_{nt}} \frac{\partial l_{nt}}{\partial S_t} \right) \end{aligned} \quad (\text{B.32})$$

The sign of $\frac{\partial^2 \max H}{\partial S_t^2} \leq 0$. This results in $\frac{\partial \mu_t}{\partial S_t} \mu_{t+1} - \mu_t = 0 \leq 0$.

Therefore, the S and μ isoclines are upward sloping and downward sloping, respectively, when we are in the region of the phase diagram where $l_{nt} > 0$ and $l_{ct} = h$.

In order to derive the equation of motion on each side of the isocline, we take the derivative of the transition equation with respect to stock as well as the derivative of the equation of motion for the user cost with respect to the user cost.

Taking the derivative of the stock with respect to the transition equation yields,

$$\frac{\partial(S_{t+1} - S_t)}{\partial S_t} = G'(S_t) - C\alpha_c f(L_{-ct}, h) - N\alpha_n \alpha_c f(L_{-nt}, l_{nt}) < 0. \quad (\text{B.33})$$

Therefore, $S_{t+1} - S_t < 0$ to the right of the S isocline and the change in stock is strictly positive to the left of the S isocline. Taking the derivative of the μ isoclines with respect to μ yields,

$$\frac{\partial(\mu_{t+1} - \mu_t)}{\partial \mu_t} = (1 - \delta) > 0. \quad (\text{B.34})$$

Therefore, $\mu_{t+1} - \mu_t > 0$ to the right of the μ isocline and the change in user cost is strictly negative to the left of the μ isocline.

Region 4. The representative community member fully specializes in the resource sector and votes to close it off to non-community members ($l_{nt} = 0, l_{ct} = h$).

Evaluating the steady state stock at the control constraints, we arrive at, $0 = G(S_t) - C\alpha_c S_t f((C-1)h, h)$. Thus, the S isocline is vertical in this region of the phase diagram.

The steady state equation representing the μ isocline is $0 = (1 - \delta)\mu_t - \delta(G'(S_t) - C\alpha_c f((C-1)h, h)) - p\alpha_c f((C-1)h, h)$. The resulting slope of the μ isocline is the following,

$$\frac{\partial \mu_t}{\partial S_t}_{\mu_{t+1} - \mu_t = 0} = \frac{\delta}{(1 - \delta)} \frac{\partial^2 G(S_t)}{\partial S_t^2}. \quad (\text{B.35})$$

Since, $\frac{\partial^2 G(S_t)}{\partial S_t^2} \leq 0$, we find $\frac{\partial \mu_t}{\partial S_t}_{\mu_{t+1} - \mu_t = 0} \leq 0$.

Therefore, the S and μ isoclines are vertical and downward sloping, respectively, when we are in the region of the phase diagram where the constraints in the control variables are both binding.

In order to derive the equation of motion on each side of the isocline, we take the derivative of the transition equation with respect to stock as well as the derivative of the equation of motion for the user cost with respect to the user cost.

Taking the derivative of the stock with respect to the transition equation yields,

$$\frac{\partial(S_{t+1} - S_t)}{\partial S_t} = G'(S_t) - C\alpha_c f(L_{-ct}, h) < 0. \quad (\text{B.36})$$

Therefore, $S_{t+1} - S_t < 0$ to the right of the S isocline and the change in stock is strictly positive to the left of the S isocline. Taking the derivative of the μ

isoclines with respect to μ yields,

$$\frac{\partial(\mu_{t+1} - \mu_t)}{\partial\mu_t} = (1 - \delta) > 0. \quad (\text{B.37})$$

Therefore, $\mu_{t+1} - \mu_t > 0$ to the right of the μ isocline and the change in user cost is strictly negative to the left of the μ isocline.

B.3 Characterizing the Steady State Solution

By inspection, the equilibrium is a saddle point in Region 4. But we can confirm it locally by linearizing the system around the steady state equilibrium. Recall that the steady state equation when $l_{nt} = 0$ and $l_{ct} = h$ can be written as,

$$\mu_{t+1} - \mu_t = (1 - \delta)\mu - \delta(G'(S) - C\alpha_c f((C-1)h, h) - p\alpha_c f((C-1)h, h)) = f(S, \mu); \quad (\text{B.38})$$

$$S_{t+1} - S_t = G(S) - C\alpha_c S f((C-1)h, h) = g(S, \mu). \quad (\text{B.39})$$

The first order approximation of the two equations above are,

$$f(S, \mu) = f(S^*, \mu^*) + f_S(S^*, \mu^*)(S - S^*) + f_\mu(S^*, \mu^*)(\mu - \mu^*); \quad (\text{B.40})$$

$$g(S, \mu) = g(S^*, \mu^*) + g_S(S^*, \mu^*)(S - S^*) + g_\mu(S^*, \mu^*)(\mu - \mu^*). \quad (\text{B.41})$$

Recall that $f(S^*, \mu^*) = g(S^*, \mu^*) = 0$. Furthermore, if we substitute for $f_S(S^*, \mu^*)$, $f_\mu(S^*, \mu^*)$, $g_S(S^*, \mu^*)$, and $g_\mu(S^*, \mu^*)$, we can write the system of equations in the following matrix formulation,

$$\begin{bmatrix} \mu_{t+1} - \mu_t \\ S_{t+1} - S_t \end{bmatrix} = \begin{bmatrix} (1 - \delta) & -\delta \frac{\partial^2 G(S)}{\partial S^2} \\ 0 & \frac{\partial G(S)}{\partial S} \end{bmatrix} \begin{bmatrix} \mu - \mu^* \\ S - S^* \end{bmatrix} \quad (\text{B.42})$$

The matrix $\begin{bmatrix} (1 - \delta) & -\delta \frac{\partial^2 G(S)}{\partial S^2} \\ 0 & \frac{\partial G(S)}{\partial S} \end{bmatrix}$ is called the Jacobian matrix. When the determinant of the Jacobian matrix is negative, the characteristics roots are opposite in sign, which implies that a saddlepoint exists. If we operate on the area beyond the maximum sustainable yield of the stock, we derive $\frac{\partial G(S_t)}{\partial S_t} < 0$. Thus, the determinant of the matrix is negative which means that this is a saddle path.

Appendix C

Deriving Effect of Change in Terms of Trade on Stock

C.1 Comparative Statics in Two-Period Model

In order to prove supermodularity, all the cross partial derivatives must be non-negative. Using the first order conditions from equations (2.8) to (2.11), we can derive the cross partial derivatives of the set $\{(-l_{c0}), l_{c1}, (-l_{n0}), (-l_{n1}); p_1\}$ on W_j . First, we take the cross partial derivatives with respect to $(-l_{c0})$,

$$\frac{\partial^2 W_j}{\partial l_{c1} \partial (-l_{c0})} = -p_1 \alpha_c \frac{\partial S_1}{\partial l_{c0}} \frac{\partial f(L_{-c1}, l_{c1})}{\partial l_{c1}} \delta \geq 0; \quad (\text{C.1})$$

since $\frac{\partial S_1}{\partial l_{c0}} \leq 0$ and $\frac{\partial f(L_{-c1}, l_{c1})}{\partial l_{c1}} \geq 0$, $\frac{\partial^2 W_j}{\partial l_{c1} \partial (-l_{c0})} \geq 0$.

$$\frac{\partial^2 W_j}{\partial (-l_{n0}) \partial (-l_{c0})} = -(p_0 - \mu_1 C) \alpha_c S_0 \frac{\partial^2 f(L_{-c0}, l_{c0})}{\partial l_{n0} \partial l_{c0}} + \mu_1 N \alpha_n S_0 \frac{\partial^2 f(L_{-c0}, l_{c0})}{\partial l_{c0} \partial l_{n0}} \geq 0; \quad (\text{C.2})$$

when $p \alpha_c - \mu_1 C (\alpha_c + \alpha_n) > 0$ and since $\frac{\partial^2 f(L_{-c0}, l_{c0})}{\partial l_{n0} \partial l_{c0}} \leq 0$, we find $\frac{\partial^2 W_j}{\partial (-l_{n0}) \partial (-l_{c0})} \geq 0$.

$$\frac{\partial^2 W_j}{\partial (-l_{n1}) \partial (-l_{c0})} = p_1 \alpha_c \frac{\partial S_1}{\partial l_{c0}} N \frac{\partial f(L_{-c1}, l_{c1})}{\partial l_{n1}} \delta \geq 0; \quad (\text{C.3})$$

since $\frac{\partial S_1}{\partial l_{c0}} \leq 0$ and $\frac{\partial f(L_{-c1}, l_{c1})}{\partial l_{n1}} \leq 0$, $\frac{\partial^2 W_j}{\partial(-l_{n1})\partial(-l_{c0})} \geq 0$.

$$\frac{\partial^2 W_j}{\partial p_1 \partial(-l_{c0})} = \alpha_c f(L_{-c1}, l_{c1}) \delta S_0 \left(C \alpha_c \frac{\partial f(L_{-c0}, l_{c0})}{\partial l_{c0}} + N \alpha_n \frac{\partial f(L_{-n0}, l_{n0})}{\partial l_{c0}} \right) \geq 0; \quad (\text{C.4})$$

since we have assumed that $\alpha_c \frac{\partial f(L_{-c0}, l_{c0})}{\partial l_{c0}} + \alpha_n \frac{\partial f(L_{-n0}, l_{n0})}{\partial l_{c0}} \geq 0$ along with $C=N$, then $\frac{\partial^2 W_j}{\partial p_1 \partial(-l_{c0})} \geq 0$.

Next, we take the cross partial derivatives with respect to l_{c1} ,

$$\frac{\partial^2 W_j}{\partial l_{c1} \partial(-l_{n0})} = p_1 \alpha_c \frac{\partial S_1}{\partial(-l_{n0})} \frac{\partial f(L_{-c1}, l_{c1})}{\partial l_{c1}} \delta \geq 0; \quad (\text{C.5})$$

since $\frac{\partial S_1}{\partial(-l_{n0})} \geq 0$ and $\frac{\partial f(L_{-c1}, l_{c1})}{\partial l_{c1}} \geq 0$, we find that $\frac{\partial^2 W_j}{\partial l_{c1} \partial(-l_{n0})} \geq 0$.

$$\frac{\partial^2 W_j}{\partial l_{c1} \partial(-l_{n1})} = -p_1 \alpha_c S_1 \frac{\partial^2 f(L_{-c1}, l_{c1})}{\partial l_{c1} \partial l_{n1}} \delta \geq 0; \quad (\text{C.6})$$

since we assume that $\frac{\partial^2 f(L_{-c1}, l_{c1})}{\partial l_{c1} \partial l_{n1}} \leq 0$, we find that $\frac{\partial^2 W_j}{\partial l_{c1} \partial(-l_{n1})} \geq 0$.

$$\frac{\partial^2 W_j}{\partial l_{c1} \partial p_1} = \alpha_c S_1 \frac{\partial f(L_{-c1}, l_{c1})}{\partial l_{c1}} \delta \geq 0; \quad (\text{C.7})$$

since we find that $\frac{\partial f(L_{-c1}, l_{c1})}{\partial l_{c1}} \geq 0$, $\frac{\partial^2 W_j}{\partial l_{c1} \partial p_1} \geq 0$.

Next, we take the cross partial derivatives with respect to $(-l_{n0})$,

$$\frac{\partial^2 W_j}{\partial(-l_{n0}) \partial(-l_{n1})} = -p_1 \alpha_c \frac{\partial S_1}{\partial l_{n0}} N \frac{\partial f(L_{-c1}, l_{c1})}{\partial(-l_{n1})} \delta \geq 0; \quad (\text{C.8})$$

since $\frac{\partial S_1}{\partial l_{n0}} \leq 0$, and $\frac{\partial f(L_{-c1}, l_{c1})}{\partial(-l_{n1})} \geq 0$, we derive $\frac{\partial^2 W_j}{\partial l_{c1} \partial p_1} \geq 0$.

$$\frac{\partial^2 W_j}{\partial(-l_{n0}) \partial p_1} = -\alpha_c f(L_{-c1}, l_{c1}) \delta S_0 \left(C \alpha_c \frac{\partial f(L_{-c0}, l_{c0})}{\partial(-l_{n0})} + N \alpha_n \frac{\partial f(L_{-n0}, l_{n0})}{\partial(-l_{n0})} \right) \geq 0; \quad (\text{C.9})$$

since we have assumed that $C=N$ and $\alpha_c \frac{\partial f(L_{-c0}, l_{c0})}{\partial l_{n0}} + \alpha_n \frac{\partial f(L_{-n0}, l_{n0})}{\partial l_{n0}} > 0$, $\frac{\partial^2 W_j}{\partial(-l_{n0})\partial p_1} \geq 0$.

Last, we take the cross partial derivative with respect to the remaining p_1 ,

$$\frac{\partial^2 W_j}{\partial p_1 \partial(-l_{n1})} = -\alpha_c S_1 N \frac{\partial f(L_{-c1}, l_{c1})}{\partial l_{n1}} \delta \geq 0 \quad (\text{C.10})$$

since $\frac{\partial f(L_{-c1}, l_{c1})}{\partial l_{n1}} \leq 0$, we derive $\frac{\partial^2 W_j}{\partial p_1 \partial(-l_{n1})} \geq 0$.

Thus, since the cross partial derivatives of the set $\{(-l_{c0}), l_{c1}, (-l_{n0}), (-l_{n1}); p_1\}$ are all non-negative, we derive the following comparative statics,

$$\frac{\partial l_{c0}}{\partial p_1} \leq 0; \frac{\partial l_{c1}}{\partial p_1} \geq 0; \frac{\partial l_{n0}}{\partial p_1} \leq 0 \text{ and } \frac{\partial l_{n1}}{\partial p_1} \leq 0.$$

C.2 Comparative Dynamics in Infinite Horizon Model

C.2.1 Deriving Shifts in Long Run Supply and Long Run Demand Curves

First, we derive the comparative statics for $\frac{\partial l_{nt}}{\partial p}$ and $\frac{\partial l_{ct}}{\partial p}$. Taking the derivative of (2.21) and (2.23) with respect to p , we derive

$$\frac{\partial^2 H}{\partial l_{ct} \partial p} = \alpha_c S_t \frac{\partial f(L_{-ct}, l_{ct})}{\partial l_{ct}} \geq 0; \quad (\text{C.11})$$

$$\frac{\partial^2 H}{\partial l_{nt} \partial p} = \alpha_c S_t \frac{\partial f(L_{-ct}, l_{ct})}{\partial l_{nt}} \leq 0. \quad (\text{C.12})$$

The comparative statics for can be derived using the following formulation,

$$\begin{bmatrix} \frac{\partial^2 H}{\partial l_{ct}^2} & \frac{\partial^2 H}{\partial l_{nt}\partial l_{ct}} \\ \frac{\partial H}{\partial l_{ct}\partial l_{nt}} & \frac{\partial^2 H}{\partial l_{nt}^2} \end{bmatrix} \begin{bmatrix} \frac{\partial l_{ct}}{\partial p} \\ \frac{\partial l_{nt}}{\partial p} \end{bmatrix} = \begin{bmatrix} \frac{\partial^2 H}{\partial l_{ct}\partial p} \\ \frac{\partial^2 H}{\partial l_{nt}\partial p} \end{bmatrix}.$$

Using Cramer's rule, we derive the following comparative statics,

$$\frac{\partial l_{ct}}{\partial p} = \frac{\frac{\partial^2 H}{\partial l_{ct}\partial p} \frac{\partial^2 H}{\partial l_{nt}^2} - \frac{\partial^2 H}{\partial l_{nt}\partial p} \frac{\partial^2 H}{\partial l_{nt}\partial l_{ct}}}{\det |H|} \quad (\text{C.13})$$

The sign of the numerator is not immediately known. However, substituting for the terms in the numerator yields,

$$\begin{aligned} \frac{\partial^2 H}{\partial l_{ct}\partial p} \frac{\partial^2 H}{\partial l_{nt}^2} - \frac{\partial^2 H}{\partial l_{nt}\partial p} \frac{\partial^2 H}{\partial l_{nt}\partial l_{ct}} &= (p - \delta\lambda_{t+1}C)\alpha_c S_t \left(\frac{\partial^2 f(L_{-ct}, l_{ct})}{\partial l_{nt}^2} \frac{\partial f(L_{-ct}, l_{ct})}{\partial l_{ct}} - \frac{\partial^2 f(L_{-ct}, l_{ct})}{\partial l_{nt}^2} \frac{\partial f(L_{-ct}, l_{ct})}{\partial l_{nt}} \right) \\ &- \delta\lambda_{t+1}N\alpha_n S_t \left(\frac{\partial^2 f(L_{-nt}, l_{nt})}{\partial^2 l_{nt}} \frac{\partial f(L_{-ct}, l_{ct})}{\partial l_{ct}} - \frac{\partial^2 f(L_{-nt}, l_{nt})}{\partial^2 l_{nt}} \frac{\partial f(L_{-ct}, l_{ct})}{\partial l_{nt}} \right) \geq 0. \end{aligned}$$

Here, $\frac{\partial^2 f(L_{-ct}, l_{ct})}{\partial l_{nt}^2} \frac{\partial f(L_{-ct}, l_{ct})}{\partial l_{ct}} - \frac{\partial^2 f(L_{-ct}, l_{ct})}{\partial l_{nt}^2} \frac{\partial f(L_{-ct}, l_{ct})}{\partial l_{nt}} > 0$ and $\frac{\partial^2 f(L_{-nt}, l_{nt})}{\partial^2 l_{nt}} \frac{\partial f(L_{-ct}, l_{ct})}{\partial l_{ct}} - \frac{\partial^2 f(L_{-nt}, l_{nt})}{\partial^2 l_{nt}} \frac{\partial f(L_{-ct}, l_{ct})}{\partial l_{nt}} < 0$ which implies that $\frac{\partial^2 H}{\partial l_{ct}\partial p} \frac{\partial^2 H}{\partial l_{nt}^2} - \frac{\partial^2 H}{\partial l_{nt}\partial p} \frac{\partial^2 H}{\partial l_{nt}\partial l_{ct}} \geq 0$. Thus, $\frac{\partial l_{ct}}{\partial p} \geq 0$.

From Cramer's Rule, we also find,

$$\frac{\partial l_{nt}}{\partial p} = \frac{\frac{\partial^2 H}{\partial l_{nt}\partial p} \frac{\partial^2 H}{\partial l_{ct}^2} - \frac{\partial^2 H}{\partial l_{ct}\partial p} \frac{\partial^2 H}{\partial l_{nt}\partial l_{ct}}}{\det |H|}. \quad (\text{C.14})$$

The sign of the numerator is not immediately known. However, substituting for the terms in the numerator yields,

$$\begin{aligned} \frac{\partial^2 H}{\partial l_{nt}\partial p} \frac{\partial^2 H}{\partial l_{ct}^2} - \frac{\partial^2 H}{\partial l_{ct}\partial p} \frac{\partial^2 H}{\partial l_{nt}\partial l_{ct}} &= (p - \delta\lambda_{t+1}C)\alpha_c S_t \left(\frac{\partial^2 f(L_{-ct}, l_{ct})}{\partial l_{ct}^2} \frac{\partial f(L_{-ct}, l_{ct})}{\partial l_{nt}} - \frac{\partial^2 f(L_{-ct}, l_{ct})}{\partial l_{ct}\partial l_{nt}} \frac{\partial f(L_{-ct}, l_{ct})}{\partial l_{ct}} \right) \\ &- \delta\lambda_{t+1}N\alpha_n S_t \left(\frac{\partial^2 f(L_{-nt}, l_{nt})}{\partial l_{ct}^2} \frac{\partial f(L_{-ct}, l_{ct})}{\partial l_{nt}} - \frac{\partial^2 f(L_{-nt}, l_{nt})}{\partial l_{ct}\partial l_{nt}} \frac{\partial f(L_{-ct}, l_{ct})}{\partial l_{ct}} \right) \\ &- \left(\frac{\partial^2 Y(K, L_{xt})}{\partial L_{xt}\partial l_{ct}} \frac{\partial f(L_{-ct}, l_{ct})}{\partial l_{nt}} - \frac{\partial^2 Y(K, L_{xt})}{\partial L_{xt}\partial l_{nt}} \frac{\partial f(L_{-ct}, l_{ct})}{\partial l_{ct}} \right) \end{aligned}$$

Thus, $\frac{\partial^2 H}{\partial l_{nt} \partial p} \frac{\partial^2 H}{\partial l_{ct}^2} - \frac{\partial^2 H}{\partial l_{ct} \partial p} \frac{\partial^2 H}{\partial l_{nt} \partial l_{ct}} > 0$ which implies that $\frac{\partial l_{nt}}{\partial p} \geq 0$.

Using the comparative statics, we can now derive the shifts in the S and u isoclines. First, we start with the shifts in the long run supply curve. Using the implicit function theorem on $0 = \frac{\partial \max H}{\partial \mu_t}$ to derive the change in marginal user cost with a price change,

$$\frac{\partial u_t}{\partial p} \Big|_{S_{t+1}-S_t=0} = \frac{-\frac{\partial^2 \max H}{\partial \mu_t \partial p}}{\frac{\partial^2 \max H}{\partial \mu_t^2}}; \quad (\text{C.15})$$

Recall that $\frac{\partial^2 \max H}{\partial \mu_t^2} \geq 0$. The sign of the $\frac{\partial u_t}{\partial p} \Big|_{S_{t+1}-S_t=0}$ depends upon $\frac{\partial^2 \max H}{\partial \mu_t \partial p}$. Here we find, $\frac{\partial^2 \max H}{\partial \mu_t \partial p} = -C\alpha_c S_t \left(\frac{\partial f(L_{-ct}, l_{ct})}{\partial l_{ct}} \frac{\partial l_{ct}}{\partial p} + \frac{\partial f(L_{-ct}, l_{ct})}{\partial l_{nt}} \frac{\partial l_{nt}}{\partial p} \right) - N\alpha_n S_t \left(\frac{\partial f(L_{-nt}, l_{nt})}{\partial l_{ct}} \frac{\partial l_{ct}}{\partial p} + \frac{\partial f(L_{-nt}, l_{nt})}{\partial l_{nt}} \frac{\partial l_{nt}}{\partial p} \right)$. This can be re-written as, $\frac{\partial^2 \max H}{\partial \mu_t \partial p} = -CS_t \left(\alpha_c \frac{\partial f(L_{-ct}, l_{ct})}{\partial l_{ct}} + \alpha_n \frac{\partial f(L_{-nt}, l_{nt})}{\partial l_{ct}} \right) \frac{\partial l_{ct}}{\partial p} - CS_t \left(\alpha_c \frac{\partial f(L_{-ct}, l_{ct})}{\partial l_{nt}} + \frac{\partial f(L_{-nt}, l_{nt})}{\partial l_{nt}} \alpha_n \right) \frac{\partial l_{nt}}{\partial p}$. Since we assumed that $\alpha_c \frac{\partial f(L_{-ct}, l_{ct})}{\partial l_{nt}} + \frac{\partial f(L_{-nt}, l_{nt})}{\partial l_{nt}} \alpha_n > 0$, and $\alpha_c \frac{\partial f(L_{-ct}, l_{ct})}{\partial l_{ct}} + \alpha_n \frac{\partial f(L_{-nt}, l_{nt})}{\partial l_{ct}} > 0$, we find $\frac{\partial^2 \max H}{\partial \mu_t \partial p} \leq 0$. Therefore, $\frac{\partial u_t}{\partial p} \Big|_{S_{t+1}-S_t=0} \geq 0$.

Using the implicit function theorem on $0 = \frac{\partial \max H}{\partial \mu_t}$ to derive the change in stock with a price change,

$$\frac{\partial S_t}{\partial p} \Big|_{S_{t+1}-S_t=0} = \frac{\frac{\partial^2 \max H}{\partial \mu_t \partial p}}{\frac{\partial^2 \max H}{\partial \mu_t \partial S_t}}.$$

Recall that $\frac{\partial^2 \max H}{\partial \mu_t \partial S_t} \leq 0$ and $\frac{\partial^2 \max H}{\partial \mu_t \partial p} \leq 0$, we derive $\frac{\partial S_t}{\partial p} \Big|_{S_{t+1}-S_t=0} \leq 0$.

Since $\frac{\partial u_t}{\partial p} \Big|_{S_{t+1}-S_t=0} \geq 0$ and $\frac{\partial S_t}{\partial p} \Big|_{S_{t+1}-S_t=0} \leq 0$, we find that the long run supply curve shifts up and to the left.

Utilizing the same procedure, we can show that the long-run demand curve shifts down to the left. Using the implicit function theorem on $0 = (1 - \delta)\mu_t - \delta \frac{\partial \max H}{\partial S_t}$, we can derive the effect of price on marginal user cost when $u_{t+1} - u_t = 0$,

$$\frac{\partial u_t}{\partial p}_{u_{t+1}-u_t=0} = \frac{\delta \frac{\partial^2 \max H}{\partial S_t \partial p}}{(1-\delta) - \delta \frac{\partial^2 \max H}{\partial \mu_t \partial S_t}};$$

Recall that $\frac{\partial^2 \max H}{\partial \mu_t \partial S_t} \leq 0$. Here, $\frac{\partial^2 \max H}{\partial S_t \partial p} = -\delta C \left(\alpha_c \frac{\partial f(L_{-ct}, l_{ct})}{\partial l_{ct}} \frac{\partial l_{ct}}{\partial p} + \alpha_n \frac{\partial f(L_{-ct}, l_{ct})}{\partial l_{nt}} \frac{\partial l_{nt}}{\partial p} \right) - p \alpha_c \left(\frac{\partial f(L_{-ct}, l_{ct})}{\partial l_{ct}} \frac{\partial l_{ct}}{\partial p} + \frac{\partial f(L_{-ct}, l_{ct})}{\partial l_{nt}} \frac{\partial l_{nt}}{\partial p} \right)$. Since, $\left| \frac{\partial f(L_{-ct}, l_{ct})}{\partial l_{ct}} \right| > \left| \frac{\partial f(L_{-ct}, l_{ct})}{\partial l_{nt}} \right|$ and $\alpha_c \frac{\partial f(L_{-ct}, l_{ct})}{\partial l_{ct}} + \alpha_n \frac{\partial f(L_{-ct}, l_{ct})}{\partial l_{nt}} > 0$, we find that $\frac{\partial^2 \max H}{\partial S_t \partial p} \leq 0$. Thus, $\frac{\partial u_t}{\partial p}_{u_{t+1}-u_t=0} \leq 0$.

Using the implicit function theorem on $0 = (1-\delta)\mu_t - \delta \frac{\partial \max H}{\partial S_t}$, we can derive the effect of price on the stock when $u_{t+1} - u_t = 0$,

$$\frac{\partial S_t}{\partial p}_{u_{t+1}-u_t=0} = \frac{\frac{\partial^2 \max H}{\partial S \partial p}}{\frac{\partial^2 \max H}{\partial S^2}}.$$

Recall that $\frac{\partial^2 \max H}{\partial S_t^2} \geq 0$ and $\frac{\partial^2 \max H}{\partial S_t \partial p} \leq 0$. Therefore, $\frac{\partial S_t}{\partial p}_{u_{t+1}-u_t=0} \leq 0$.

Since $\frac{\partial u_t}{\partial p}_{u_{t+1}-u_t=0} \leq 0$ and $\frac{\partial S_t}{\partial p}_{u_{t+1}-u_t=0} \leq 0$, we find that the long run demand curve shifts down and to the left.

C.2.2 Deriving the Change in Long-Run Equilibrium Stock and Marginal User Cost

In order to obtain the change in the steady state values given a change in price, we simultaneously solve for the impact of price using (2.28) and (2.29). The μ isocline is derived from $(1-\delta)\mu_t - \delta \frac{\partial \max H}{\partial S_t} = 0$. Totally differentiating with respect to price yields,

$$(1-\delta) \frac{d\mu^{eq}}{dp} - \delta \left(\frac{\partial^2 \max H}{\partial S_t \partial \mu_t} \frac{d\mu^{eq}}{dp} + \frac{\partial^2 \max H}{\partial S_t^2} \frac{dS^{eq}}{dp} + \frac{\partial^2 \max H}{\partial S_t \partial p} \right) = 0. \quad (\text{C.16})$$

The S isocline is derived from $\frac{\partial \max H}{\partial \mu_t} = 0$. Totally differentiating with respect to price yields,

$$\frac{\partial^2 \max H}{\partial \mu_t^2} \frac{d\mu^{eq}}{dp} + \frac{\partial^2 \max H}{\partial \mu_t \partial S_t} \frac{dS^{eq}}{dp} + \frac{\partial^2 \max H}{\partial \mu_t \partial p} = 0 \quad (\text{C.17})$$

We can re-write (C.16) and (C.17) in matrix form,

$$\begin{bmatrix} -\frac{\partial^2 \max H}{\partial S_t^2} & (1 - \delta) - \delta \frac{\partial^2 \max H}{\partial S_t \partial \mu_t} \\ \frac{\partial^2 \max H}{\partial \mu_t \partial S_t} & \frac{\partial^2 \max H}{\partial \mu_t^2} \end{bmatrix} \begin{bmatrix} \frac{dS^{eq}}{dp} \\ \frac{d\mu^{eq}}{dp} \end{bmatrix} = \begin{bmatrix} \delta \frac{\partial^2 \max H}{\partial S_t \partial p} \\ -\frac{\partial^2 \max H}{\partial \mu_t \partial p} \end{bmatrix}.$$

The effect of price on the steady state stock and steady state marginal user cost can be derived using Cramer's Rule,

$$\frac{dS^{eq}}{dp} = \frac{1}{\Delta} \left(\delta \frac{\partial^2 \max H}{\partial \mu_t^2} \frac{\partial^2 \max H}{\partial S_t \partial p} + \left((1 - \delta) - \delta \frac{\partial^2 \max H}{\partial \mu_t \partial S_t} \right) \frac{\partial^2 \max H}{\partial \mu_t \partial p} \right) \leq 0; \quad (\text{C.18})$$

where $\Delta = -\frac{\partial^2 \max H}{\partial \mu_t^2} \frac{\partial^2 \max H}{\partial S_t^2} - \left((1 - \delta) - \delta \frac{\partial^2 \max H}{\partial \mu_t \partial S_t} \right) \frac{\partial^2 \max H}{\partial \mu_t \partial S_t}$. Here, recall that $\frac{\partial^2 \max H}{\partial \mu_t^2} \geq 0$, $\frac{\partial^2 \max H}{\partial S_t \partial p} \leq 0$, $\frac{\partial^2 \max H}{\partial \mu_t \partial S} \leq 0$, and $\frac{\partial^2 \max H}{\partial \mu_t \partial p} \leq 0$. Since, $\Delta \geq 0$. Consequently, $\frac{dS^{eq}}{dp} \leq 0$.

The effect of price on the steady state marginal user cost is as follows,

$$\frac{d\mu^{eq}}{dp} = \frac{1}{\Delta} \left(\frac{\partial^2 \max H}{\partial \mu_t \partial p} \frac{\partial^2 \max H}{\partial S_t^2} - \delta \frac{\partial^2 \max H}{\partial \mu_t \partial S_t} \frac{\partial^2 \max H}{\partial S_t \partial p} \right) \leq 0;$$

However, since $\frac{\partial^2 \max H}{\partial \mu_t \partial p} \frac{\partial^2 \max H}{\partial S_t^2} > 0$ and $\frac{\partial^2 \max H}{\partial \mu_t \partial S_t} \frac{\partial^2 \max H}{\partial S_t \partial p} > 0$, we cannot determine the overall effect of price on the steady state marginal user cost. Thus,

$$\frac{d\mu^{eq}}{dp} \leq 0.$$

Appendix D

Phase Diagram Derivation with Endogenous Tariffs

In order to derive the phase diagram in the infinite horizon model with endogenous tariffs, we follow the same procedure as in Appendix B. We obtain the comparative statics needed to derive the isoclines in the regions of the phase diagram. Then, we characterize the steady state equilibrium point.

The signs from the Hessian matrix of the Lagrangean remains the same as in Appendix B. To show this, we derive the effect of l_{ct} and l_{nt} on p^* , where $p^* = \frac{a(q_K - q_S)(p_{S,t}^d)^2}{a(q_K - q_S)p_{S,t}^d p_{K,t}^d + Y_x(K, L_{xt})}$. Here,

$$\frac{\partial p^*}{\partial l_{ct}} = -\frac{a(q_S - q_K)(p_{S,t}^d)^2}{(a(q_S - q_K)p_{S,t}^d p_{K,t}^d + Y_x(K, L_{xt}))^2} \frac{\partial Y(K, L_{xt})}{\partial l_{ct}} \geq 0 \quad (\text{D.1})$$

$$\frac{\partial p^*}{\partial l_{nt}} = -\frac{a(q_S - q_K)(p_{S,t}^d)^2}{(a(q_S - q_K)p_{S,t}^d p_{K,t}^d + Y_x(K, L_{xt}))^2} \frac{\partial Y(K, L_{xt})}{\partial l_{nt}} \geq 0. \quad (\text{D.2})$$

We find that $\frac{\partial p^*}{\partial l_{ct}} \geq 0$ and $\frac{\partial p^*}{\partial l_{nt}} \geq 0$ since $\frac{\partial Y(K, L_{xt})}{\partial l_{nt}} \leq 0$ and $\frac{\partial Y(K, L_{xt})}{\partial l_{ct}} \leq 0$.

Taking the second derivative with respect to (4.21) and (4.22) yields,

$$\begin{aligned}\frac{\partial^2 \mathcal{L}}{\partial l_{ct}^2} &= (p^* - \delta\lambda_{t+1}C)\alpha_c S_t \frac{\partial^2 f(L_{-ct}, l_{ct})}{\partial l_{ct}^2} + \frac{\partial p^*}{\partial l_{ct}} \alpha_c S_t \frac{\partial f(L_{-ct}, l_{ct})}{\partial l_{ct}} \\ &\quad - \delta\lambda_{t+1}N\alpha_n S_t \frac{\partial^2 f(L_{-nt}, l_{nt})}{\partial l_{ct}^2} - \frac{\partial^2 Y(K, L_{xt})}{\partial L_{xt} \partial l_{ct}}\end{aligned}\quad (\text{D.3})$$

$$\begin{aligned}\frac{\partial^2 \mathcal{L}}{\partial l_{nt}^2} &= (p^* - \delta\lambda_{t+1}C)\alpha_c S_t \frac{\partial^2 f(L_{-ct}, l_{ct})}{\partial l_{nt}^2} + \frac{\partial p^*}{\partial l_{nt}} \alpha_c S_t \frac{\partial f(L_{-ct}, l_{ct})}{\partial l_{nt}} \\ &\quad - \delta\lambda_{t+1}N\alpha_n S_t \frac{\partial^2 f(L_{-nt}, l_{nt})}{\partial l_{nt}^2};\end{aligned}\quad (\text{D.4})$$

$$\begin{aligned}\frac{\partial^2 \mathcal{L}}{\partial l_{ct} \partial l_{nt}} &= (p^* - \delta\lambda_{t+1}C)\alpha_c S_t \frac{\partial^2 f(L_{-ct}, l_{ct})}{\partial l_{ct} \partial l_{nt}} + \frac{\partial p^*}{\partial l_{nt}} \alpha_c S_t \frac{\partial f(L_{-ct}, l_{ct})}{\partial l_{ct}} \\ &\quad - \delta\lambda_{t+1}N\alpha_n S_t \frac{\partial^2 f(L_{-nt}, l_{nt})}{\partial l_{ct} \partial l_{nt}} - \frac{\partial^2 Y(K, L_{xt})}{\partial L_{xt} \partial l_{nt}};\end{aligned}\quad (\text{D.5})$$

$$\begin{aligned}\frac{\partial^2 \mathcal{L}}{\partial l_{nt} \partial l_{ct}} &= (p^* - \delta\lambda_{t+1}C)\alpha_c S_t \frac{\partial f(L_{-ct}, l_{ct})}{\partial l_{nt} \partial l_{ct}} + \frac{\partial p^*}{\partial l_{ct}} \alpha_c S_t \frac{\partial f(L_{-ct}, l_{ct})}{\partial l_{ct}} \\ &\quad - \delta\lambda_{t+1}N\alpha_n S_t \frac{\partial f(L_{-nt}, l_{nt})}{\partial l_{nt} \partial l_{ct}}\end{aligned}\quad (\text{D.6})$$

The addition of $\frac{\partial p^*}{\partial l_{ct}}$ and $\frac{\partial p^*}{\partial l_{nt}}$ does not change the sign of the second order conditions, $\frac{\partial^2 \mathcal{L}}{\partial l_{ct}^2} \leq 0$, $\frac{\partial^2 \mathcal{L}}{\partial l_{nt}^2} \leq 0$, $\frac{\partial^2 \mathcal{L}}{\partial l_{ct} \partial l_{nt}} \geq 0$ and $\frac{\partial^2 \mathcal{L}}{\partial l_{nt} \partial l_{ct}} \geq 0$.

The sign of the cross partial derivatives with respect to S_t and μ_t also do not change,

$$\frac{\partial^2 \mathcal{L}}{\partial l_{ct} \partial S_t} = (p^* - \delta\lambda_{t+1}C)\alpha_c \frac{\partial f(L_{-ct}, l_{ct})}{\partial l_{ct}} + \frac{\partial p^*}{\partial l_{ct}} \alpha_c \frac{\partial f(L_{-ct}, l_{ct})}{\partial l_{ct}} - \delta\lambda_{t+1}N\alpha_n \frac{\partial f(L_{-nt}, l_{nt})}{\partial l_{ct}} \leq 0;\quad (\text{D.7})$$

$$\frac{\partial^2 \mathcal{L}}{\partial l_{nt} \partial S_t} = (p - \delta \lambda_{t+1} C) \alpha_c \frac{\partial f(L_{-ct}, l_{ct})}{\partial l_{nt}} + \frac{\partial p^*}{\partial l_{nt}} \alpha_c \frac{\partial f(L_{-ct}, l_{ct})}{\partial l_{nt}} - \delta \lambda_{t+1} N \alpha_n \frac{\partial f(L_{-nt}, l_{nt})}{\partial l_{nt}} \leq 0; \quad (\text{D.8})$$

$$\frac{\partial^2 \mathcal{L}}{\partial l_{ct} \partial \mu_t} = C \alpha_c S_t \frac{\partial f(L_{-ct}, l_{ct})}{\partial l_{ct}} + N \alpha_n S_t \frac{\partial f(L_{-nt}, l_{nt})}{\partial l_{ct}} \geq 0; \quad (\text{D.9})$$

$$\frac{\partial^2 \mathcal{L}}{\partial l_{nt} \partial \mu_t} = C \alpha_c S_t \frac{\partial f(L_{-ct}, l_{ct})}{\partial l_{nt}} + N \alpha_n S_t \frac{\partial f(L_{-nt}, l_{nt})}{\partial l_{nt}} \geq 0. \quad (\text{D.10})$$

The comparative statics for S_t can be derived using the following formulation,

$$\begin{bmatrix} \frac{\partial^2 \mathcal{L}}{\partial l_{ct}^2} & \frac{\partial^2 \mathcal{L}}{\partial l_{nt} \partial l_{ct}} \\ \frac{\partial \mathcal{L}}{\partial l_{ct} \partial l_{nt}} & \frac{\partial^2 \mathcal{L}}{\partial l_{nt}^2} \end{bmatrix} \begin{bmatrix} \frac{\partial l_{ct}}{\partial S_t} \\ \frac{\partial l_{nt}}{\partial S_t} \end{bmatrix} = \begin{bmatrix} \frac{\partial^2 \mathcal{L}}{\partial l_{ct} \partial S_t} \\ \frac{\partial^2 \mathcal{L}}{\partial l_{nt} \partial S_t} \end{bmatrix}.$$

Using Cramer's rule, we derive the following comparative statics,

$$\frac{\partial l_{ct}}{\partial S_t} = \frac{\frac{\partial^2 \mathcal{L}}{\partial l_{ct} \partial S_t} \frac{\partial^2 \mathcal{L}}{\partial l_{nt}^2} - \frac{\partial^2 \mathcal{L}}{\partial l_{nt} \partial S_t} \frac{\partial^2 \mathcal{L}}{\partial l_{nt} \partial l_{ct}}}{\det |H|} \geq 0 \quad (\text{D.11})$$

$$\frac{\partial l_{nt}}{\partial S_t} = \frac{\frac{\partial^2 \mathcal{L}}{\partial l_{nt} \partial S_t} \frac{\partial^2 \mathcal{L}}{\partial l_{ct}^2} - \frac{\partial^2 \mathcal{L}}{\partial l_{ct} \partial S_t} \frac{\partial^2 \mathcal{L}}{\partial l_{ct} \partial l_{nt}}}{\det |H|} \geq 0. \quad (\text{D.12})$$

The comparative statics for μ_t can be derived using the following formulation,

$$\begin{bmatrix} \frac{\partial^2 \mathcal{L}}{\partial l_{ct}^2} & \frac{\partial^2 \mathcal{L}}{\partial l_{nt} \partial l_{ct}} \\ \frac{\partial \mathcal{L}}{\partial l_{ct} \partial l_{nt}} & \frac{\partial^2 \mathcal{L}}{\partial l_{nt}^2} \end{bmatrix} \begin{bmatrix} \frac{\partial l_{ct}}{\partial \mu_t} \\ \frac{\partial l_{nt}}{\partial \mu_t} \end{bmatrix} = \begin{bmatrix} \frac{\partial^2 \mathcal{L}}{\partial l_{ct} \partial \mu_t} \\ \frac{\partial^2 \mathcal{L}}{\partial l_{nt} \partial \mu_t} \end{bmatrix}.$$

Using Cramer's rule, we derive the following comparative statics,

$$\frac{\partial l_{ct}}{\partial \mu_t} = \frac{\frac{\partial^2 \mathcal{L}}{\partial l_{ct} \partial \mu_t} \frac{\partial^2 \mathcal{L}}{\partial l_{nt}^2} - \frac{\partial^2 \mathcal{L}}{\partial l_{nt} \partial \mu_t} \frac{\partial^2 \mathcal{L}}{\partial l_{nt} \partial l_{ct}}}{\det |H|} \leq 0 \quad (\text{D.13})$$

$$\frac{\partial l_{nt}}{\partial \mu_t} = \frac{\frac{\partial^2 \mathcal{L}}{\partial l_{nt} \partial \mu_t} \frac{\partial^2 \mathcal{L}}{\partial l_{ct}^2} - \frac{\partial^2 \mathcal{L}}{\partial l_{ct} \partial \mu_t} \frac{\partial^2 \mathcal{L}}{\partial l_{ct} \partial l_{nt}}}{\det |H|} \leq 0. \quad (\text{D.14})$$

Using the comparative statics showing the relationship between the marginal user cost and stock on labor allocation choices, we derive the isoclines in each region of the phase space.

Region 1. An interior solution exists for both controls ($l_{nt} > 0$, $l_{ct} < h$).

The isoclines for S_t and μ_t can be derived using the following equations, $0 = \frac{\partial \max H}{\partial \mu_t}$ and $0 = (1 - \delta)\mu_t - \delta \frac{\partial \max H}{\partial S_t}$, respectively. Using the implicit function theorem, we can derive the slopes of the S isocline and μ isocline. The slope of the S isocline is the following,

$$\frac{\partial \mu_t}{\partial S_t}_{S_{t+1}-S_t=0} = - \frac{\frac{\partial^2 \max H}{\partial \mu_t \partial S_t}}{\frac{\partial^2 \max H}{\partial \mu_t^2}}. \quad (\text{D.15})$$

Here,

$$\begin{aligned} \frac{\partial^2 \max H}{\partial \mu_t \partial S_t} &= \frac{\partial G(S_t)}{\partial S_t} - C\alpha_c \left(f(L_{-ct}, l_{ct}) + S_t \frac{\partial f(L_{-ct}, l_{ct})}{\partial l_{ct}} \frac{\partial l_{ct}}{\partial S_t} + S_t \frac{\partial f(L_{-ct}, l_{ct})}{\partial l_{nt}} \frac{\partial l_{nt}}{\partial S_t} \right) \\ &\quad - N\alpha_n \left(f(L_{-nt}, l_{nt}) + S_t \frac{\partial f(L_{-nt}, l_{nt})}{\partial l_{ct}} \frac{\partial l_{ct}}{\partial S_t} + S_t \frac{\partial f(L_{-nt}, l_{nt})}{\partial l_{nt}} \frac{\partial l_{nt}}{\partial S_t} \right) \end{aligned} \quad (\text{D.16})$$

$$\begin{aligned} \frac{\partial^2 \max H}{\partial \mu_t^2} &= -C\alpha_c S_t \left(\frac{\partial f(L_{-ct}, l_{ct})}{\partial l_{ct}} \frac{\partial l_{ct}}{\partial \mu_t} + \frac{\partial f(L_{-ct}, l_{ct})}{\partial l_{nt}} \frac{\partial l_{nt}}{\partial \mu_t} \right) \\ &\quad - N\alpha_n S_t \left(\frac{\partial f(L_{-nt}, l_{nt})}{\partial l_{ct}} \frac{\partial l_{ct}}{\partial \mu_t} + \frac{\partial f(L_{-nt}, l_{nt})}{\partial l_{nt}} \frac{\partial l_{nt}}{\partial \mu_t} \right) \end{aligned} \quad (\text{D.17})$$

Since the endogenous tariff rate does not change the comparative statics for $\frac{\partial l_{nt}}{\partial S_t}$, $\frac{\partial l_{ct}}{\partial S_t}$, $\frac{\partial l_{ct}}{\partial \mu_t}$ and $\frac{\partial l_{nt}}{\partial \mu_t}$, we derive the same sign as in Appendix B. Thus,

$$\frac{\partial \mu_t}{\partial S_t}_{S_{t+1}-S_t=0} \geq 0.$$

The slope of the μ isocline is the following,

$$\frac{\partial \mu_t}{\partial S_t \mu_{t+1} - \mu_t = 0} = \frac{\delta \frac{\partial^2 \max H}{\partial S_t^2}}{(1 - \delta) - \frac{\partial^2 \max H}{\partial S_t \partial \mu_t}}. \quad (\text{D.18})$$

Here,

$$\begin{aligned} \frac{\partial^2 \max H}{\partial S_t^2} = & \delta \left(\frac{\partial^2 G(S_t)}{\partial S_t^2} - C\alpha_c \frac{\partial f(L_{-ct}, l_{ct})}{\partial l_{ct}} \frac{\partial l_{ct}}{\partial S_t} - N\alpha_n \frac{\partial f(L_{-nt}, l_{nt})}{\partial l_{nt}} \frac{\partial l_{nt}}{\partial S_t} \right) \\ & - p\alpha_c \left(\frac{\partial f(L_{-ct}, l_{ct})}{\partial l_{ct}} \frac{\partial l_{ct}}{\partial S_t} + \frac{\partial f(L_{-nt}, l_{nt})}{\partial l_{nt}} \frac{\partial l_{nt}}{\partial S_t} \right) \end{aligned} \quad (\text{D.19})$$

Similar to Appendix B, we find that $\frac{\partial \mu_t}{\partial S_t \mu_{t+1} - \mu_t = 0} \leq 0$.

Therefore, the S and μ isoclines are upward sloping and downward sloping, respectively, when we are in the region of the phase diagram where interior solutions exist for both control variables.

In order to derive the equation of motion on each side of the isocline, we take the derivative of the transition equation with respect to stock as well as the derivative of the equation of motion for the user cost with respect to the user cost.

Taking the derivative of the stock with respect to the transition equation yields,

$$\frac{\partial(S_{t+1} - S_t)}{\partial S_t} = G'(S_t) - C\alpha_c f(L_{-ct}, l_{ct}) - N\alpha_n \alpha_c f(L_{-nt}, l_{nt}) < 0. \quad (\text{D.20})$$

Therefore, $S_{t+1} - S_t < 0$ to the right of the S isocline and the change in stock is strictly positive to the left of the S isocline. Taking the derivative of the μ isoclines with respect to μ yields,

$$\frac{\partial(\mu_{t+1} - \mu_t)}{\partial \mu_t} = (1 - \delta) > 0. \quad (\text{D.21})$$

Therefore, $\mu_{t+1} - \mu_t > 0$ to the right of the μ isocline and the change in user cost is strictly negative to the left of the μ isocline.

Region 2. An interior solution exists for own labor and the resource sector is fully closed ($l_{nt} = 0, l_{ct} < h$).

The isoclines for S_t and μ_t can be derived using the same equations earlier, $0 = \frac{\partial \max H}{\partial \mu_t}$ and $0 = (1 - \delta)\mu_t - \delta \frac{\partial \max H}{\partial S_t}$, respectively, but now evaluated at $l_{nt} = 0$. Using the implicit function theorem, we can derive the slopes of the S isocline and μ isocline. The slope of the S isocline is the following,

$$\frac{\partial \mu_t}{\partial S_t}_{S_{t+1}-S_t=0} = - \frac{\frac{\partial^2 \max H}{\partial \mu_t \partial S_t}}{\frac{\partial^2 \max H}{\partial \mu_t^2}}. \quad (\text{D.22})$$

Here,

$$\begin{aligned} \frac{\partial^2 \max H}{\partial \mu_t \partial S_t} &= \frac{\partial G(S_t)}{\partial S_t} - C\alpha_c \left(f(L_{-ct}, l_{ct}) + S_t \frac{\partial f(L_{-ct}, l_{ct})}{\partial l_{ct}} \frac{\partial l_{ct}}{\partial S_t} + S_t \frac{\partial f(L_{-ct}, 0)}{\partial l_{nt}} \frac{\partial l_{nt}}{\partial S_t} \right) \\ &\quad - N\alpha_n \left(S_t \frac{\partial f(L_{-nt}, 0)}{\partial l_{ct}} \frac{\partial l_{ct}}{\partial S_t} + S_t \frac{\partial f(L_{-nt}, 0)}{\partial l_{nt}} \frac{\partial l_{nt}}{\partial S_t} \right) \end{aligned} \quad (\text{D.23})$$

$$\begin{aligned} \frac{\partial^2 \max H}{\partial \mu_t^2} &= -C\alpha_c S_t - C\alpha_c S_t \left(\frac{\partial f(L_{-ct}, l_{ct})}{\partial l_{ct}} \frac{\partial l_{ct}}{\partial \mu_t} + \frac{\partial f(L_{-ct}, l_{ct})}{\partial l_{nt}} \frac{\partial l_{nt}}{\partial \mu_t} \right) \\ &\quad - N\alpha_n S_t \left(\frac{\partial f(L_{-nt}, 0)}{\partial l_{ct}} \frac{\partial l_{ct}}{\partial \mu_t} + \frac{\partial f(L_{-nt}, 0)}{\partial l_{nt}} \frac{\partial l_{nt}}{\partial \mu_t} \right) \end{aligned} \quad (\text{D.24})$$

As in Appendix B, we find $\frac{\partial \mu_t}{\partial S_t}_{S_{t+1}-S_t=0} \geq 0$.

The slope of the μ isocline is the following,

$$\frac{\partial \mu_t}{\partial S_t}_{\mu_{t+1}-\mu_t=0} = \frac{\delta \frac{\partial^2 \max H}{\partial S_t^2}}{(1 - \delta) - \frac{\partial^2 \max H}{\partial S_t \partial \mu_t}}. \quad (\text{D.25})$$

Here,

$$\begin{aligned} \frac{\partial^2 \max H}{\partial S_t^2} &= \delta \left(\frac{\partial^2 G(S_t)}{\partial S_t^2} - C\alpha_c \frac{\partial f(L_{-ct}, l_{ct})}{\partial l_{ct}} \frac{\partial l_{ct}}{\partial S_t} - N\alpha_n \frac{\partial f(L_{-nt}, 0)}{\partial l_{nt}} \frac{\partial l_{nt}}{\partial S_t} \right) \\ &\quad - p\alpha_c \left(\frac{\partial f(L_{-ct}, l_{ct})}{\partial l_{ct}} \frac{\partial l_{ct}}{\partial S_t} + \frac{\partial f(L_{-nt}, 0)}{\partial l_{nt}} \frac{\partial l_{nt}}{\partial S_t} \right) \end{aligned} \quad (\text{D.26})$$

The sign of $\frac{\partial^2 \max H}{\partial S_t^2} \leq 0$. This results in $\frac{\partial \mu_t}{\partial S_t} \mu_{t+1} - \mu_t \leq 0$.

Therefore, the S and μ isoclines are upward sloping and downward sloping, respectively, when we are in the region of the phase diagram where $l_{nt} = 0$ and $l_{ct} < h$.

Taking the derivative of the stock with respect to the transition equation yields,

$$\frac{\partial(S_{t+1} - S_t)}{\partial S_t} = G'(S_t) - C\alpha_c f(L_{-ct}, l_{ct}) < 0. \quad (\text{D.27})$$

Therefore, $S_{t+1} - S_t < 0$ to the right of the S isocline and the change in stock is strictly positive to the left of the S isocline. Taking the derivative of the μ isoclines with respect to μ yields,

$$\frac{\partial(\mu_{t+1} - \mu_t)}{\partial \mu_t} = (1 - \delta) > 0. \quad (\text{D.28})$$

Therefore, $\mu_{t+1} - \mu_t > 0$ to the right of the μ isocline and the change in user cost is strictly negative to the left of the μ isocline.

Appendix E

Laboratory Experiment

E.1 Sample Instruction Sheet

ID _____ Session name _____

Your ID and Session names are provided above. If you are accidentally logged off the main experiment, raise your hand and someone will come to you. Please Note: DO NOT CLOSE YOUR INTERNET EXPLORER FOR THE MAIN EXPERIMENT. Also, DO NOT click the “Back” button on the browser unless instructed to do so and refrain from clicking “next” on the screen multiple times.

Earnings:

By just appearing today, you will receive a \$5 show up fee. More money can be earned by accumulating “computer dollars” during the experiment. The more computer dollars you make during the experiment, the more real dollars you receive. One real dollar is equivalent to 26 computer dollars. You may also earn more money during the post survey questionnaire. If you follow all instructions carefully and make good decisions, you may earn a considerable amount of money which will be paid to you in cash at the end of the experiment. Please note: your earnings may suffer if you proceed in the experiment without understanding the

instructions!

Grouping:

You have been randomly assigned into one of the six-person clusters. There are two distinct groups in each cluster: group 1 and group 2. Five individuals are in group 1 and the remaining person is the sole representative of group 2. Throughout the duration of the experiment, you will stay in these groups. Any decision made by the representative from group 2 will be weighted 5 times more. This will be fully explained later on. For this experiment, you are a group ____ member.

Sequence of choices:

Please look at the projector screen in front of you to see the sequence of choices. There are two sets in the experiment with each set lasting a total of 10 rounds. In each round, group 1 members will act first. Every individual is endowed with 10 labor hours during each round, which can be allocated to market 1 or market 2. Only values up to 1 decimal point between 0 and 10 are allowed (for example 5.2 is allowed but not 5.25). Group 1 members will place in the box the number of labor hours to allocate in market 1. The remaining labor hours will be allocated into market 2. Each group 1 member will also vote on how much group 2 labor hours they allow in market 1. Next, the group 2 representative will choose how many labor units to allocate in market 1 given the maximum allowed by group 1. The remaining labor hours not in market 1 will be allocated in market 2. The wage, voting outcome, labor allotment in each market and total earnings for that round will be posted, after which, a new round will begin again. Each round will last a maximum of 2 minutes: 1 minutes for group 1 decisions and 1 minute for group 2 decisions.

Decisions and Scenario in Market 1:

If you allocate labor hours in market 1, you are engaged in collecting a stock. Your earnings in market 1 are equal to your labor hours (LH) as a fraction of total labor (TL) hours in market 1 multiplied by your efficiency parameter (E), the price of the stock (P) and total stock collected (SC),

$$\text{Earnings from market 1} = \text{SC} \times (\text{LH} / \text{TL}) \times (\text{E}) \times (\text{P}).$$

The efficiency parameter (E) is a number reflecting how well you collect the stock relative to other individuals. The larger the parameter, the more you can earn in market 1. In the first 10 rounds of the experiment, all group 1 members have different efficiency parameters. You will know the ranking of efficiency parameters within your cluster based on the login name shown in the messenger program. The ranking of the efficiency parameter of the group 1 members in your cluster from highest to lowest are: Highest (1) cluster _____; (2) cluster _____; (3) cluster _____; (4) cluster _____; and (5) cluster _____ Lowest. You are ranked _____. The efficiency parameter of all group 1 members is larger than the efficiency parameter of the group 2 representative. It is important to note that the person in group 2 represents 5 people. So, 1 unit of labor hour by the representative from group 2 in market 1 is equivalent to 5 units of labor hours. Total stock collected (SC) depends on total labor (TL) in market 1 as well as the current stock (CS). The amount of stock will grow over time. If there is more current stock (CS) available, you can collect more of it and earn more money. The stock in the next round (SN) is equal to the growth of the stock (GS) plus the current stock (CS) minus total collection of all members in the cluster (CC), *i.e.* $SN = GS + CS - CC$. In the first round of the set, stock is equal to 10 but the maximum stock can potentially grow to 80 over several rounds. Allowing the

		Stock				
		10	30	45	60	80
5 labor hours	5.00 currency dollars	14.99 currency dollars	22.48 currency dollars	29.97 currency dollars	39.96 currency dollars	

stock to grow can impact your earnings significantly. For example, if everyone in your cluster allocates 5 units of labor hours when the stock is 10, everyone earns approximately 5 currency dollars. But if the stock reaches 80 and everyone puts in 5 units of labor hours, everyone earns 40 currency dollars (see Table 1 for estimated earnings at different stock levels)! In order to make the stock grow faster, less stock needs to be collected in the current round. Collection of all members in the cluster (CC) is equal to the sum of collection of each individual member in the cluster. Individuals with larger efficiency parameters will decrease more the available stock in the next round. In summary, your earnings will depend on the fraction of your labor relative to total labor, stock, price and an efficiency parameter. The larger these factors, the larger your earnings in market 1. You can only control your own labor and stock. The available stock in the next round depends on the growth of the stock, current stock and total collected stock from all members.

If you are a group 1 member, you will also vote to determine the maximum labor hours you allow the person from group 2 to allocate in market 1. Group 1 members will first vote on either fully closing the stock or keep it open to the group 2 representative. If majority prefer to close the stock, group 2 members will not be allowed to allocate any labor hours in market 1. All labor hours of group 2 members will immediately go to market 2. If majority in your cluster prefer to keep the stock open, a secondary voting question will be tallied. In the

secondary voting question, you will be given a choice from 1 to 10. You will vote on the average labor hours of each group 2 member you allow in market 1. The majority choice will be carried through. If the majority is in favor of an average of 5 labor hours allowed in market 1, the group 2 representative can allocate less than or equal to 5 labor hours in market 1. If a tie occurs, the average of the top choices will be taken. Again, 1 unit of labor hour in market 1 is equivalent to 5 labor hours for the group 2 representative. Note that even if you vote to fully close the stock, it is still important to vote on the second question. If the group votes to keep the stock open but you prefer to close it, your vote in the second question will still be tallied!

Decisions and Scenario in market 2:

Earnings in market 2 are equal to the wage multiplied by the remaining amount of labor hours not allocated into market 1, *i.e.*

$$\text{Earnings in market 2} = \text{wage} \times (10 - \text{labor hours in market 1})$$

The wage is determined by how many labor hours are allocated in market 2. If more participants devote labor hours into market 2, wage decreases. Thus, wage may vary in each round. The range of wage is from 0.25 to 6.75 currency dollars per labor hour, with a mean of 3.5. If everyone in your cluster devoted all their labor hours in market 2, each individual would earn 0.25×10 labor hours = 2.50 computer dollars for that particular round. If everyone in the cluster allocates 5 labor hours in market 2, each individual earns 3.50×5 labor hours = 17.50 computer dollars for that round. Again, the person in group 2 represents 5 people. So, 1 unit of labor hour in market 2 is equivalent to 5 units of labor hours. Note that when the stock is fully closed, all labor hours from the group 2 representative enters into market 2 thereby decreasing wage for everyone!

Calculator box:

In order to aid your decision, a calculator box is provided. In the first box, place the number of labor hours you allocate in market 1. In the second box, place how many labor hours in total you expect all other individuals to put in market 1. Press “calculate” when you are finished. The estimated stock in the next round, wage, and earnings in each sector will be provided. Note that this will only be an estimated amount since there are differences in the efficiency parameter across individuals and only the average efficiency parameter is used in the calculator. During the experiment you will only be able to use the calculator 5 times during each round. So choose carefully!

Communication:

As stated earlier, group 1 members will be able to identify the efficiency of each member in market 1 as well as each other through the messenger system. All group 1 members will be allowed to communicate throughout all the rounds while using the calculator box. Before the beginning of the experiment, members from Group 1 will be given 3 minutes to chat with other members of their group about the experiment. Once the 3 minutes are finished, group 1 members will be given 2 minutes to input their choice for the first round. Please note: YOUR CHAT MANUSCRIPT WILL BE COLLECTED AFTER THE EXPERIMENT SO PLEASE DO NOT CLOSE YOUR CHAT BROWSER. Group 2 representative will not be allowed to chat.

Summary

1. If you are a group 1 member, you will allocate labor hours in market 1 and market 2 as well as vote on the maximum number of labor hours allowed in market 1. In the voting questions, the majority decision will be implemented.

Even if you vote to “close off”, you will still need to vote in the second question in case majority prefer to keep the stock open.

2. Group 1 members can communicate throughout the duration of the actual experiment while using the calculator box.

3. If you are a group 2 member, you will allocate labor hours in market 1 and market2 given the maximum allowed by group 1 members. All decisions by the group 2 representative are weighted five times.

4. Earnings in market 1 will depend on the fraction of your labor relative to total labor, stock, price and an efficiency parameter. The larger these factors, the larger your earnings in market 1.

5. In market 1, you can only control your own labor and stock. If less stock is collected in the current round, the stock will grow faster and more will be available in the next period. Individuals with larger efficiency parameters can harvest more of the stock but this means that they take away more of the stock for the next rounds. The group 2 representative has the lowest efficiency parameter in the cluster.

6. In market 2, earnings are equal to wage multiplied by remaining labor hours not allocated in market 1. Wage decreases when more labor hours are in market 2. If market 1 is closed off to group 2, all their labor hours will immediately go to market 2 thereby decreasing wage for everyone.

The first internet explorer that is currently opened is a test run. We will now conduct 2 rounds as a test to familiarize yourselves with the experimental setup. Your earnings in the first two rounds will not go toward your total earnings. After you have finished with the 2 rounds, please close this internet browser. Are there any questions before we start?

E.2 Computer Interface Screens

http://www.hibalo.com/garyo/surveygroup1.asp - Microsoft Internet Explorer

Address http://www.hibalo.com/garyo/surveygroup1.asp

Group 1 Questionnaire

User: session5_05, Round: 12, Session: session5a, Group: 1

Please indicate if you want to close the resource stock to group 2 members:
 Fully closed Open

How many average permits for every group 2 member would you prefer?

1	2	3	4	5	6	7	8	9	10
<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

Out of a total of 10 labor hours, how many labor hours would you allocate in the resource sector (0-10):

Calculator

Calculate	Your Labor (0-10)	Other Labor Total (0-90)	Stock in next period	Wage	Earnings in Market 1	Earnings in Market 2	Profit
<input type="button" value="Calculate"/>	<input type="text"/>	<input type="text"/>					
<input type="button" value="Calculate"/>	<input type="text"/>	<input type="text"/>					
<input type="button" value="Calculate"/>	<input type="text"/>	<input type="text"/>					
<input type="button" value="Calculate"/>	<input type="text"/>	<input type="text"/>					
<input type="button" value="Calculate"/>	<input type="text"/>	<input type="text"/>					

Your History

Period	Wage	Voting Result	Permits Voted On	Labor in Harvesting	Total Labor in Market 1	Earnings in Market 1	Earnings in Market 2	Profit
1	2	Close	-	4	27	4.4	12.03	16.43
2	2.07	Close	-	6	28	6.44	8.28	14.72
3	2.07	Close	-	5	28	5.14	10.35	15.49
4	2.4	Close	-	8	33	7.91	4.79	12.7
5	1.80	Close	-	3	25	2.56	13.12	15.69
6	1.42	Close	-	4	18	3.53	8.52	12.05
7	1.62	Close	-	7	21	7.24	4.84	12.08
8	1.74	Close	-	6	23	11.79	6.98	18.77
9	2.07	Close	-	7	28	14.5	6.21	20.71
10	2.26	Close	-	8	31	15.74	4.53	20.27
11	2.07	Close	-	7	28	12.31	6.21	18.52
12	-	-	-	-	-	-	-	-

http://www.hibalo.com/garyo/surveygroup1.asp - Microsoft Internet Explorer

Address http://www.hibalo.com/garyo/surveygroup1.asp

Calculator

Calculate	Your Labor (0-10)	Other Labor Total (0-90)	Stock in next period	Wage	Earnings in Market 1	Earnings in Market 2	Profit
<input type="button" value="Calculate"/>	<input type="text"/>	<input type="text"/>					
<input type="button" value="Calculate"/>	<input type="text"/>	<input type="text"/>					
<input type="button" value="Calculate"/>	<input type="text"/>	<input type="text"/>					
<input type="button" value="Calculate"/>	<input type="text"/>	<input type="text"/>					
<input type="button" value="Calculate"/>	<input type="text"/>	<input type="text"/>					

Your History

Period	Wage	Voting Result	Permits Voted On	Labor in Harvesting	Total Labor in Market 1	Earnings in Market 1	Earnings in Market 2	Profit
1	2	Close	-	4	27	4.4	12.03	16.43
2	2.07	Close	-	6	28	6.44	8.28	14.72
3	2.07	Close	-	5	28	5.14	10.35	15.49
4	2.4	Close	-	8	33	7.91	4.79	12.7
5	1.80	Close	-	3	25	2.56	13.12	15.69
6	1.42	Close	-	4	18	3.53	8.52	12.05
7	1.62	Close	-	7	21	7.24	4.84	12.08
8	1.74	Close	-	6	23	11.79	6.98	18.77
9	2.07	Close	-	7	28	14.5	6.21	20.71
10	2.26	Close	-	8	31	15.74	4.53	20.27
11	2.07	Close	-	7	28	12.31	6.21	18.52
12	-	-	-	-	-	-	-	-

Sample Screen for Group 1 Members

Http://www.hibalo.com/goryo/surveygroup2.asp - Microsoft Internet Explorer

File Edit View Favorites Tools Help

Address http://www.hibalo.com/goryo/surveygroup2.asp

Group 2 Questionnaire

User: session5_06, Round: 12, Session: session5a, Group: 2

Available permits: 5

How many labor hours would you allocate in market 1 (0 - 5):

Calculator

Calculate	Your Labor (0-10)	Other Labor Total (0-90)	Stock in next period	Wage	Earnings in Market 1	Earnings in Market 2	Profit
<input type="button" value="Calculate"/>	<input type="text"/>	<input type="text"/>					
<input type="button" value="Calculate"/>	<input type="text"/>	<input type="text"/>					
<input type="button" value="Calculate"/>	<input type="text"/>	<input type="text"/>					
<input type="button" value="Calculate"/>	<input type="text"/>	<input type="text"/>					
<input type="button" value="Calculate"/>	<input type="text"/>	<input type="text"/>					

Your History

Period	Wage	Voting Result	Permits Voted On	Labor in Harvesting	Total Labor in Market 1	Earnings in Market 1	Earnings in Market 2	Profit
1	2	Close	-	0	27	0	20.05	20.05
2	2.07	Close	-	0	20	0	20.7	20.7
3	2.07	Close	-	0	28	0	20.7	20.7
4	2.4	Close	-	0	33	0	23.95	23.95
5	1.88	Close	-	0	25	0	18.75	18.75
6	1.47	Close	-	0	18	0	14.7	14.7

Done Internet

Sample Screen for Group 2 Members

E.3 GAMS Program Commands

<pre> sets t time periods /1*10/ firstyr(t) first time period lastyr(t) last time period; firstyr(t) = yes\$(ord(t) eq 1); lastyr(t) = yes\$(ord(t) eq card(t)); scalars a intrinsic growth rate /0.59/ b maximum stock /80/ c wage intercept /6.75/ d wage slope /0.0325/ f harvest function int /50/ g harvest function sl /0.001/ h labor endowment /10/ e harvesting efficiency for comm mem .0004/ z harvesting efficiency for non commm .00025/ p price /5/ r discount rate /0.0/; variables w wealth of representative community mber m(t) own labor n(t) non-community labor s(t) resource stock; integer variables m(t), n(t); equations objfunc objective function start(t) initial condition for stock stock(t) intermediate stock const(t) constraint nconstone(t) nash constraint one ; objfunc.. w =e= sum(t, ((1/(1+r))**((ord(t)-1))) * ((c- d*5*((h-m(t))+h-n(t)))) * (h-m(t)) + p*e*s(t)*(f-g*5*(m(t)+n(t)))*m(t)); const(t).. (c-2*d*5*((h-m(t))+h-n(t))) = p*z*s(t)*(f-g*5*(m(t)+2*n(t))); nconstone(t).. -(c-2*d*5*((h-m(t))+h- t)))+p*e*s(t)*(f-g*(6*m(t)+5*n(t)))+ p*e*(5*z*s(t)*g*n(t)-5*e*s(t)*(f- (6*m(t)+5*n(t))))*(f- 5*(m(t+1)+n(t+1)))*m(t+1) =1= 0; start(firstyr).. s(firstyr) =e= 10; stock(t+1).. s(t+1) =e= s(t)+a*s(t)*(1- (t)/b) -5*e*s(t)*(f-g*5*(m(t)+n(t)))*m(t)- z*s(t)*(f-g*5*(m(t)+n(t)))*n(t); </pre>	<pre> MODEL FISH /ALL/; m.up(t) = 10; m.lo(t) = 0; n.up(t) = 10; n.lo(t) = 0; *s.up(t) = b; s.lo(t) = 0; m.l(t) = 5; n.l(t) = 0; *option nlp=conopt2; *option mip=cplex; *option rminlp=conopt2; option minlp=sbb; *option iterlim=10000; *SOLVE FISH USING RMINLP MAXIMIZING w ; *abort\$(fish.modelstat>2.5) "relaxed model could not be solved"; Solve FISH USING rminLP MAXIMIZING w ; *Solve FISH USING RMINLP MAXIMIZING w ; PARAMETERS manup(t) manufacturing profit resp(t) resource sector profit totprof(t) total profit wage(t) wage over time wageln(t) wage when the other guy comes in vmprln(t) other vmp evaluated at ln; vmprln(t) = p*z*s.l(t)*(f- g*5*(m.l(t)+2*n.l(t))); manup(t) = (c-2*d*5*((h-m.l(t))+h- n.l(t)))*h-m.l(t); resp(t) = p*e*s.l(t)*(f- g*5*(m.l(t)+n.l(t)))*m.l(t) ; totprof(t) = p*e*s.l(t)*(f- g*5*(m.l(t)+n.l(t)))*m.l(t)+ (c-2*d*5*((h-m.l(t))+h-n.l(t)))*h- m.l(t); wage(t) = (c-2*d*5*((h-m.l(t))+h- n.l(t))); wageln(t) = (c-2*d*5*((h-m.l(t))+h- n.l(t))); DISPLAY manup, resp, wage, vmprln, wageln, totprof; </pre>
---	---

Sample GAMS program for homogeneous community members

```

sets
t time periods /1*10/
firstyr(t) first time period
lastyr(t) last time period;
firstyr(t) = yes$(ord(t) eq 1);
lastyr(t) = yes$(ord(t) eq card(t));
scalars
a intrinsic growth rate /0.59/
b maximum stock /80/
c wage intercept /6.75/
d wage slope /0.0325/
f harvest function int /50/
g harvest function sl /0.001/
h labor endowment /10/
e1 harvesting efficiency for comm mem 1 /0.0003/
e2 harvesting efficiency for comm mem 2 /0.00035/
e3 harvesting efficiency for comm mem 3 /0.0004/
e4 harvesting efficiency for comm mem 4 /0.00045/
e5 harvesting efficiency for comm mem 5 /0.0005/
z harvesting efficiency for non commm /0.00025/
p price /5/
r discount rate /0.0/;
variables
w wealth of representative community member
m1(t) own labor of comm1
m2(t) own labor of comm2
m3(t) own labor of comm3
m4(t) own labor of comm4
m5(t) own labor of comm5
n(t) non-community labor
s(t) resource stock;
integer variables m1(t), m2(t), m3(t), m4(t), m5(t), n(t);
equations
objfunc objective function
start(t) initial condition for stock
stock(t) intermediate stock
const(t) constraint
nconstone1(t) nash constraint 1
nconstone2(t) nash constraint 2
nconstone3(t) nash constraint 3
nconstone4(t) nash constraint 4
nconstone5(t) nash constraint 5
;

```

Sample GAMS program for heterogeneous community members

```

objfunc.. w =e=
sum(t,((1/(1+r))**((ord(t)-1)))*((c-2*d*((5*h-m1(t)-m2(t)-m3(t)-m4(t)-
m5(t))+
5*(h-n(t))))*(5*h-m1(t)-m2(t)-m3(t)-m4(t)-m5(t))+
p*e1*s(t)*(f-g*(m1(t)+m2(t)+m3(t)+m4(t)+m5(t)+5*n(t)))*m1(t)+
p*e2*s(t)*(f-g*(m1(t)+m2(t)+m3(t)+m4(t)+m5(t)+5*n(t)))*m2(t)+
p*e3*s(t)*(f-g*(m1(t)+m2(t)+m3(t)+m4(t)+m5(t)+5*n(t)))*m3(t)+
p*e4*s(t)*(f-g*(m1(t)+m2(t)+m3(t)+m4(t)+m5(t)+5*n(t)))*m4(t)+
p*e5*s(t)*(f-g*(m1(t)+m2(t)+m3(t)+m4(t)+m5(t)+5*n(t)))*m5(t));
const(t).. (c-2*d*((5*h-m1(t)-m2(t)-m3(t)-m4(t)-m5(t))+
5*(h-n(t)))) =1= p*z*s(t)*(f-g*(m1(t)+m2(t)+m3(t)+m4(t)+m5(t)+10*n(t)));
nconstone1(t).. -(c-2*d*((5*h-m1(t)-m2(t)-m3(t)-m4(t)-m5(t))+5*(h-n(t))))+
p*e1*s(t)*(f-g*(2*m1(t)+m2(t)+m3(t)+m4(t)+m5(t)+5*n(t)))

p*e1*(5*z*s(t)*g*n(t)+e2*s(t)*g*m2(t)+e3*s(t)*g*m3(t)+e4*s(t)*g*m4(t)+e5*s(t)*g
*m5(t)-
e1*s(t)*(f-g*(2*m1(t)+m2(t)+m3(t)+m4(t)+m5(t)+5*n(t)))*
(f-g*(m1(t+1)+m2(t+1)+m3(t+1)+m4(t+1)+m5(t+1)+5*n(t+1)))*m1(t+1) =g= 0;
nconstone2(t).. -(c-2*d*((5*h-m1(t)-m2(t)-m3(t)-m4(t)-m5(t))+5*(h-n(t))))+
p*e2*s(t)*(f-g*(m1(t)+2*m2(t)+m3(t)+m4(t)+m5(t)+5*n(t)))

p*e2*(5*z*s(t)*g*n(t)+e1*s(t)*g*m1(t)+e3*s(t)*g*m3(t)+e4*s(t)*g*m4(t)+e5*s(t)*g
*m5(t)-
e2*s(t)*(f-g*(m1(t)+2*m2(t)+m3(t)+m4(t)+m5(t)+5*n(t)))*
(f-g*(m1(t+1)+m2(t+1)+m3(t+1)+m4(t+1)+m5(t+1)+5*n(t+1)))*m2(t+1) =g= 0;
nconstone3(t).. -(c-2*d*((5*h-m1(t)-m2(t)-m3(t)-m4(t)-m5(t))+5*(h-n(t))))+
p*e3*s(t)*(f-g*(m1(t)+m2(t)+2*m3(t)+m4(t)+m5(t)+5*n(t)))

p*e3*(5*z*s(t)*g*n(t)+e1*s(t)*g*m1(t)+e2*s(t)*g*m2(t)+e4*s(t)*g*m4(t)+e5*s(t)*g
*m5(t)-
e3*s(t)*(f-g*(m1(t)+m2(t)+2*m3(t)+m4(t)+m5(t)+5*n(t)))*
(f-g*(m1(t+1)+m2(t+1)+m3(t+1)+m4(t+1)+m5(t+1)+5*n(t+1)))*m3(t+1) =g= 0;
nconstone4(t).. -(c-2*d*((5*h-m1(t)-m2(t)-m3(t)-m4(t)-m5(t))+5*(h-n(t))))+
p*e4*s(t)*(f-g*(m1(t)+m2(t)+m3(t)+2*m4(t)+m5(t)+5*n(t)))

p*e4*(5*z*s(t)*g*n(t)+e1*s(t)*g*m1(t)+e2*s(t)*g*m2(t)+e3*s(t)*g*m3(t)+e5*s(t)*g
*m5(t)-
e4*s(t)*(f-g*(m1(t)+m2(t)+m3(t)+2*m4(t)+m5(t)+5*n(t)))*
(f-g*(m1(t+1)+m2(t+1)+m3(t+1)+m4(t+1)+m5(t+1)+5*n(t+1)))*m4(t+1) =g= 0;
nconstone5(t).. -(c-2*d*((5*h-m1(t)-m2(t)-m3(t)-m4(t)-m5(t))+5*(h-n(t))))+
p*e5*s(t)*(f-g*(m1(t)+m2(t)+m3(t)+m4(t)+2*m5(t)+5*n(t)))

p*e5*(5*z*s(t)*g*n(t)+e1*s(t)*g*m1(t)+e2*s(t)*g*m2(t)+e3*s(t)*g*m3(t)+e4*s(t)*g
*m4(t)-
e5*s(t)*(f-g*(m1(t)+m2(t)+m3(t)+m4(t)+2*m5(t)+5*n(t)))*
(f-g*(m1(t+1)+m2(t+1)+m3(t+1)+m4(t+1)+m5(t+1)+5*n(t+1)))*m5(t+1) =g= 0;
start(firstyr).. s(firstyr) =e= 10;
stock(t+1).. s(t+1) =e= s(t)+a*s(t)*(1-(s(t)/b))-
e1*s(t)*(f-g*(m1(t)+m2(t)+m3(t)+m4(t)+m5(t)+5*n(t)))*m1(t)-
e2*s(t)*(f-g*(m1(t)+m2(t)+m3(t)+m4(t)+m5(t)+5*n(t)))*m2(t)-
e3*s(t)*(f-g*(m1(t)+m2(t)+m3(t)+m4(t)+m5(t)+5*n(t)))*m3(t)-
e4*s(t)*(f-g*(m1(t)+m2(t)+m3(t)+m4(t)+m5(t)+5*n(t)))*m4(t)-
e5*s(t)*(f-g*(m1(t)+m2(t)+m3(t)+m4(t)+m5(t)+5*n(t)))*m5(t)-
5*z*s(t)*(f-g*(m1(t)+m2(t)+m3(t)+m4(t)+m5(t)+5*n(t)))*n(t);

```

Sample GAMS program for heterogeneous community members (continued)

```

MODEL FISH /ALL/;
  m1.up(t) = 10; m1.lo(t) = 0;
  m2.up(t) = 10; m2.lo(t) = 0;
  m3.up(t) = 10; m3.lo(t) = 0;
  m4.up(t) = 10; m4.lo(t) = 0;
  m5.up(t) = 10; m5.lo(t) = 0;
  n.up(t) = 10; n.lo(t) = 0;
  *s.up(t) = b;
  s.lo(t) = 0;
  m1.l(t) = 5;
  m2.l(t) = 5;
  m3.l(t) = 5;
  m4.l(t) = 5;
  m5.l(t) = 5;
  n.l(t) = 0;
  *option nlp=conopt2;
  *option mip=cplex;
  *option rminlp=conopt2;
  option minlp=sbb;
  *option iterlim=10000;
  *SOLVE FISH USING RMINLP MAXIMIZING w ;
  *abort$(fish.modelstat>2.5) "relaxed model could not be solved";
  Solve FISH USING rminLP MAXIMIZING w ;
  *Solve FISH USING RMINLP MAXIMIZING w ;
  PARAMETERS
  manup1(t) manufacturing profit for 1
  manup2(t) manufacturing profit for 2
  manup3(t) manufacturing profit for 3
  manup4(t) manufacturing profit for 4
  manup5(t) manufacturing profit for 5
  resp1(t) resource sector profit for 1
  resp2(t) resource sector profit for 2
  resp3(t) resource sector profit for 3
  resp4(t) resource sector profit for 4
  resp5(t) resource sector profit for 5
  totprof1(t) total profit for 1
  totprof2(t) total profit for 2
  totprof3(t) total profit for 3
  totprof4(t) total profit for 4
  totprof5(t) total profit for 5
  wage(t) wage over time

```

Sample GAMS program for heterogeneous community members (continued)


```

*wageln(t) wage when the other guy comes in
*vmpnrln(t) other vmp evaluated at ln
;
*vmpnrln(t) = p*z*s.l(t)*(f-g*5*(m.l(t)+2*n.l(t)));
manup1(t) = (c-2*d*((5*h-m1.l(t)-m2.l(t)-m3.l(t)-m4.l(t)-m5.l(t))+5*(h-
n.l(t))))*(h-m1.l(t));
manup2(t) = (c-2*d*((5*h-m1.l(t)-m2.l(t)-m3.l(t)-m4.l(t)-m5.l(t))+5*(h-
n.l(t))))*(h-m2.l(t));
manup3(t) = (c-2*d*((5*h-m1.l(t)-m2.l(t)-m3.l(t)-m4.l(t)-m5.l(t))+5*(h-
n.l(t))))*(h-m3.l(t));
manup4(t) = (c-2*d*((5*h-m1.l(t)-m2.l(t)-m3.l(t)-m4.l(t)-m5.l(t))+5*(h-
n.l(t))))*(h-m4.l(t));
manup5(t) = (c-2*d*((5*h-m1.l(t)-m2.l(t)-m3.l(t)-m4.l(t)-m5.l(t))+5*(h-
n.l(t))))*(h-m5.l(t));
resp1(t) = p*e1*s.l(t)*(f-
g*(m1.l(t)+m2.l(t)+m3.l(t)+m4.l(t)+m5.l(t)+5*n.l(t)))*m1.l(t) ;
resp2(t) = p*e2*s.l(t)*(f-
g*(m1.l(t)+m2.l(t)+m3.l(t)+m4.l(t)+m5.l(t)+5*n.l(t)))*m2.l(t) ;
resp3(t) = p*e3*s.l(t)*(f-
g*(m1.l(t)+m2.l(t)+m3.l(t)+m4.l(t)+m5.l(t)+5*n.l(t)))*m3.l(t) ;
resp4(t) = p*e4*s.l(t)*(f-
g*(m1.l(t)+m2.l(t)+m3.l(t)+m4.l(t)+m5.l(t)+5*n.l(t)))*m4.l(t) ;
resp5(t) = p*e5*s.l(t)*(f-
g*(m1.l(t)+m2.l(t)+m3.l(t)+m4.l(t)+m5.l(t)+5*n.l(t)))*m5.l(t) ;
totprof1(t) = p*e1*s.l(t)*(f-
g*(m1.l(t)+m2.l(t)+m3.l(t)+m4.l(t)+m5.l(t)+5*n.l(t)))*m1.l(t)+
(c-2*d*((5*h-m1.l(t)-m2.l(t)-m3.l(t)-m4.l(t)-m5.l(t))+5*(h-n.l(t))))*(h-
m1.l(t));
totprof2(t) = p*e2*s.l(t)*(f-
g*(m1.l(t)+m2.l(t)+m3.l(t)+m4.l(t)+m5.l(t)+5*n.l(t)))*m2.l(t)+
(c-2*d*((5*h-m1.l(t)-m2.l(t)-m3.l(t)-m4.l(t)-m5.l(t))+5*(h-n.l(t))))*(h-
m2.l(t));
totprof3(t) = p*e3*s.l(t)*(f-
g*(m1.l(t)+m2.l(t)+m3.l(t)+m4.l(t)+m5.l(t)+5*n.l(t)))*m3.l(t)+
(c-2*d*((5*h-m1.l(t)-m2.l(t)-m3.l(t)-m4.l(t)-m5.l(t))+5*(h-n.l(t))))*(h-
m3.l(t));
totprof4(t) = p*e4*s.l(t)*(f-
g*(m1.l(t)+m2.l(t)+m3.l(t)+m4.l(t)+m5.l(t)+5*n.l(t)))*m4.l(t)+
(c-2*d*((5*h-m1.l(t)-m2.l(t)-m3.l(t)-m4.l(t)-m5.l(t))+5*(h-n.l(t))))*(h-
m4.l(t));
totprof5(t) = p*e5*s.l(t)*(f-
g*(m1.l(t)+m2.l(t)+m3.l(t)+m4.l(t)+m5.l(t)+5*n.l(t)))*m5.l(t)+
(c-2*d*((5*h-m1.l(t)-m2.l(t)-m3.l(t)-m4.l(t)-m5.l(t))+5*(h-n.l(t))))*(h-
m5.l(t));
wage(t) = (c-2*d*((5*h-m1.l(t)-m2.l(t)-m3.l(t)-m4.l(t)-m5.l(t))+5*(h-
n.l(t)))));
*wageln(t) = (c-2*d*5*((h-m.l(t))+(h-1)));
DISPLAY manup1, manup2, manup3, manup4, manup5, resp1, resp2, resp3, resp4,
resp5,
totprof1, totprof2, totprof3, totprof4, totprof5, wage;

```

Sample GAMS program for heterogeneous community members (continued)

E.4 Nash Equilibrium Path for Heterogeneous Community Members

Treatment	Period	Community member with Efficiency Parameter 0.0003		Community member with Efficiency Parameter 0.00035		Community member with Efficiency Parameter 0.0004		Community member with Efficiency Parameter 0.00045		Community member with Efficiency Parameter 0.0005	
		Labor in Market 1	Total Earnings	Labor in Market 1	Total Earnings	Labor in Market 1	Total Earnings	Labor in Market 1	Total Earnings	Labor in Market 1	Total Earnings
Baseline	1	0	6.2	0	6.2	0	6.2	0	6.2	5.8	9.9
	2	0	8.6	0	8.6	0	8.6	0	8.6	9.3	16.6
	3	0	10.8	0	10.8	0	10.8	2.7	13.1	10	21.5
	4	0	12.4	0	12.4	0	12.4	5.2	17.6	10	24.8
	5	0	13.3	0	13.3	0	13.3	6.7	20.5	10	26.7
	6	0	13.8	0	13.8	0	13.8	7.3	21.9	10	27.5
	7	0	13.9	0	13.9	0	13.9	7.6	22.4	10	27.9
	8	0	14	0	14	0	14	7.7	22.6	10	28
	9	0	14	0	14	0	14	7.7	22.7	10	28.1
	10	0	14	0	14	0	14	7.7	22.7	10	28.1
<i>Sum</i>			<i>121.1</i>		<i>121.1</i>		<i>121.1</i>		<i>178.3</i>		<i>239</i>
Price Change	1	0	6.2	0	6.2	0	6.2	0	6.2	5.8	9.9
	2	0	8.6	0	8.6	0	8.6	0	8.6	9.3	16.6
	3	0	10.8	0	10.8	0	10.8	2.7	13.1	10	21.5
	4	0	12.4	0	12.4	0	12.4	5.2	17.6	10	24.8
	5	0	22.7	1	23.6	10	36.3	10	40.8	10	45.3
	6	0	16.8	0	16.8	2	18.8	10	30.2	10	33.6
	7	0	16.1	0	16.1	0.9	17	10	29	10	32.2
	8	0	15.9	0	15.9	0.5	16.4	10	28.5	10	31.7
	9	0	15.8	0	15.8	0.4	16.1	10	28.4	10	31.5
	10	0	15.7	0	15.7	0.3	16.1	10	28.3	10	31.5
<i>Sum</i>			<i>140.9</i>		<i>141.8</i>		<i>158.6</i>		<i>230.7</i>		<i>278.5</i>

Myopic Nash Equilibrium Paths for Individual Heterogeneous Community Members

E.5 Test for Ordering Effects

Treatment	Community Member Labor			Stock			Property Rights Regime Pattern		
	Session 1	Session 2	T-Stat	Session 1	Session 2	T-Stat	Session 1	Session 2	T-Stat
Homogeneous Community Members									
1	25.5	23.5	0.6	10	10	-	1	1	0
2	19.75	28.13	-3.51**	8.12	7.89	0.19	1	1	0
3	17.75	35.75	-5.60**	7.34	7.31	0.01	1	0.5	1.73
4	20.55	27.75	-2.15	7.44	6.06	0.53	0.75	1	-1
5	19.88	30.63	-3.52**	6.79	5.69	0.46	0.75	1	-1
6	22.38	33	-2.68	6.57	5.22	0.52	1	0.75	1
7	20.75	23.8	-0.96	5.6	5.36	0.08	1	0.5	1.73
8	18.3	22.6	-1.69	5.22	5.06	0.06	0.75	0.5	0.65
9	24	20.18	1.04	5.8	5.77	0.01	1	0.5	1.73
10	21.13	20.75	0.11	5.05	6.88	-0.48	1	0.75	1
Heterogeneous Community Members									
1	24	22	0.43	10	10	-	1	1	0
2	27.25	22.28	1.12	8.33	9.53	-0.74	0.75	1	-1
3	30.5	24.5	1.26	7.36	9.4	-0.85	1	1	0
4	23.75	24.35	-0.13	4.16	8.9	-1.9	1	1	0
5	22.88	23.13	-0.05	3.77	8.65	-2.07	0.75	1	-1
6	27.13	20.38	1.18	3.86	8.4	-1.92	0.75	1	-1
7	24.15	26.63	-0.51	3.68	8.06	-1.66	1	1	0
8	25	24.6	0.07	2.93	6.53	-1.54	1	0.75	1
9	22.88	21.58	0.26	2.2	6.54	-2	0.75	1	-1
10	21.9	21.03	0.17	2.12	6.38	-1.8	1	1	0

Note: ** 5% level of significance

Critical t: 2.353, 3.182

Test for Ordering Effects of Baseline Treatments

Treatment	Community Member Labor			Stock			Property Rights Regime Pattern		
	Session 3	Session 4	T-Stat	Session 3	Session 4	T-Stat	Session 3	Session 4	T-Stat
Homogeneous Community Members									
1	32.43	25.05	1.49	10	10		1	0.5	1.73
2	26.43	17.33	1.81	7.9	9.53	-1.12	0.75	0.75	0
3	15.23	19.5	-1.08	6.58	10.19	-1.76	1	0.75	1
4	19.03	18.65	0.09	7.52	9.47	-0.79	1	0.75	1
5	25.13	21.75	0.6	7.32	9.91	-0.88	1	0.75	1
6	22.7	23.13	-0.09	6.43	8.46	-0.63	1	0.75	1
7	19.88	21.05	-0.24	5.92	7.83	-0.69	0.75	1	-1
8	18.7	21.88	-0.66	6.13	6.45	-0.16	1	1	0
9	18.15	23.3	-1.05	6	5.98	0.01	1	0.5	1.73
10	16	18.83	-0.74	6.18	5.64	0.21	1	0.75	1
Heterogeneous Community Members									
1	23.83	17.88	1.22	10	10		1	0.75	0.5
2	22.18	22.5	-0.08	8.94	10.1	-0.94	1	0.75	0.5
3	23.43	16.13	1.76	8.17	8.91	-0.34	1	1	0
4	23.65	11.63	2.79	7.04	7.41	-0.21	0.5	0.75	-0.43
5	29.9	18	2.36	7.6	7.54	0.04	0.75	1	-1
6	18.98	15.75	0.71	5.98	7.13	-0.67	1	1	0
7	25.13	11.7	2.82	5.26	6.76	-1.07	0.75	1	-1
8	26.38	14.58	2.29	4.69	6.54	-0.94	0.75	1	-1
9	29.63	9.2	4.66**	4.63	5.65	-0.66	1	1	0
10	23.68	8.43	3.17	4.17	6.13	-1.04	1	1	0

Note: ** 5% level of significance

Critical t: 2.353, 3.182

Test for Ordering Effects of Price Change Treatments

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