

**Essays on the use of Natural Resources in Indebted Economies**

**Scott Thomas Reid**

**Ph.D.  
The University of Edinburgh  
1996**



### **Declaration of Originality**

This thesis consists entirely of my own original work and has been composed by myself.

## Abstract

The thesis investigates the use of natural resources by indebted economies. This issue is motivated by arguments which suggest that, as a consequence of high external debt burdens, developing economies have been forced to over exploit their natural resources. The thesis employs analytical and econometric modelling techniques to assess this hypothesised debt-resources link, which in the more popular literature has lacked any basis in economic theory or econometric evidence.

The thesis begins by placing the debt-resources link within the context of established theoretical literature. It is argued that the literatures on optimal resource use and optimal foreign borrowing provide an appropriate analytical framework. The conditions under which a link between external indebtedness and natural resource use may arise are then highlighted. This discussion emphasises that any link depends on imperfections in international capital markets.

The thesis presents two theoretical models which extend previous literature. The first model considers the case of exhaustible resources. In this model a three sector open economy is outlined: a traded good sector, a non-traded good sector and an enclave resource sector. The economy has access to international capital markets, but may face limits on its ability to borrow. It is shown that optimal resource extraction may be higher for “problem” debtors, where a “problem” debtor is defined by a constrained regime for foreign borrowing. This model is presented in discrete time for the purpose of deriving a theory-consistent econometric model.

The second theoretical model analyses the relationship between indebtedness and forest clearance. The economy trades a good produced with forest inputs. Demand for these forest inputs results in forest clearance, i.e. deforestation. The effect of indebtedness is considered in two ways. Firstly, the relationship between the

stock of debt and the demand for deforestation. It is shown that there is no relationship if the economy is able to freely borrow on international capital markets. If borrowing is constrained, then a higher stock of debt will increase the demand for forest inputs and therefore deforestation. The second result is that deforestation increases for a given decrease in the level of the binding credit ceiling. Thus the greater is the severity of borrowing constraints, then the greater is the level of forest clearance.

The thesis also presents two econometric analyses of the debt-resources link. The first empirical investigation focuses on the case of non-renewable resources and provides a test of the theoretical model developed earlier in the thesis. A panel data-set over the period 1968-1989 was constructed for this analysis and Generalised Method of Moments (GMM) techniques were employed in the estimation and testing of liquidity constrained extraction Euler equations. The empirical results reject a link between indebtedness and mineral extraction.

The second econometric analysis considers the link between indebtedness and tropical deforestation. Cross-sectional data on tropical deforestation for the periods 1981-1985 and 1986-1990 was used to estimate and test an empirical model of deforestation. The specification of this empirical model was guided by the theoretical model of forest clearance presented in the thesis. GMM techniques are again employed in this analysis. On balance, the results indicates a positive correlation between deforestation and debt variables in both periods. There are also significant differences between unconstrained and constrained countries. In addition, the results indicate the relationship between deforestation and debt variables is quadratic, rather than linear.

The thesis concludes with a review of the analytical and econometric results and suggests some avenues for future research.

## Acknowledgements

I wish to express my heartfelt thanks to the individuals who have provided supervision and guidance throughout my work for this thesis. These are Dr. Andy Snell and Dr. Colin J. Roberts of the Department of Economics, University of Edinburgh. I wish to express my gratitude to Professor Gordon Hughes, World Bank and Department of Economics, University of Edinburgh who provided ideas, guidance and access to invaluable data-sources. I would also like to express thanks to Professors George Norman and Brian Main, who in their capacity as Head of Department during my research, provided a conducive working environment.

I am grateful to Professor Robert Deacon, Department of Economics, University of California and Will Cavendish, University of Oxford who provided thoughtful comments on an earlier version of Chapter 5. The same appreciation goes to an anonymous reviewer of *Resource and Energy Economics* who provided some insights on an earlier version of Chapter 3. A general thanks goes to seminar participants at the Universities of Edinburgh, Stirling, and Keele and those in attendance at the International Sustainable Development Conference, Manchester Conference Centre, 1995 who were all exposed to material drawn from this thesis. I hope all the contributions made by these "reviewers" has made this thesis a better finished product.

In the early days of undertaking research for a Ph.D., it is re-assuring to receive correspondence which provides help in developing ideas and identifying relevant literature. Thanks are therefore due to Professor David Pearce, Department of Economics, University College London and Ms. Joanne Burgess, Department of Environmental Economics and Management, University of York.

The inputs to a research thesis are not simply academic. During the period of my study I was extremely fortunate to benefit from the hospitality of Tony and Nicky White, who provided accommodation, food and occasional merriment. To them I express heartfelt thanks.

Finally, to Sara and Rebecca, I can only say thank you a million times over. Hopefully, normal service is now resumed !

## TABLE OF CONTENTS

Abstract.....	iii
Acknowledgements.....	vi
Table of Contents.....	viii
List of Tables.....	x
List of Figures.....	x
Chapter 1 Introduction.....	1
Chapter 2 Optimal foreign borrowing and optimal natural resource use : a theoretical review .....	7
2.1 Introduction .....	7
2.2 Optimal foreign borrowing in open economies .....	9
2.3 The optimal use of natural resources in the closed economy .....	20
2.4 The optimal use of natural resources in the open economy.....	29
2.5 Concluding thoughts.....	41
Appendix: Local stability analysis and comparative dynamics in the Rauscher model.....	44
Chapter 3 Exhaustible resource extraction by indebted economies: a theoretical model and empirical issues.....	51
3.1 Introduction .....	51
3.2 An intertemporal model of exhaustible resource extraction and foreign borrowing.....	53
3.3 The optimisation problem with unconstrained borrowing.....	58
3.4 Production, consumption and resource extraction with constrained borrowing.....	62
3.5 Econometric estimation and testing of the extraction Euler equations.....	74
3.5.1 Resource use and dynamic efficiency: a review of empirical evidence.....	76
3.5.2 Econometric estimation and testing of the extraction Euler equation under unconstrained and constrained foreign borrowing regimes.....	91
3.6 Concluding summary.....	97
Chapter 4 Exhaustible resource extraction by indebted economies:an econometric analysis.....	99
4.1 Introduction and related literature.....	99
4.2 Specification issues.....	103
4.2.1 The extraction cost function .....	103
4.2.3 Constrained and unconstrained foreign borrowing regimes .....	107
4.3 Data, econometric estimation and specification testing.....	111
4.3.1 Data.....	111
4.3.2 Econometric estimation and specification tests.....	112
a) Econometric methods for dynamic panels.....	112
b) Specification Tests .....	120
4.4 Empirical results .....	125

4.4.1 Estimation and testing of the extraction Euler equation with unconstrained and constrained sub-samples .....	127
4.4.2 Estimation and testing of the extraction Euler equation with the full sample.....	139
4.5 Conclusions.....	144
Appendix : Asymptotic properties of the GMM specification tests.....	146
Data Appendix: Sample, Variable Definitions and Sources .....	149
Chapter 5. External indebtedness and the causes of deforestation: a theoretical model.....	153
5.1 Introduction .....	153
5.2 The global forest resource and its rate of change: an overview.....	160
5.3 A model of deforestation in an indebted economy.....	167
5.3.1 Domestic production possibilities and the balance of payments .....	169
5.3.2 Unconstrained and constrained equilibria.....	173
5.4 External indebtedness as a cause of deforestation: comparative static analysis .....	178
5.4.1 The case of unconstrained foreign borrowing .....	178
5.4.2 The case of constrained foreign borrowing .....	181
a) The effect of debt on deforestation.....	182
b) The effect of credit ceilings on deforestation .....	185
5.5 Conclusions.....	187
Appendix : Comparative static results .....	190
Chapter 6 External indebtedness and the causes of deforestation: an econometric analysis .....	206
6.1. Introduction and Related Literature.....	206
6.2 The Empirical Model.....	214
6.3 Econometric Estimation and Testing.....	219
6.3.1 Constrained vs Unconstrained Regimes .....	225
6.4 Data and empirical results.....	227
6.4.1 Data.....	227
6.4.2 Empirical results .....	233
(a) The basic deforestation model.....	235
(b) Testing for debt effects .....	240
(c) Testing for the Absence of Debt Regimes.....	244
6.5 Conclusions.....	249
Data Appendix.....	252
Chapter 7 Conclusions.....	258
7.1 Reflections on the main findings .....	259
7.2 Future avenues and extensions .....	265
7.3 A final few words .....	267
References.....	269

## List of Tables

Table IV.1 Estimation of the Extraction Euler Equation with Unconstrained and Constrained Sub-Samples .....	128
Table IV.3 GMM Estimation and Testing of the Extraction Euler Equation with Unconstrained and Constrained Sub-Samples: II .....	134
Table IV.4 Tests of Parameter Restrictions with GMM Estimates: Unconstrained and Constrained Sub-Samples .....	136
Table IV.5 GMM Tests of Parameter Stability: Unconstrained v Constrained Sub-Samples .....	139
Table IV.6 Estimation and Testing of the Extraction Euler Equation: Full Sample .....	140
Table IV.7 GMM Estimation and Testing of the Extraction Euler Equation with Debt Instruments: Full Sample .....	141
Table IV.8 Tests of Parameter Restrictions with GMM Estimates: Full Sample .....	142
Table IV.9 Structural cost parameter estimates : Full Sample .....	143
Table IV.10 Structure and characteristics of the country-minerals panel .....	149
Table V.1 Estimates of the Global Forest Resource .....	161
Table V.2 Three Estimates of Tropical Deforestation in the 1970s .....	164
Table V.3: Tropical Deforestation 1981-90 .....	166
Table VI.1: Deforestation in Sample Countries: Summary Statistics .....	228
Table VI.2: GMM estimation of the basic deforestation model .....	237
Table VI.3: Testing for the absence of debt effects in the basic model .....	241
Table VI.4: Parameter Estimates for debt variables in basic deforestation model .....	242
Table VI.5: Testing for Absence of Debt Regimes: Specification Tests .....	245
Table VI.6: Testing for Absence of Debt Regimes: Parameter Estimates .....	246
Table VI.7: Countries (n=55) in Sample and Debt Regime Classifications .....	252
Table VI.8: Explanatory variables: summary statistics for full sample .....	255
Table VI.9: Explanatory variables: summary statistics for unconstrained and constrained sub-samples .....	257

## List of Figures

Figure 2.1 Investment and capital dynamics .....	18
Figure 2.2 Evolution of foreign borrowing over time .....	19
Figure 2.3 Resource stock and extraction dynamics .....	39
Figure 2.4 Optimal extraction time paths with an increase in debt .....	40
Figure 3.1 Production and consumption of tradeables and non-tradeables with constrained and unconstrained borrowing .....	65

## Chapter 1

### Introduction

This thesis presents an analysis of the use of natural resources by indebted economies. The motivation for this analysis can be traced to a popular view originating towards the end of the 1980s which began to associate the external debt problems of many developing countries with the contemporaneous observation of increasing environmental degradation.<sup>1</sup> This view raises two sets of interesting questions. Firstly, is there an economic rationale for the idea that debt and resource use may be linked and if so, what are the precise mechanisms which underlie any such link ? The second set of questions concern the empirical significance of the debt environment association. Does the argument that external debt is a determinant of resource use, and more specifically that high debt burdens encourage the over-use of natural resources have empirical validity ? This thesis represents an attempt to provide some answers to these two set of questions. To this end the thesis employs analytical and econometric modelling techniques which are well established in a wide range of economic and econometric literature, but which to date have not been evident to any great extent in the small academic literature on the debt environment issue and largely absent in more popular literature.

Over the last decade there has been a tremendous upsurge in the analysis of environmental problems in the developing country context (see for example World Commission of Environment and Development, 1987; Dasgupta and

---

<sup>1</sup>See for example George (1989).

Mäler, 1991; World Bank, 1992). Increasingly it has been recognised that many developing countries face serious environmental problems which are interwoven with structural economic problems. The problem of deforestation in the world's tropical forests has been extensively documented (Food and Agriculture Organisation, 1993; World Resources Institute, 1994). Equally, desertification in the drylands of Latin America, Asia and Africa has contributed to a severe degradation of the agricultural resource base (Barbier, 1991). Moreover, the World Commission on Environment and Development (1987), hereafter W.C.E.D., reported an annual increase of 6 million hectares in the area of land lost to desert. A further 21 million hectares were rendered economically unproductive by desertification. It is not only rural areas which are facing the problems of environmental degradation. The urban environment in developing countries also faces increasing strain. W.C.E.D. again note:

"On the river Ganges, 114 cities with 50,000 or more inhabitants dump untreated sewage into the river every day. DDT factories, tanneries, paper and pulp mills, petrochemical and fertiliser complexes, rubber factories and a host of others use the river to get rid of their wastes. ...Sixty percent of Calcutta's population suffer from pneumonia, and other respiratory diseases related to air pollution. ....In Malaysia, the highly urbanised Klang Valley has two to three times the pollution levels of major cities in the United States, and the Klang river system is heavily contaminated with agricultural and industrial effluents and sewage." (W.C.E.D., 1987, p240)

This evidence of environmental degradation has given impetus to a recent and rapidly expanding literature. Much of this work has been couched in terms of "sustainability" i.e. patterns of economic development which incorporate

preservation of the resource base as a key policy objective.<sup>2</sup> The precise meaning of the concept "sustainable development", popularised by W.C.E.D. (1987), remains elusive and is discussed at length in Pearce, Barbier and Markandya (1990), van den Bergh and Nijkamp (1991), Klaassen and Opschoor (1991) and Victor (1991). This said the questions and issues are now the concern of an increasingly analytical economics literature. (see for example Pezzey, 1989; Goldin and Winters, 1995)

At a less prescriptive level analyses of the causes of environmental degradation in developing countries have varied in their conclusions. Mahar (1989) and Repetto and Gillis (1988) have, for example, pointed to the role of domestic government policies in tropical deforestation. Hecht and Cockburn (1990) offer a more political prognosis emphasising the role of vested interests (e.g. landowners) in the case of the Amazon. Others have stressed underlying economic conditions. W.C.E.D. (1987) highlighted environmental degradation as a consequence of the dire poverty in many countries. Thus the fuelwood crisis in Africa, the destruction of tropical forest for a myriad of reasons and the overuse of poor soils are all rooted in the failures of development. Against this background it has been increasingly argued that the burden of external debt is adding to the pressures which lead to environmental neglect in developing countries. Miller states it thus:

---

<sup>2</sup>Within this literature has emerged a recent debate about the appropriate resource base. A "weak" sustainability view would define the resource base as the economy's stock of capital (physical, human and natural). A "strong" view defines the relevant capital stock (from a sustainability perspective) more narrowly by focusing on the stock of environmental resources. With both the objective is to maintain or preserve the relevant stock. With the weak view this permits substitution between natural and other forms of capital, whilst this is ruled out by a strong view. See Victor (1991) for a good overview.

"When the "costs" of environmental damage are subtle and in any case felt only in the longer-term, and when the benefits of environmentally-damaging activities are financially tangible and immediate, it is not difficult to fathom which option the stressed-out debtors will choose. Among the immediate financial benefits would count the enhancement of their ability to service their debts...." (Miller, 1991, p. 4)

The linkage between external debt and environmental resources has had a number of interpretations. One claim is that debtor economies have had to forego budgeting for environmental conservation programmes because of financial strictures (George, 1989). A second is that the uses of debt-financed investment have encouraged environmental degradation, e.g. the flooding of areas of the Amazon to create dams for hydro-power schemes (George, 1989). However the central theme of this literature, as implied by Miller, has been that debtor countries are forced to liquidate their stocks of environmental resources to meet debt-service obligations. It is this interpretation of the relationship between indebtedness and the environment which provides the motivation for the analysis presented in this thesis.

The thesis provides four related but reasonably self-contained contributions to the analysis of the debt-resources hypothesis. The basic proposition is put under theoretical scrutiny in chapters 2, 3 and 5. Chapter 2 presents an overview of intertemporal models of foreign borrowing and resource use to provide a basic framework for understanding debt-resource interactions. In chapter 3 a model of exhaustible resource extraction in a small open economy is presented and analysed with the effect of binding foreign borrowing constraints considered in detail. The main result which emerges is that foreign borrowing constraints are not in themselves sufficient to lead to a link between the economy's indebtedness and extraction of exhaustible resources. Rather, it is the severity of

borrowing constraints which may matter. In chapter 5 a static theoretical analysis of the link between debt and deforestation is presented. The motivation for a static analysis is partly empirical and partly institutional. As noted in chapter 5 various institutional factors contribute to economic agents (in the developing country context) having shortened planning horizons which means a static model is a reasonable approximation to their decision making. The empirical motivation reflects data available for testing theoretical propositions. In the context of deforestation the best data covers five yearly periods. Consequently only the predictions of a static model can be subjected to the data.

The rest of the thesis is empirical in nature. Chapters 4 and 6 respectively present self contained econometric analyses of the theoretical models of chapters 3 and 5. Chapter 4 considers the case of mineral production in developing economies as an example of exhaustible resource depletion and frames the basic debt-resources hypothesis in terms of the econometric estimation and testing of theoretical Euler equations. In this context the evidence which is presented would reject the notion of a debt-resource link. Chapter 6 considers the empirical association between indebtedness and deforestation by testing some of the key propositions derived in chapter 5. Here the results are more favourable to the hypothesis of interest, particularly in the early 1980s. A technical feature of the two econometric analyses is the use of the Generalised Method of Moments, a methodology which is increasingly used in econometric practice. Each chapter provides its own motivation for this methodology, but in essence these techniques provide a useful way of thinking about the debt-resources hypothesis. More specifically, the validity of moment restrictions which under the null state the covariance between the set of

instruments used in estimation and the error term to be zero are examined. The thesis concludes with chapter 7. The aim in this short chapter is to review and reflect on some of the main findings. Some suggestions for future research are then outlined in light of the questions which remain unanswered by the thesis.

## Chapter 2

### Optimal foreign borrowing and optimal natural resource use : a theoretical review.

#### 2.1 Introduction.

The aim of this chapter is to present the issue of a debt-resources link within an analytical framework. To this end the chapter presents an overview of relevant theoretical models which are useful tools for assessing the question of interest. The primary intent of this overview is to show that the issue of a debt-resources link can be usefully addressed with a class of economic models which, although to date have not considered the debt-resources question to any great extent, are more than capable of illuminating some of its key aspects.

The theoretical framework considered in this chapter is that of optimal growth theory which concerns itself with intertemporal allocation problems at the macroeconomic level. The most basic of these problems can be summarised with the simple question: "How much of its income should a nation save ?" (Ramsey, 1928, p. 543) Ever since this question was first posed by Frank Ramsey economists have grappled with the technical, philosophical and policy dimensions to the economic problem in its intertemporal form. Any question which is concerned with the problems of external indebtedness and the potential link with the problem of resource depletion must similarly grapple with an economic problem which is intertemporal in nature. Moreover these twin issues highlight two obvious limitations of the intertemporal problem considered by Ramsey. The first follows from the assumption of a closed economy. All investment is thus generated through domestic savings. The second is that the economy's production possibilities are defined entirely in terms of some

function of the economy's stock of reproducible capital and its labour force (population). Endowments of natural capital are ignored in the most basic analysis of optimal growth.<sup>1</sup>

Given the existence of international capital markets the first assumption obviously need not hold. Domestic savings can be augmented by inflows by foreign capital which extends the capacity to create new domestic capital. The second limitation is somewhat different in character. Unlike the potential for foreign borrowing to extend an economy's production possibilities, the concern over endowments of natural capital at the macroeconomic level is about the potential limit on economic activity which the finite nature of exhaustible resources and the possibly finite nature of regenerative resources and pollution assimilation capacities may impose. At the very least, there are thus two additional questions for Ramsey-type growth models to answer. Firstly, under what conditions does debt accumulation represent an optimal choice given it constitutes a transfer of negative wealth from present generations to future generations and secondly, what conditions characterise the optimal rate of resource use / exploitation ?

These two broad questions have largely been addressed separately in the literatures on optimal foreign borrowing and optimal resource use. The central theme of this chapter is that by considering these two allocation problems together within the framework of capital theory, some useful insights concerning the hypothesis of a link between resource depletion and external debt can be elaborated.

---

<sup>1</sup>Natural capital refers to the stock of natural resources in its broadest sense. Thus included in this category of capital would be non-renewable resources such as oil, gas, minerals; renewable / regenerative resources such as forests, fisheries, soil. In addition the assimilative capacities of the oceans and atmosphere mean these resources can also be regarded as natural capital. Common to each of the types of natural resource is the idea that they generate flows of services to economic systems either as direct inputs to production, indirect contributions to welfare (i.e. amenity values) or as sinks for the wastes / pollution generated by production.

The rest of the chapter is structured as follows. Given the separate development of the optimal foreign borrowing and resource depletion literatures, the initial focus is on the foreign borrowing decision and the key results which emerge from examination of an open economy growth model. The model is outlined in section 2.2 with some standard results derived as a way of elaborating on the issue of optimal debt accumulation. The chapter then moves on to consider, briefly, optimal resource depletion in the closed economy. Section 2.3 outlines some of the key results which have emerged in this literature. Once the analysis is extended to the open economy some interesting differences emerge and the issues of optimal resource use and optimal debt accumulation can be considered jointly. Section 2.4 presents the overview of the optimal use of natural resources in the open economy setting. One of the key findings to emerge is the role that capital market imperfections, in the form of an upward sloping supply curve for international credit, play in providing a link between resource use decisions and the indebtedness situation of the economy. This theme of imperfections is continued further in the concluding section. A brief outline of recent literature on sovereign debt is used to motivate an alternative interpretation of imperfect international capital markets. This is the idea of credit ceilings which has been considered widely in the theoretical and empirical literatures on sovereign debt. This type of imperfection provides much of the focus for the theoretical and empirical analysis in the remaining chapters of the thesis.

## **2.2 Optimal foreign borrowing in open economies.**

Bardhan (1967) and Hamada (1969) represent early contributions to the analysis of optimal growth in open economies with access to international capital markets. In this section the insights provided by these contributions are discussed within the context

of a simple model of optimal foreign borrowing. The intention therefore is not to be comprehensive in the sense of detailing the large literature which has subsequently followed these initial contributions. For surveys of this literature see McDonald (1982), Glick and Kharas (1986), Eaton and Taylor (1986), Eaton (1989) and Cohen (1991), and see also the discussions in Kletzer (1988) and Eaton (1993). This section, by way of contrast with these earlier reviews, restricts its attention to a simple analytical framework which conveys the key ideas and results in the optimal foreign borrowing literature.

To illustrate optimal foreign borrowing decisions consider the following model of savings and investment in small open economies presented by Blanchard and Fischer (1989). The economy produces a single good which may be consumed or invested. The opportunities afforded by the economy's domestic production possibilities are augmented by access to international capital markets which are taken to be perfect. The notion of a perfect international capital market is to be understood in the following sense. The economy is able to freely borrow at a given rate of interest subject only to the restriction of solvency. In other words the ability to borrow foreign capital is not unlimited, even in a perfect international capital market. Such a restriction is obvious from the perspective of international lenders. Without the solvency restriction the borrowing economy could borrow indefinitely to finance its debt service obligations implying that lenders as a group incur losses on their lending. In other words the net transfer of resources is always in the direction of the borrower. More formally, debt accumulation with perfect capital markets must satisfy two conditions. Firstly, the level of accumulated debt in any period must be less than or equal to the present discounted value of the borrower's future income stream, i.e. the borrower is solvent. Secondly, the accumulation of debt is subject to a transversality condition which ensures the discounted value of future debt cannot be positive. This

need not rule out the possibility that the economy remains a net debtor for the infinite future, but it does require that in the long-run the level of indebtedness cannot grow faster than the rate of interest (Eaton, 1993).

The social planner for this simple economy faces two questions: should debt be accumulated and if so, what should be the time profile of the economy's debt over the planning horizon ? The answer to the first question will be determined by one of two factors. First whether the planner wishes to expand the capital stock / productive base of the domestic economy beyond that allowed by domestic savings. The second will depend on whether the planner wishes to compensate for an uneven profile of domestic income / output with borrowing to smooth consumption over time. In the case of the latter borrowing may be a means of postponing structural adjustments to adverse income shocks (Martin and Selowsky, 1983; Pitchford, 1989). In the context of developing countries both factors are clearly relevant. Foreign borrowing provides a means of achieving a rate of capital accumulation beyond the constraints of low domestic savings and import capacities or, in the terms of the early development economics literature, of overcoming the "dual gap" (see Eaton, 1989 for discussion). Additionally, in the face of international macroeconomic shocks in the 1970s and 1980s, for many developing economies foreign borrowing provided a bridge between rising expectations and falling income growth and thus obviated any short-run need for structural adjustments at the macroeconomic level. The high debt burdens of the 1980s arose in part from the (over) willingness to use foreign borrowing to finance immediate consumption rather than investment (Allsopp and Joshi, 1985; Dornbusch and Fischer, 1985; Sachs, 1989).

These general considerations can be made more concrete by considering in more formal terms the optimisation problem faced by the social planner and its solution. In

anticipation of a key result this will:

"normally depict economies as progressing towards a stable equilibrium, characterised by equality between the marginal productivity of capital, the social discount rate and the marginal cost of (foreign) funds." (Glick and Kharas, 1986, p. 293)

Assume the planner wishes to maximise the integral of discounted utility from consumption over an infinite planning horizon.<sup>2</sup> That is:

$$(2.1) \quad \max V = \int_0^{\infty} u(c(t))e^{-\delta t} dt$$

where  $\delta$  denotes the utility rate of discount and the utility function  $u(\cdot)$  satisfies the standard properties, i.e.  $u_c > 0$ ,  $u_{cc} < 0$ ,  $u_c(0) = \infty$  and  $u_c(\infty) = 0$ .<sup>3</sup>

The economy's domestic production possibilities are described by:

$$(2.2) \quad y(t) = f(k(t)),$$

where  $k$  denotes the stock of domestic reproducible capital per capita and the production function obeys  $f_k > 0$ ,  $f_{kk} < 0$ ,  $f_k(0) = \infty$  and  $f_k(\infty) = 0$ .

The economy faces two intertemporal constraints on this maximisation:

$$(2.3) \quad \dot{d}(t) = c(t) + i(t)\{1 + A(i(t)/k(t))\} + r(t)d(t) - y(t),$$

$$(2.4) \quad \dot{k}(t) = i(t).$$

The accumulation of debt,  $d(t)$ , as defined in (2.3) is equal to the excess of absorption (consumption plus investment spending less interest payments on debt, where  $r(t)$  is the given market rate of interest) over production, i.e. debt is accumulated to finance

---

<sup>2</sup>All variables are defined in per capita terms.

<sup>3</sup>Subscripts denotes derivatives with respect to the argument of the function.

current account deficits. Alternatively, using (2.4) and noting that domestic savings in equilibrium are given by  $s(t)=y(t)-c(t)-r(t)d(t)$ , the change in debt over time or the current account balance equals the difference between investment spending and domestic savings. Thus in this simple model debt may be used to finance consumption or investment. Note that by (2.4) capital accumulation is not identical to investment spending; investment spending of  $i(t)\{1+A(i(t))/(k(t))\}$  is required to accumulate capital of  $i(t)$ . This indicates that investment is not costless in the sense that adjustment of the capital stock incurs installation costs of  $A(.)$  per unit of investment, i.e. the economy foregoes output by devoting resources to the installation of new capital. This cost function  $A(.)$  is assumed convex.<sup>4</sup> Introducing these capital installation costs, as Blanchard and Fischer note, will make investment and saving decisions distinct, a feature which is reinforced by the introduction of foreign borrowing to the model.<sup>5</sup>

The planner now maximises (2.1) subject to (2.3) and (2.4) with  $d(0)$  and  $k(0)$  assumed given. To solve this problem define the current value Hamiltonian given by:<sup>6</sup>

$$(2.5) \quad H(d, k, c, i, \lambda, \psi) = u(c) - \lambda \left( c + i \left\{ 1 + A(i/k) \right\} + rd - f(k) \right) + \psi i,$$

where  $\lambda(t)$  and  $\psi(t)$  are the respective co-state variables (interpreted as shadow prices) for the state variables debt and capital. Note that the current value Hamiltonian (2.5) can be interpreted as a measure of the net national product (NNP), measured in the utility numeraire, of this economy at instant  $t$ . NNP therefore comprises the current flow of consumption benefits and the value of growth in the state variables at instant  $t$ .<sup>7</sup> However, since the accumulation of debt increases the

---

<sup>4</sup>It is also assumed that  $A(0)=0$ .

<sup>5</sup>This model in effect represents an open-economy extension of Abel and Blanchard (1983).

<sup>6</sup>That is the Hamiltonian is defined such that it represents a value in period  $t$ . Note also that time notation is omitted for brevity.

<sup>7</sup>See for example Dasgupta (1995).

economy's external liabilities, an increase in the value of the economy's debt should reduce NNP at instant  $t$ . Hence the minus sign on  $\lambda(t)$  in (2.5).

Necessary and sufficient conditions for a solution to this problem are given by:<sup>8</sup>

$$(2.6) \quad H_c = 0: \quad u_c = \lambda,$$

$$(2.7) \quad H_i = 0: \quad \lambda(1 + A(i/k) + (i/k)A_i(i/k)) = \psi,$$

$$(2.8) \quad \dot{\lambda} = (\delta - r)\lambda,$$

$$(2.9) \quad \dot{\psi} = \delta\psi - (f_k + (i/k)^2 A_i)\lambda,$$

$$(2.10) \quad \lim_{t \rightarrow \infty} \lambda e^{-\delta t} = 0,$$

$$(2.11) \quad \lim_{t \rightarrow \infty} \psi k e^{-\delta t} = 0.$$

For optimal consumption plans at each instant (2.6) gives the condition that the marginal utility of consumption is equal to its shadow price. With respect to an optimal path for investment, (2.7) gives the condition which is required to be satisfied at each instant. Defining  $q = \psi/\lambda$  where  $q$  is the shadow price of installed capital relative to the shadow price of consumption, (2.7) can be written as:

$$(2.12) \quad q = 1 + A(i/k) + (i/k)A_i(i/k),$$

which states that at the margin the real value of additional capital is equated with its real marginal cost. Note this marginal cost has two components: the cost of foregone consumption and the cost of installing capital. Eq. (2.12), as noted by Blanchard and Fischer (1989), highlights that investment is a function only of  $q$ . That is, (2.12) implies  $q$  can be expressed in terms of the function  $q = \Psi(i/k)$  with  $\partial\Psi/\partial(i/k) > 0$  and  $\Psi(0) = 1$ . Equally, by defining the inverse function  $\phi(q)$ , (2.12) also implies  $i/k = \phi(q)$  with  $\partial\phi/\partial q > 0$  and  $\phi(1) = 0$ . Eqs.(2.10) and (2.11) are the transversality conditions

---

<sup>8</sup>Sufficiency requires the Hamiltonian to be concave which is guaranteed by the assumptions of concave utility and production functions and a convex installation cost function.

on debt and capital accumulation respectively. Note then that (2.10) expresses the restriction on borrowing already noted. In the limit (i.e. the infinite future) the discounted value of the economy's debt is zero.

Now consider the question of optimal debt accumulation for this economy. This, as noted earlier, implies analysis of current account dynamics which depend on the optimal paths of investment and domestic savings. These two determinants of debt accumulation, as Blanchard and Fischer note, will be independent given access to capital markets at an exogenous rate of interest.<sup>9</sup> In other words, the maximisation of present value wealth and present value utility can be determined separately. More specifically, the implied dynamics of the economy are recursive. The maximisation of present value wealth determines optimal time paths for investment, capital and output. Given this, the dynamics of consumption, saving and debt can then be determined.

Consider initially therefore the dynamics of investment and capital. To simplify the analysis, the economy's discount rate is assumed equal to the exogenous rate of interest. This, as noted by Blanchard and Fischer, avoids the need to specify the time path for  $r$  as the economy converges to its steady-state equilibrium. Moreover, this assumption ensures that the rate of interest is indeed exogenous with respect to the economy's accumulation / decumulation of foreign liabilities. To illustrate, substituting (2.6) into (2.8) gives:

$$(2.13) \quad \delta - r = \frac{u_{cc}}{u_c} \dot{c},$$

which by defining the constant  $\eta(c)$ , the elasticity of the marginal utility of consumption with respect to consumption, by  $\eta(c) = -c u_{cc}/u_c$ , allows (2.13) to be re-written as:

---

<sup>9</sup>This is a standard result with perfect capital markets which is referred to as the Separation Theorem. This is discussed in more detail in section 2.4.

$$(2.14) \quad \frac{\dot{c}}{c} = \frac{(r - \delta)}{\eta}.$$

Eq. (2.14) describes optimal consumption over time and is shown to depend on the discount rate, the elasticity of marginal utility of consumption and the marginal cost of borrowing or the world rate of interest. This is of course Ramsey's famous rule of optimal saving. Note from (2.14) that  $r > \delta$  implies consumption growth is positive and for  $r < \delta$  it is negative. In the case of the latter the economy is decumulating (accumulating) foreign liabilities (assets), which if maintained for the indefinite future might imply the economy becoming a net lender of a size to influence the determination of world rates of interest. Conversely, in the former case the economy is accumulating (decumulating) foreign liabilities (assets). Again, if maintained indefinitely the economy may become a large debtor with influence over international rates of interest. The assumption of  $r = \delta$  thus avoids the possibility that the rate of interest may become endogenous at some point in the indefinite future and thereby ensures consistency with the type of capital market considered here.

Using the inverse function implied by (2.12), the dynamics of the capital stock given by (2.4) can be re-written as:

$$(2.15) \quad \dot{k} = i = k\varphi(q),$$

whilst the time change in the shadow price  $q$  by definition satisfies  $\dot{\psi} = \dot{q} + \dot{\lambda}$ . Note the assumption  $r = \delta$  simplifies this definition to  $\dot{\psi} = \dot{q}$  which allows (2.9) to be expressed as:

$$(2.16) \quad \begin{aligned} \dot{q} &= \delta q - f_k + (i/k)^2 A_i(i/k) \\ &= \delta q - f_k + (\varphi(q))^2 A_i(\varphi(q)). \end{aligned}$$

(2.15) and (2.16) can now be used to characterise the steady-state equilibrium in  $(k, q)$

space for the economy. For  $\dot{k} = 0$ , (2.15) combined with the properties of the function  $\Psi(i/k)$  define the steady-state shadow price  $q^* = 1$ . It follows from (2.16) for  $\dot{q} = 0$  and the properties of  $\varphi(q)$  that the steady-state capital stock is chosen such that  $f_k(k^*) = r = \delta$ . Thus as anticipated by the quote from Glick and Kharas (1986), the steady-state equilibrium is characterised by the equality between the marginal productivity of capital, the rate of discount and the marginal cost of borrowing. This constitutes the basic result of the OFB literature.<sup>10</sup> It remains to confirm the Glick and Kharas observation that this equilibrium is stable. Linearising (2.15) and (2.16) around this steady-state gives (see Blanchard and Fischer, 1989):<sup>11</sup>

$$(2.17) \quad \begin{bmatrix} \dot{k} \\ \dot{q} \end{bmatrix} = \begin{bmatrix} 0 & k^* \varphi_q(q^*) \\ -f_{kk}(k^*) & 0 \end{bmatrix} \begin{bmatrix} k - k^* \\ q - 1 \end{bmatrix}.$$

The Jacobian determinant in (2.17) is negative which indicates the presence of a positive and a negative eigenvalue. The steady-state is therefore stable in the saddlepoint sense. Figure 2.1 illustrates the associated phase diagram and may be interpreted as follows. Suppose the initial capital stock is below the steady-state value. The corresponding initial value for  $q$  is determined by the saddlepath and so  $q_0 > 1$  ( $q^*$ ). Initial investment is therefore positive since the shadow price of capital must exceed the shadow price of consumption. Capital is therefore accumulated, but by decreasing amounts as the economy converges to  $k^*$  and  $q^* = 1$ . Total output and net output (i.e. total output less investment expenditure) increase over time as the economy converges to the steady-state.<sup>12</sup>

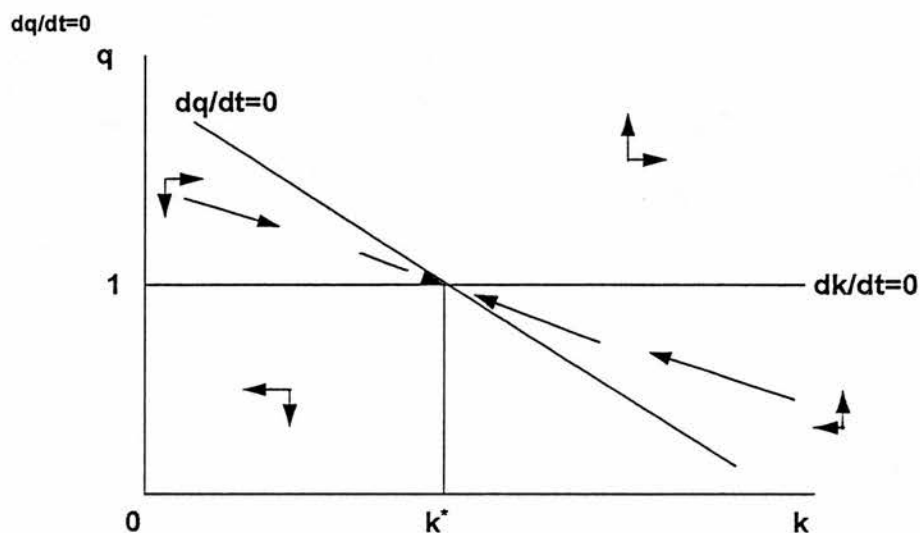
---

<sup>10</sup>One exception to this is the interesting case analysed by Long (1974) where international borrowing funds the capital expenditure required for resource extraction. In this case borrowing has an additional shadow cost, namely the user cost of the resource which the capital is used to deplete.

<sup>11</sup>Linearising around the steady state implies attention is restricted to local stability, i.e. the dynamic properties of the model in the local neighbourhood of the steady-state.

<sup>12</sup>If  $k > k^*$  then  $q_0 < 1$ , i.e. the shadow price of consumption exceeds that of capital. Capital is therefore "consumed" rather than accumulated with the effect that the capital stock and output decline as the economy converges to  $k^*$ .

Figure 2.1: Investment and capital dynamics



Source: Blanchard and Fischer (1989)

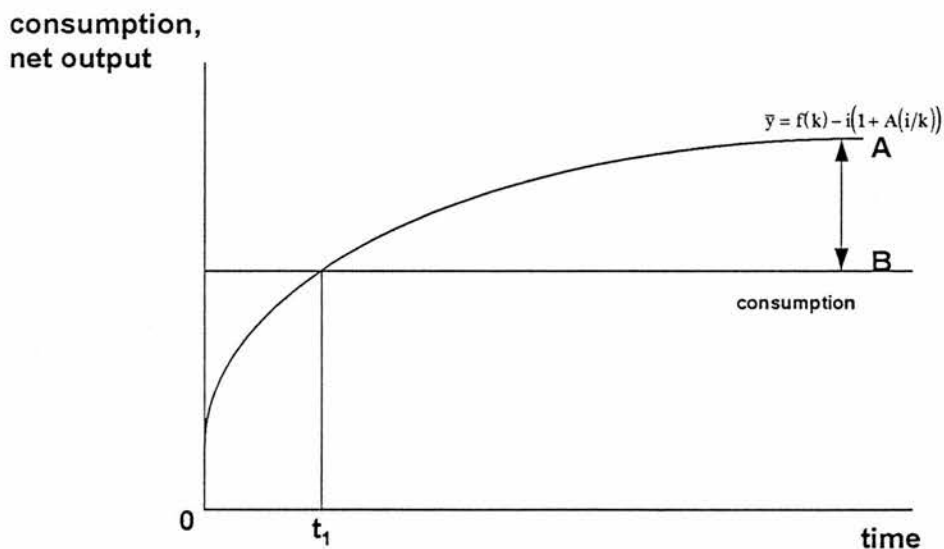
Now consider the economy's accumulation of debt. Debt dynamics are determined by (2.3) where the only unknown, given the paths of investment, capital and output, is consumption. The assumption  $r = \delta$  will imply consumption is constant over time (see (2.13)). In addition this constant level of consumption must be chosen such that in the steady-state:

$$(2.18) \quad f(k^*) - c^* = rd^*,$$

i.e. interest payments on the steady-state level of debt are matched by the steady-state trade surplus. Figure 2.2 illustrates a plausible scenario for the evolution of the economy's debt. In this scenario it is assumed (for simplicity) that the initial level of debt is zero. Between  $t = 0$  and  $t = t_1$ , the economy is running a trade deficit which is financed by foreign borrowing. As net output,  $\bar{y} = f(k) - i(1 + A(i/k))$ , increases over time (recall earlier discussion of investment and capital stock dynamics), but

consumption is constant, the economy reaches balanced trade at  $t_1$ . At this point debt accumulation is financing debt interest payments. With net output continuing to rise as the economy converges to the steady-state, after time  $t_1$  the burden of debt servicing is increasingly financed from trade surpluses, i.e. the excess of net output over consumption. Debt is still being accumulated at this time, but at a decreasing rate. This accumulation is chosen such that in the steady state (2.18) is satisfied. In Figure 2.2 distance AB is the trade surplus which equals interest payments in the steady state.

Figure 2.2: Evolution of foreign borrowing over time



For this accumulation of debt to be optimal a further condition is required. That is:

$$(2.19) \quad \int_0^{t_1} (c - \bar{y}) e^{-\pi t} dt = \int_{t_1}^{\infty} (\bar{y} - c) e^{-\pi t} dt,$$

which states that in present value terms current and future trade surpluses sum to zero. In terms of Figure 2.2, the constant level of consumption and steady state level of debt are chosen such that the area between the time path of consumption and net

output up to  $t_1$  in present value is equal to the area between the two time paths after  $t_1$  in present value.

To summarise, the model of open economy investment and saving considered in this section suggests two important conditions govern the optimal foreign borrowing decision. The first is that efficient accumulation of debt requires the marginal cost of borrowing to equal the marginal product of capital, and in turn the rate of discount. The second is that investment, capital, consumption and debt should evolve over time such that in the steady-state equilibrium debt interest payments are financed by the surplus of net output over consumption. This first condition is the usual efficiency condition from capital theory: at the margin the rate of return on alternative assets should be equalised. As will become evident in sections 2.3 and 2.4 the solution to any problem which can be characterised in terms of the efficient management of capital assets will yield this result. It is this similarity in the structure of optimal foreign borrowing to that of optimal resource depletion which makes the framework of intertemporal allocation an appealing framework for the analysis of a debt-resources link.

### **2.3 The optimal use of natural resources in the closed economy.**

In this section a brief overview of the theory of optimal resource use in the closed economy context is provided. The intention, as with the discussion of optimal foreign borrowing, is not to be comprehensive, but rather to outline the basic structure of the resource use problem and identify some key results.

A basic distinction in the natural resources literature is between exhaustible resources the stock of which (known and unknown) is finite and fixed and renewable resources

where stocks can be replenished by regenerative processes. Initially the case of exhaustible resources is considered, but as developed later this is easily extended to the case of renewable resources.

The issue of the optimal depletion of exhaustible resources has, particularly since the resource "scare" of the early 1970s, been the subject of a large economic literature.<sup>13</sup> This literature has addressed two key issues. Firstly what conditions characterise the optimal depletion of a stock of exhaustible resource and secondly, is the finite nature of the resource a limit to economic activity? Amongst others these questions have motivated the analyses presented by Koopmans (1973), Vousden (1973), Dasgupta and Heal (1974, 1979) and Solow (1974). A succinct overview is provided in Heal (1993). For the sake of brevity, the discussion in this section will focus on the first issue. For a flavour of the debate on the second issue see Dasgupta and Heal (1974, 1979) and Victor (1991).

The simplest model presents the "cake-eating problem". This seeks to solve the problem of allocating optimally a fixed stock of exhaustible resource. The problem is then simply to maximise the same objective as in (2.1) but over a finite time period subject to the constraint:

$$(2.20) \quad \dot{S} = -c, \quad S(t) = S(0) - \int_0^t c(t) dt,$$

where  $S_0$  is the initial stock of the resource. The relevant current value Hamiltonian is then defined by:

---

<sup>13</sup>The issues are not entirely new. To quote Hotelling (1931): "Contemplation of the world's disappearing supplies of minerals, forest and other exhaustible assets has led to demands for the regulation of their exploitation. The feeling that those products are now too cheap for the good of future generations, that they are being selfishly exploited at too rapid a rate, and that in consequence of their excessive cheapness they are being produced and consumed has given rise to the conservation movement."

$$(2.21) \quad H = u(c) - \phi c,$$

where  $\phi$  is the co-state variable interpreted as the shadow price of resource stock. Two results then emerge. First that efficiency requires the present value of marginal utility to be equal in all time periods and second, the discount rate and the elasticity of marginal utility of consumption determine the optimal depletion path which in this case is also the path for consumption. The problem of allocating a fixed stock of natural resource leads to an equivalent expression to (2.14) given by  $\dot{c}/c = -\delta/\eta$ . This states that the rate of growth in consumption (extraction) declines over time for a positive discount rate and moreover, a higher discount rate implies consumption / extraction declines more quickly with a shift of extraction from the future to the present. The discount rate also determines the optimal path for the shadow price of the resource stock with the equation of motion for the co-state from (2.21) given by  $\dot{\phi}/\phi = \delta$ ; the standard Hotelling rule. This rule can be interpreted as saying that the capital gain from holding resource stock should rise at the rate of discount, i.e. the return on alternative assets.

A more interesting problem than this simple cake-eating one is the situation where the finite stock of resources are used as an input to production. The economy now has two state variables to control: the stock of natural resource as in the cake-eating problem and the stock of reproducible capital. A key feature of the model is that this latter capital stock and the flow of extraction represents inputs to the production process which is summarised by constant returns to scale technology. Note also the reproducible nature of non-resource capital implies the allocation problem is not restricted to a finite time horizon if reproducible capital can substitute for resource inputs. The basic problem is then, as before, to maximise the integral of discounted

utility subject to:<sup>14</sup>

$$(2.22) \quad \dot{K} = f(K, R) - c; \quad \dot{S} = -R,$$

where  $F(K, R)$  denotes the production function,  $K$  is the stock of reproducible capital and  $R$  is the flow of extraction. Again denoting the co-state for the resource stock by  $\phi$  and the co-state for capital as  $\psi$ , necessary conditions for a solution are given by:

$$(2.23) \quad u_c = \psi, \quad \phi = \psi F_R,$$

$$(2.24) \quad \dot{\phi} = \delta\phi, \quad \dot{\psi} = (\delta - F_K)\psi.$$

Thus at each point in time marginal utility equals the shadow price of capital, the real resource rent  $\phi$  (i.e. relative to  $\psi$ ) at the margin equals the marginal product of the resource, whilst over time the Hotelling rule emerges for the resource rent and the rate of change in  $\psi$  is determined by the discount rate and the marginal product of capital. These expressions combined provide insight into the optimal time paths for consumption and extraction over time. For consumption the usual Ramsey rule follows as:

$$(2.25) \quad \frac{\dot{c}}{c} = \frac{(F_K - \delta)}{\eta},$$

which compared to the cake-eating problem shows that the ability to substitute for  $R$  in production allows consumption to increase (or at least not fall) along the optimal path. Moreover given  $f_k = r$  in the context of the optimal foreign borrowing problem, (2.25) and (2.14) are equivalent expressions (in different contexts) which shows that the conditions for an optimal consumption path in models with foreign borrowing and exhaustible resource extraction are essentially the same. The point made earlier is worth re-iterating. This equivalence follows from viewing both problems in terms of the intertemporal management of capital assets. Thus there is a striking similarity to

---

<sup>14</sup>Note here that the variables are not defined in per capita terms.

the problems of optimal foreign borrowing and resource depletion.

For extraction, a little manipulation of the necessary conditions permits the derivation of:

$$(2.26) \quad \frac{\dot{R}}{R} = \frac{-F_K}{\eta_R},$$

where  $\eta_R = -RF_{RR}/F_R$  is the elasticity of the marginal product of extraction with respect to extraction. Thus the rate at which extraction now decreases along the optimal path is governed by the marginal product of capital and the production technology. An equivalent way of stating (2.26) would be that intertemporal efficiency requires the rate of increase in the marginal productivity of the resource to equal the marginal product of capital. An intuitively obvious finding when resources are viewed as capital assets. Moreover this optimality condition which equates the rates of return also sheds light on the issue of substituting reproducible inputs K for resource inputs in production. Thus note that (2.26) implies  $\dot{F}_R/F_R = F_K$  and define  $x \equiv K/R$  (i.e. the capital to resource ratio) and  $f(x) = F(K/R, 1)$ . Since  $F(\cdot)$  satisfies homogeneity of degree one the marginal productivity of the natural resource can be defined in terms of  $x$  alone, i.e.  $F_R = f(x) - xf_x$ , and it also follows  $F_K = f_x > 0$ ,  $F_{KK} = f_{xx} < 0$ . The elasticity of substitution ( $\sigma$ ) between K and R is also usefully expressed in terms of  $x$ . That is:

$$(2.27) \quad \sigma = \frac{-f_x(f(x) - xf_x)}{xf(x)f_{xx}},$$

which implies  $\dot{F}_R/F_R = F_K$  can be written as:

$$(2.28) \quad \frac{\dot{x}}{x} = \sigma \frac{f(x)}{x}$$

Thus the rate at which the capital to resource ratio changes equals the product of the

elasticity of substitution between K and R and the average productivity of reproducible capital inputs. Evidently, the greater the ease of substitution and the larger the "importance" of K in production, then the rate at which K is substituted for R will be higher. Dasgupta and Heal (1974, 1979) identify  $\sigma$  as a crucial parameter in terms of the debate concerning exhaustibility and the limits to economic activity.<sup>15</sup> However, the ease of capital-resource substitution is not the only issue. Two further conditions are also of relevance. The first is the nature of the production technology and whether resource inputs are essential to production. Dasgupta and Heal argue that the debate about exhaustibility makes most sense when resource inputs are essential to production. An example of such a technology would be Cobb-Douglas. However, it is well known that with Cobb-Douglas production functions the elasticity of substitution is one. The key parameters are then the elasticities of output with respect to capital and resource inputs, i.e. the exponents in the Cobb-Douglas specification. So long as the capital elasticity is greater than the resource elasticity, then output and consumption growth can be maintained indefinitely. That is, the exhaustibility of resources is not a constraint on economic activity. Dasgupta and Heal (1979) take comfort from the historical observation that the factor share of capital is approximately four times larger than that of resource inputs. A second issue is whether it is fact optimal to exhaust the resource in finite time. If the marginal productivity of resource inputs tends to infinity as the level of resource inputs tends to zero, then it can never be optimal to exhaust the resource stock (see Dasgupta and Heal, 1974 for details).<sup>16</sup>

This basic analysis of exhaustible resource use in closed economies has been extended in a number of ways, a few of which given the analysis to be presented in chapter 3

---

<sup>15</sup>For a succinct overview see Victor (1991).

<sup>16</sup>It can be also noted here that the supporting empirical evidence provides only limited support for the approach to resource use considered here. Chapter 3 provides more detailed discussion of this evidence and related issues.

are worthy of note.<sup>17</sup> One extension has been the introduction of extraction costs. Solow and Wan (1976), for example, introduce differential costs of extraction to the standard marcoeconomic problem of optimal depletion. The differentials arise from the assumption of differences in ore grade qualities. Their analysis presents two findings of interest. First, they show that it is rational, i.e. efficient, to fully exploit low cost resource deposits before extracting from the high cost deposit. Weitzman (1976) and Hartwick (1978) have reached similar conclusions. Second a wedge, termed the degradation cost, is created between the shadow price of resources and the shadow value of the marginal productivity of the resource (recall eq. 2.23). This cost arises because depletion of low cost resources in the present implies higher costs for every unit extracted in the future. With respect to the latter Heal (1976) arrives at very similar conclusions. Extraction costs are introduced with average costs an increasing function of cumulative extraction. Heal, like Solow and Wan, then shows that efficiency requires the shadow value of resource productivity to be equated with the full social cost of extraction which comprises marginal extraction cost and a "surcharge" for the impact of current extraction on future costs. The analysis to be presented in chapter 3 has similar features. Solow and Wan's result that low cost resources are depleted first is reflected in the assumption that extraction costs are a decreasing function of remaining reserves. Further, the degradation effect found by Solow and Wan, or equivalently Heal's "surcharge" reflect the notion of "user cost" familiar from the analysis of resource extraction at the level of individual mines / firms. This "user cost" is also a feature of the analysis presented in chapter 3.

A second extension of the basic model which has been extensively investigated is the role of uncertainty in resource use decisions. Fisher (1981) provides a concise summary of the different types of uncertainty relevant in the analysis of optimal

---

<sup>17</sup>Devarajan and Fisher (1981) provide a concise overview of these extensions.

resource depletion. The first is uncertainty associated with resource demand and where uncertainty is related to the time horizon, i.e. resource extractors are less certain about demand conditions a decade away compared to those one year into the future. In this case Weinstein and Zeckhauser (1975) show uncertainty creates an incentive to shift extraction to the present. However, demand uncertainty may also create incentives for extraction to be deferred to the future. Assuming variations in the returns from extraction to be proportional to the level of extraction itself, Lewis (1977) has shown that with risk aversion extraction is shifted to the future. This result simply reflects the idea that with extraction falling monotonically over time, then so must the variation in returns. A third type of demand uncertainty arises from the introduction of cheaper substitutes or a new backstop at some unknown future date.<sup>18</sup> Dasgupta and Heal (1974) show that with the uncertain arrival of a technological innovation which presents a substitute to an exhaustible resource, resource depletion will shift to the present since the introduction of uncertainty requires an increase in the utility discount rate.<sup>19</sup> A final type of uncertainty concerns the supply side. Here uncertainty concerns the size of the resource stock. Intuitively, if resource extractors are risk averse and are extracting from a stock of unknown size then there will be an incentive to conserve the resource and shift depletion to the future, see for example Gilbert (1979) and Loury (1978). Hoel (1978) provides a variation of this analysis by also introducing uncertainty about future extraction costs. He shows that by contrast with the effect of an increase in stock uncertainty, increases in cost uncertainty lead to a shift of extraction to the present. This arises simply because expected welfare is decreasing in stock uncertainty, but increasing in future cost uncertainty. The analysis to be presented in chapter 3 considers a resource depletion problem where the decision maker faces uncertainty about future price and cost conditions. Thus

---

<sup>18</sup>The threat of expropriation would also come into this category. See Long (1975).

<sup>19</sup>More precisely they show that the certainty equivalent problem is solved with the use of a discount rate which is modified to include the probability of the substitute arriving at time  $t$  conditional on no previous arrival.

elements of demand and supply uncertainty are a feature of the analysis presented in the next chapter.

The discussion so far of optimal resource use in the closed economy can be considered a special case of the more general problem of renewable resource use. To motivate some of the analysis in the open economy context, consider now this more general problem. The simplest approach is to modify the resource use constraint to:

$$(2.29) \quad \dot{S} = g(S) - R,$$

where  $g(S)$  defines a stock replenishment or growth function. This function is usually assumed to be concave and positive in the interval  $[0, S^{\max}]$ , see for example Clark (1976). Note  $S^{\max}$  denotes the equilibrium level of stock that obtains in the absence of resource exploitation. From (2.29) it is evident that the equation of motion for the resource co-state  $\phi$  is modified to:

$$(2.30) \quad \dot{\phi} = (\delta - g_s) \phi,$$

implying that the rate of increase in the resource rent is now given by the rate of discount less the marginal physical return to holding resource stock. It then follows that optimal resource use requires the rate of growth in the marginal productivity of resource inputs to be equalised with the marginal product of capital net of the marginal growth in resource stock since the opportunity cost of resource use is lower given the stock is now capable of regeneration. Note also from (2.30) the steady-state equilibrium condition is  $g_s = \delta$ . This implies in equilibrium resource exploitation is less than the maximum sustainable yield since at this rate of use  $g_s = 0$ .

## 2.4 The optimal use of natural resources in the open economy.

Early extensions of the closed economy analysis of the optimal use of natural resources to the open economy context are provided in Dasgupta, Eastwood and Heal, hereafter D, E & H, (1978) and Aarrestad (1978, 1979).<sup>20</sup> In the former the case of an open economy endowed with a stock of exhaustible resources is considered.<sup>21</sup> This resource can either be exported or used in domestic production. Reproducible capital, in addition, is now held in the form of domestic capital or foreign investments which can earn interest at rate  $r$ . The issues addressed in Aarrestad (1978) are similar with an intertemporal choice problem which focuses on the optimal use of an exhaustible resource and optimal capital accumulation in the open economy context, whilst Aarrestad (1979) analyses explicitly the issue of optimal debt accumulation for a small open economy exporting an exhaustible resource.

In general terms these extensions to the closed economy analysis can be viewed as a bringing together of the analyses previously outlined in sections 2.2 and 2.3.<sup>22</sup> Taken together the models of optimal foreign borrowing and optimal resource extraction have comprised a total of three capital assets: foreign assets (in 2.2 defined to be negative), domestic reproducible capital and natural capital. In the analysis of optimal growth in open economies endowed with natural resources it would therefore be appropriate to consider all three capital stocks implying consideration of the optimal

---

<sup>20</sup>The analysis of resource extraction in a trading economy by Vousden (1974) is another example. However since this analysis assumes balanced trade, unlike the papers by D, H & E and Aarrestad the link between resource use and international capital flows cannot be addressed.

<sup>21</sup>Note that the description "small" is not attached to this economy since D, E & H assume that the export price for the resource is a function of this economy's level of export.

<sup>22</sup>In the case of D, E & H the assumption is that the economy is a net creditor with outstanding foreign assets defined as total accumulated financial wealth less domestic reproducible capital. Note however defining this stock of wealth to be negative implies that the economy can be interpreted as a net debtor with  $r$  denoting the marginal cost of foreign liabilities, i.e. borrowing.

time paths for domestic capital accumulation, foreign capital (debt) accumulation and resource use. In general however the analysis of intertemporal problems with three state variables is complex since a system of six differential equations is implied (equations of motion for state and co-state variables). Consequently the literature on the optimal use of resources in the open economy has focused on simplified models to permit the analysis of dynamic systems with at most two state variables. Thus in D, E & H the state variables are the resource stock and  $W$  which denotes the sum of domestic and foreign capital. Aarrestad (1978) considers only  $S$  and  $K$  in the notation of section 2.3 and in Aarrestad (1979) the analysis is restricted to resource use and foreign capital flows (e.g. borrowing). A further restriction imposed by Aarrestad (1979) but not in D, E & H is the assumption that all resource extraction is exported. In the context of the debt-resources link it can be argued that the primary case of interest centres on resource exporters and the potential consequences that the economy's external indebtedness may have for extraction programs. For simplicity (and brevity) therefore, the remaining discussion of resource use in the open economy context will concentrate on the case of the resource exporter.<sup>23</sup>

A key result which emerges from the analysis of the resource exporter is highlighted by Siebert (1985). That is, optimal consumption and optimal resource extraction are independent when the economy has access to a perfect international capital market. This finding is an obvious analogue of Fischer's Separation Theorem which states production and exchange (i.e. consumption) decisions are independent if agents can freely borrow or lend on capital markets. (for detailed discussions of this theorem see Hirshleifer, 1970). In the present context the ability to borrow freely (subject to solvency) at a given rate of interest permits the separation of the maximisation of

---

<sup>23</sup>Though this implies consideration of a special case the key results outlined below would still emerge from a more general model where resource extraction can also be used in domestic production, see for example the analysis in Dasgupta, Eastwood and Heal (1978).

present value resource earnings from the maximisation of discounted benefits from consumption. This separation of extraction and consumption decisions can be illustrated by considering the intertemporal maximisation problem which faces the resource exporter. To simplify the problem capital accumulation is not considered. The state variables are thus the stock of debt and the stock of natural resources.

Consider an economy importing a single consumption good financed by the export of a natural resource which for the moment is treated as non-renewable. With the ability to borrow trade need not balance in every time period. In other words debt can be accumulated to finance any current account deficit. The intertemporal problem facing the social planner for this economy can be written as:

$$\max \int_0^{\infty} U(c)e^{-\delta t} dt$$

subject to:

$$(2.31) \quad \begin{aligned} \dot{d} &= rd + c - pq \\ \dot{s} &= -q \\ d(0) &= d_0, \quad s(0) = s_0, \end{aligned}$$

where  $c, d, s, r$  and  $\delta$  are defined as above. In addition  $p$  now denotes the exogenously determined real price (in terms of consumption imports) of the exported resource  $q$ . Note that for simplicity extraction is assumed to be costless.

The current value Hamiltonian for this problem is written as:

$$(2.32) \quad H = u(c) - \phi q - \lambda(rd + c - pq),$$

where as before  $\phi$  denotes the shadow price of resource stock and  $\lambda$  is the shadow cost of foreign borrowing. The canonical system of equations given by:

$$(2.33) \quad u_c - \lambda = 0,$$

$$(2.34) \quad \dot{\phi} - \lambda p = 0,$$

$$(2.35) \quad \dot{\lambda} = (\delta - r)\lambda,$$

$$(2.36) \quad \dot{\phi} = \delta\phi,$$

$$(2.37) \quad \dot{d} = rd + c - pq,$$

$$(2.38) \quad \dot{s} = -q,$$

together with the transversality conditions  $\lim_{t \rightarrow \infty} e^{-\delta t} \lambda(t) d(t) = 0$  and  $\lim_{t \rightarrow \infty} e^{-\delta t} \phi(t) s(t) = 0$

describe necessary and sufficient conditions for an optimal solution.

Differentiating (2.34) with respect to time and using (2.35) and (2.36) it can be observed that:

$$(2.39) \quad \frac{\dot{p}}{p} = r,$$

i.e. the rate of change in the resource price is determined entirely by the given rate of interest. In other words the time path for the resource price follows Hotelling's rule. It is also implied that the optimal time profile for extraction is independent of the time path of consumption.<sup>24</sup> Note that substituting (2.34) into (2.32) allows the current value Hamiltonian to be written as:

$$(2.40) \quad H = u(c) - \lambda(rd + c).$$

Thus with the condition for optimal extraction satisfied, the social planner can independently choose the level of consumption which maximises (2.40). Moreover, note (2.34) and the optimal extraction program can be obtained from maximising the present value of resource export earnings ( $pq$ ) over the period  $[0, T]$  where the rate of discount employed is the given rate of interest  $r$  (Siebert, 1985). In other words consumption and extraction decisions can be made separately. One consequence of this is that extraction decisions are now independent of preferences. Aarrestad (1979)

---

<sup>24</sup>The optimal time-path for consumption is given by the usual Ramsey rule, see eq. (2.14).

demonstrates this for the resource exporter by showing the utility discount rate to have no role in the time path for extraction. Even when some of the resource is employed in domestic production D, E & H (1978) show optimal extraction decisions in an open economy faced with perfect capital markets will be independent of preferences, i.e.  $\delta$  and  $\eta$ . This contrasts the analysis of section 2.3 which showed that optimal extraction in the closed economy would be sensitive to these preference parameters.<sup>25</sup> A second consequence of this separation result is that optimal extraction is determined independently of indebtedness. The assumption of a perfect capital market ensures exogenously determined interest rates for borrowers. A necessary condition for optimal extraction is that the shadow price of resource stock rises at a rate equal to this exogenous interest rate. The independence of interest rates with respect to levels of debt ensures extraction is determined independently of the economy's level of debt. In sum, the analysis so far suggests any link between resource extraction and indebtedness is ruled out under conditions of perfect markets for foreign capital. As a corollary, the existence of a relationship between resource extraction and external indebtedness would appear to require the presence of imperfections in international capital markets.

The role of imperfections in international capital markets as a determinant in resource extraction is demonstrated most clearly by the related analyses in Rauscher (1989, 1990). Imperfections in capital markets are introduced by dropping the assumption that the rate of interest payable on external debt is exogenous. Instead interest payments,  $r(d)d = h(d)$ , are a convex function of debt, i.e.  $h_d > 0$  and  $h_{dd} > 0$ . The risk of borrower default, which is pervasive in lending to sovereign borrowers, provides the rationale for this assumption. Since this risk is likely to increase with levels of

---

<sup>25</sup>This was obvious in the cake-eating problem, but less so in the closed economy model with production. Substituting for the marginal product of capital in (2.26) using (2.25) reveals the dependence of the optimal time profile for extraction on preferences.

indebtedness, interest rates will be also increasing in debt levels given an increasing default risk premium. This intuitively reasonable justification for a convex interest payments function has been demonstrated formally by Eaton and Gersovitz (1981). They show that in a market for international credit in which default penalties exist and lenders are competitive, equilibrium will be characterised by an upward-sloping supply curve for loans over the range  $[0, \bar{d}]$  where  $\bar{d}$  denotes the set of available loans.<sup>26</sup>

Rauscher considers a small open economy exporting a good which is produced with inputs of renewable natural resource and importing a single consumption good. Exports are given by the production function  $f(q)$  with  $f_q > 0$ ,  $f_{qq} < 0$ ,  $f_q(0) = \infty$  and  $f_q(\infty) = 0$ . Without loss of generality, export production is assumed costless. The resource constraint faced by the economy takes the form:

$$(2.41) \quad \dot{s} = g(s) - q \quad s_0 \text{ given,}$$

where  $q$  is the flow of extraction,  $s$  denotes the resource stock and  $g(s)$  is the regeneration function that satisfies the properties noted earlier in section 2.3. Debt flows comprise the only capital flows in the model. The balance of payments constraint is then denoted by:

$$(2.42) \quad \dot{d} = h(d) + c - pf(q) \quad d_0 \text{ given and } \lim_{t \rightarrow \infty} d(t) \leq d^\#,$$

where  $c$  is imported consumption and  $p$  is the real resource price (in terms of the consumption good). This resource price, given the small open economy assumption, is exogenous and for simplicity constant. Note also from (2.42) that the initial level of debt is given and debt accumulation in the long run is constrained by an upper limit  $d^\#$ . This is in essence a solvency condition which ensures the borrower cannot increase its debt without limit.

---

<sup>26</sup>For more details see Theorems 2 and 3 and the associated proofs in Appendix A of Eaton and Gersovitz (1981).

Subject to the constraints (2.41) and (2.42) the economy faces the standard Ramsey-type problem. That is to maximise the present value of future utility over the interval  $[0, \infty]$  from consumption. The current value Hamiltonian associated with this problem is:<sup>27</sup>

$$(2.43) \quad H = u(c) + \lambda(h(d) + c - pf(q)) + \phi(g(s) - q),$$

with the canonical system of equations given by:

$$(2.44) \quad u_c + \lambda = 0,$$

$$(2.45) \quad \phi + \lambda pf_q = 0,$$

$$(2.46) \quad \dot{\lambda} = (\delta - h_d)\lambda,$$

$$(2.47) \quad \dot{\phi} = (\delta - g_s)\phi,$$

$$(2.48) \quad \dot{d} = h(d) + c - pf(q),$$

$$(2.49) \quad \dot{s} = g(s) - q.$$

Together with the transversality condition  $\lim_{t \rightarrow \infty} e^{-\delta t} \{\lambda(t)d(t) + \phi(t)s(t)\} = 0$ , (2.44) to (2.49) describe necessary and sufficient conditions for an optimal solution (Feichtinger and Novak, 1991).<sup>28</sup>

Combining (2.44) and (2.46), the optimal consumption path follows the Ramsey rule:

$$(2.50) \quad \dot{c} = \frac{u_c}{u_{cc}} (\delta - h_d),$$

and it is implied that consumption grows over time if  $h_d > \delta$  and falls over time for  $h_d$

---

<sup>27</sup>Note that the costate  $\lambda$ , following Rauscher, is positive in (2.43) unlike earlier models. The difference is simply a matter of definition and does not alter the analysis. Defined in this way  $\lambda$  is the shadow cost of borrowing. Its negative will be the shadow price of consumption, see eq. (2.44).

<sup>28</sup>Rauscher does note, however, that an optimal solution may not exist under certain circumstances. For example, if  $d_0$  is high and  $d^\#$  is low then it may be impossible to find a path for  $q(t)$  which satisfies the conditions:  $\int_0^\infty (g(s) - q)dt + s_0 \geq 0$  and  $\int_0^\infty (h(d) + c - pf(q))dt - d_0 \leq d^\#$ .

$< \delta$ . Thus if the marginal cost of debt is greater than the marginal cost of deferring consumption then the economy should choose to enjoy higher consumption in the future. When the opposite condition holds consumption is higher in the present. Similar considerations are evident with the optimal path for extraction. Differentiating (2.45) with respect to time and using (2.47), (2.46) and (2.44), the optimal extraction path is given by:

$$(2.51) \quad \dot{q} = \frac{f_q}{f_{qq}} (h_d - g_s).$$

Along the optimal path extraction increases over time if the return to holding the resource as stock ( $g_s$ ) is greater than the marginal cost of borrowing. Extraction, in other words, is deferred to the future. When this return to resource stock is less than  $h_d$ , the marginal cost of extraction is less than the marginal cost of borrowing which makes it attractive to finance current account deficits with export. Extraction in the present is higher, but falls over time. An alternative interpretation of (2.51) is in terms of the rate of growth in the marginal productivity of the resource, i.e.  $\dot{f}_q/f_q = f_{qq}\dot{q}/f_q = h_d - g_s$ . If  $h_d < g_s$ , growth in marginal productivity is negative and extraction is deferred to the future. When marginal productivity growth is positive extraction takes place in the present.

A further observation about (2.50) and (2.51) is that the optimal time paths for consumption and extraction are not independent of the level of debt given the role of  $h_d(d)$  in both expressions. Note also that in (2.51) the optimal path for extraction is independent of preferences, in particular  $\delta$ . Thus, the introduction of capital market imperfections means consumption and extraction decisions are no longer separate in the sense that their optimal paths are dependent on the economy's level of debt.

Now consider the relationship between optimal extraction, consumption and the level

of indebtedness. The first step is to characterise the steady state equilibrium in which  $\dot{q} = 0$ ,  $\dot{c} = 0$ ,  $\dot{s} = 0$ ,  $\dot{d} = 0$ ,  $\dot{\phi} = 0$  and  $\dot{\lambda} = 0$ . Equilibrium values for the state and control variables are implied by the steady-state conditions:

$$(2.52) \quad \begin{aligned} q^* &= g(s^*) \\ c^* &= pf(q^*) - h(d^*) \\ h_d(d^*) &= g_s(s^*) = \delta. \end{aligned}$$

The third condition in (2.52) determines the equilibrium levels of debt and resource stock:  $d^*$  and  $s^*$  are chosen to satisfy equality between the marginal cost of borrowing and the marginal rate of regeneration in the steady-state. These in turn are equal to the rate of discount. Note therefore that the equilibrium resource stock is below the level of stock consistent with the maximum sustainable yield ( $g_s(s^{msy})=0$ ). With values for  $d^*$  and  $s^*$  determined, the first two conditions in (2.52) are used to determine steady state extraction and consumption.<sup>29</sup> The nature of the relationship between extraction, consumption and debt will depend on how, if at all, the optimal solution converges to the equilibrium described by (2.52). In an appendix to this chapter it is shown that the steady-state equilibrium is a saddlepoint with a non-cyclical saddlepath. The important result which follows is that along the stable manifold of the saddlepoint extraction is increasing in the level of debt, whilst consumption is decreasing in debt. This is also shown in the chapter appendix.

A qualitative interpretation of this positive relationship between extraction and debt cannot be represented in less than four dimensions. A phase diagram analysis is only obtainable by imposing further restrictions onto the model.<sup>30</sup> Therefore, to illustrate the intuition of the results derived in the appendix it is necessary to simplify the

---

<sup>29</sup>The existence of this steady-state equilibrium requires  $c^*$  to be positive, see Rauscher (1990)

<sup>30</sup>This is a feature of optimal control problems with two state variables. Qualitative analysis of optimal solutions typically relies on consideration of distinct phases with simpler solutions (Léonard and Long, 1992). This approach is adopted here.

interest payments function such that  $h_{dd} = 0$ . With this assumption the sub-system  $(s,q)$  is independent of  $(d,c)$  which allows the optimal solution in this simplified model to be illustrated with a phase diagram (see Proposition 3 in appendix). Interest payments are now assumed to be determined by the step function:

$$(2.53) \quad h_d(d) = \begin{cases} r^h & \text{for } d > \tilde{d} \\ r^l & \text{for } d \leq \tilde{d} \end{cases},$$

with  $r^h > r^l$ . Thus borrowers can face one of two rates of interest. The rate of interest  $r^h$  is charged if debt is above the "problem" level  $\tilde{d}$ . Consider first the scenario of  $d \leq \tilde{d}$ . The steady state in the  $(s,q)$  sub-system is characterised by:

$$(2.54) \quad \begin{aligned} \dot{s} = 0: & \quad q^* = g(s^*) \\ \dot{q} = 0: & \quad r^l = g_s(s^*) = \delta. \end{aligned}$$

Linearising the dynamic system (2.49) and (2.51) around this steady-state gives:

$$(2.55) \quad \begin{bmatrix} \dot{s} \\ \dot{q} \end{bmatrix} = \begin{bmatrix} \delta & -1 \\ -f_q g_{ss} / f_{qq} & 0 \end{bmatrix} \begin{bmatrix} s - s^* \\ q - q^* \end{bmatrix}.$$

The determinant of the Jacobian in (2.55) is negative which confirms this equilibrium as a saddlepoint.<sup>31</sup> Figure 2.3 illustrates the phase diagram for (2.55).

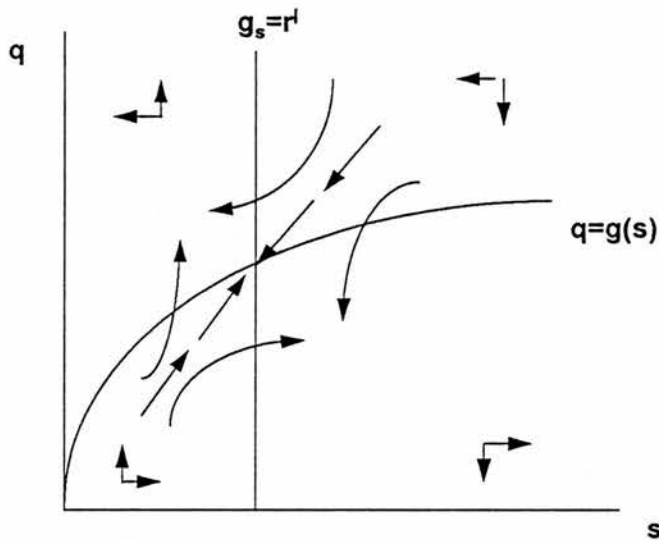
Now consider the scenario where debt is above the "problem" level and the borrower faces a marginal cost of borrowing equal to  $r^h$ . From (2.52) it is evident that the steady-state equilibrium in this scenario is associated with a higher marginal rate of regeneration and therefore smaller resource stock. It then follows from (2.52) that the steady state level of extraction is lower for the case  $d > \tilde{d}$ . As illustrated in Figure 2.4 the "problem" debt steady-state equilibrium,  $E^h$ , therefore lies to the left of the equilibrium  $E^l$  from Figure 2.3. Figure 2.4 also illustrates why for the initial values  $s_0$

---

<sup>31</sup>Note equilibrium is attained, given (2.52), when  $g_s > 0$  (i.e. below maximum sustainable yield) and therefore  $g_{ss} < 0$ .

and  $q_0$ , the saddlepath converging to the first scenario equilibrium ( $E^1$ ) is no longer optimal. At the point  $E^1$  the first scenario time path enters an unstable manifold of the "problem" debt phase space. On this time path extraction in the long run tends to zero and the resource stock converges on its ecological equilibrium of  $s^{\max}$ . The system therefore

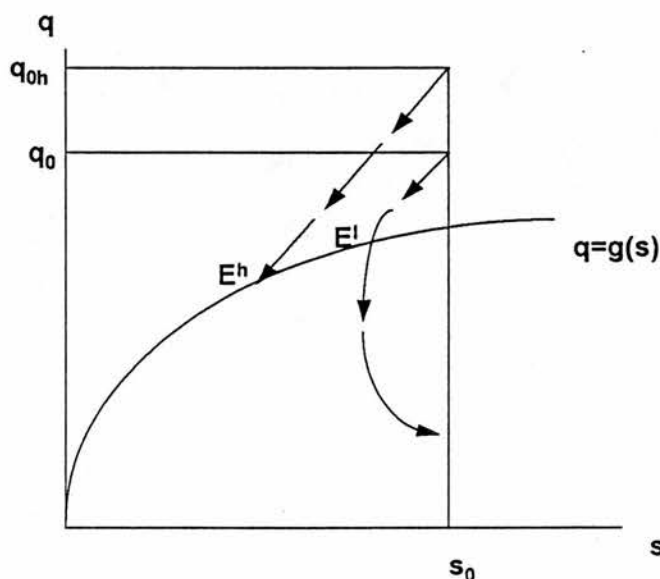
Figure 2.3: Resource stock and extraction dynamics



converges to a point where the resource is not utilised which cannot be an equilibrium given the steady-state conditions and  $f_q(0) = \infty$ . This situation can only be avoided if, for the given  $s_0$ , initial extraction is increased to, say  $q_{0h}$ , which enables the system to converge to  $E^h$  on a stable manifold of the "problem" debt phase space. Thus, extraction is higher along the optimal path when debt is above its "problem" level. This result, as noted by Rauscher, has a simple intuition. The cost of indebtedness increases with the level of debt. The incentive to reduce indebtedness thus rises with the level of debt. When the ability to reduce debt is provided by the export of resource goods, this incentive will imply a shift in resource extraction from the future to the

present.

Figure 2.4: Optimal extraction time paths with an increase in debt



The discussion so far has concentrated on the role of imperfect capital markets. Rauscher (1990) considers a further avenue for the link between indebtedness and resource use. Specifically, it is assumed that environmental quality as measured by the resource stock is a source of utility. Rauscher then shows that resource use and indebtedness are linked even with perfect capital markets. The idea here is that an increase in the initial level of debt represents an inward shift of the economy's budget constraint. Assuming consumption and environmental quality to be normal, the fall in income reduces demand for each good, which implies a fall in consumption and an increase in resource use. A further feature of this extended model is that the stability properties of the model are no longer well defined. The optimal solution features non-cyclical saddlepaths only with fairly restrictive assumptions, i.e.  $f_q \rightarrow 0$ . In general, unstable and cyclical solutions cannot be ruled out. The latter suggests debt cycles and cyclical resource exploitation can be optimal strategies for the resource exporter. The

stability of the cyclical solutions is established using numerical methods by Feichtinger and Novak (1991).

## **2.5 Concluding thoughts.**

The open economy models presented in this chapter emphasise the role that capital market imperfections play in linking external debt and resource extraction. The approach adopted in, for example, Rauscher (1989, 1990) was to assume that rationing of credit was achieved by a convex interest payments function. In the theoretical literature on sovereign debt the existence of upward sloping supply curves for international credit even in competitive loans markets is well established. Eaton and Gersovitz (1981), for example, formally demonstrate that in a competitive market equilibrium there exists the convex function  $h(d)$ . This is a feature of optimal foreign borrowing which section 2.2 did not explicitly address. The simple model outlined took as given a horizontal supply schedule for international credit. The level of steady state debt would, in other words, be entirely demand determined. From the debtor's perspective (and the lender's) the only factor ultimately governing the borrowing decision would be the solvency criteria; i.e. the present value of interest payments on steady-state debt would equal the present value of current account surpluses. However even where the intertemporal budget constraint is satisfied the nature of sovereign lending and borrowing, as suggested by the Eaton and Gersovitz (1981) analysis, does not rule out the existence of credit rationing. The analysis of sovereign debt reveals incentives for quantity rationing over price rationing (i.e. the interest rate). This reflects the default risks and asymmetric information that is characteristic of sovereign borrowing (see for example Kletzer, 1984; Kharas, 1984).

The idea that default risk motivates quantity rationing of international credit can be

shown with a simple stylised representation of a trade between a debtor and a creditor (see Eaton, 1993). A country borrows amount  $B$  from the international loans market in period 1 which incurs a period 2 debt service obligation  $D = B(1 + r)$  where  $r$  is the interest payable on the debt. If the debtor repays anything less than  $D$  in period 2 a penalty equal to  $P$  (in terms of income) is incurred. Repayment occurs therefore if  $P \geq D$  and an incentive to default exists if  $D > P$ . Creditors therefore ensure that  $B(1 + r)$  is always less than  $P$  or equivalently that the available credit,  $B$ , is at or below the level  $P/(1 + r)$ . If debt accumulation satisfies this constraint competitive lenders should be willing to lend at the competitive rate of interest  $r$ . However this assumes no asymmetries in information between borrowers and lenders with regard to the level of indebtedness. If the penalty is finite and lenders are unable to observe  $B$ , borrowing by debtors is greater than their willingness to repay which leads to the default outcome. Rational lenders anticipate such an outcome and thus have no incentive to lend. Therefore, as demonstrated in Kletzer (1984), debtors can in fact benefit from making  $B$  public knowledge. Moreover, Kletzer also shows that the observability of the debtor's total debt will in combination with default risk lead to the *quantity* rationing of loans.

This theoretical explanation for quantity rationing also appears to have empirical validity, particularly in the context of lending to developing countries. For example, Hajivassiliou (1987) notes evidence which suggests that interest rates for international loans appear to be exogenous, i.e. interest rates are not used to ration access to credit. Instead, the level of available supply appears to be related to creditworthiness indicators of the debtor. Evidence in Lensink and van Bergeijk (1991) also supports the idea that quantity rationing prevails in the supply of credit to developing countries, with lenders using information on indicators such as income growth and investment shares to determine the creditworthiness of a borrower. In sum, the empirical

evidence would suggest that interest rate spreads, which reflect default risk, are insufficient to explain the observed patterns of international lending. Lender assessments of creditworthiness are reflected in decisions about the quantity rather than price of loans.

These brief observations from the sovereign debt literature suggest two questions about the role of imperfect capital markets as the important determinant of the debt-resources link. Firstly, at the level of theory, how are debt and resource use related when debtors face credit ceilings rather than convex interest payments? This motivates the analysis presented in the next chapter and in chapter 5. Of interest in chapter 5 it is observed that when resource use decisions are taken in a static context, debt influences the rate of resource use *only* in the presence of binding credit ceilings. The second question concerns the empirical relevance of the debt-resource link. The analyses in chapters 4 and 6 show that empirical testing of the hypothesis is usefully pursued by distinguishing between constrained and unconstrained lending regimes which arise from the possibility that international credit is quantity rationed.

## Appendix

### Local stability analysis and comparative dynamics in the Rauscher model.

In this Appendix the stability properties of the Rauscher model are established by Proposition 1. In section 2.4 it was noted that a higher level of debt will increase current resource extraction and decrease current consumption. These results are formally derived in the proof of Proposition 2. Finally, a third proposition confirms the separation of the  $(s, q)$  and  $(d, c)$  phase space which arises with the use of the interest payments step function (2.53). This permits the phase diagram analysis outlined in section 2.4. The dynamics of the model are governed by the differential equations for the state and co-state variables. Recall these are:

$$(A2.1) \quad \begin{aligned} \dot{s} &= g(s) - q, \\ \dot{d} &= h(d) + c - pf(q), \\ \dot{\phi} &= (\delta - g_s)\phi, \\ \dot{\lambda} &= (\delta - h_d)\lambda. \end{aligned}$$

(A2.1) represents a dynamic system with four dimensions and six variables:  $s$ ,  $d$ ,  $\phi$ ,  $\lambda$ ,  $q$ , and  $c$ . Two unknowns, the control variables, can be eliminated using the optimality conditions (2.44) and (2.45). This permits analysis of stability in state-co-state space. Total differentiation of (2.44) and (2.45) yields:

$$(A2.2) \quad \begin{bmatrix} dc \\ dq \end{bmatrix} = \begin{bmatrix} \partial c / \partial \lambda & \partial c / \partial \phi \\ \partial q / \partial \lambda & \partial q / \partial \phi \end{bmatrix} \begin{bmatrix} d\lambda \\ d\phi \end{bmatrix} = \begin{bmatrix} -1/u_{cc} & 0 \\ pf_q/u_c pf_{qq} & 1/u_c pf_{qq} \end{bmatrix} \begin{bmatrix} d\lambda \\ d\phi \end{bmatrix}$$

Using (A2.2), linearising the dynamic system (A2.1) around the steady-state equilibrium and evaluating all derivatives at steady-state values gives:

$$(A2.3) \quad \begin{bmatrix} \dot{s} \\ \dot{d} \\ \dot{\phi} \\ \dot{\lambda} \end{bmatrix} = \begin{bmatrix} \delta I & F \\ G & 0 \end{bmatrix} \begin{bmatrix} s - s^* \\ d - d^* \\ \phi - \phi^* \\ \lambda - \lambda^* \end{bmatrix},$$

where  $I$  is a 2x2 identity matrix and the matrices  $F$  and  $G$  are given by:

$$(A2.4) \quad F = \begin{bmatrix} -(\mathbf{u}_c \mathbf{p} \mathbf{f}_{qq})^{-1} & -\mathbf{f}_q (\mathbf{u}_c \mathbf{f}_{qq})^{-1} \\ -\mathbf{f}_q (\mathbf{u}_c \mathbf{f}_{qq})^{-1} & -(\mathbf{u}_{cc}^{-1} + (\mathbf{p} \mathbf{f}_q)^2 (\mathbf{u}_c \mathbf{p} \mathbf{f}_{qq})^{-1}) \end{bmatrix} \quad G = \begin{bmatrix} -\mathbf{u}_c \mathbf{p} \mathbf{f}_q \mathbf{g}_{ss} & 0 \\ 0 & \mathbf{u}_c \mathbf{h}_{dd} \end{bmatrix}.$$

Note that  $F$  and  $G$  are both positive definite. The stability properties of (A2.3) are stated in Proposition 1.

*Proposition 1.* All four eigenvalues of the Jacobian matrix are real, two are positive and two are negative. The steady-state equilibrium is therefore a saddlepoint and saddlepath stable.

*Proof.* The eigenvalues associated with the Jacobian can be computed from (see Dockner, 1985):

$$(A2.3) \quad \lambda_{1,2,3,4} = \frac{\delta}{2} \pm \sqrt{\frac{\delta^2}{4} - Z_{1,2}},$$

where  $Z_{1,2} = \frac{K}{2} \pm \sqrt{\left(\frac{K}{2}\right)^2 - \det(J)}$ . The term  $\det(J)$  denotes the determinant of the

Jacobian and  $K$  defines the constant:

$$(A2.4) \quad K = \begin{vmatrix} \delta & \mathbf{f}_{11} \\ \mathbf{g}_{11} & 0 \end{vmatrix} + \begin{vmatrix} \delta & \mathbf{f}_{22} \\ \mathbf{g}_{22} & 0 \end{vmatrix} + 2 \begin{vmatrix} 0 & \mathbf{f}_{12} \\ \mathbf{g}_{12} & 0 \end{vmatrix}, \text{ with } \mathbf{f}_{ij}, \mathbf{g}_{ij} \text{ being } ij \text{ elements of } F \text{ and } G.$$

Using Theorem 1-10-2 in Barnett and Storey (1970) it is easy to show that the determinant of the partitioned Jacobian is given by:

$$(A2.5) \quad \det(J) = \mathbf{g}_{11} \mathbf{g}_{22} (\mathbf{f}_{11} \mathbf{f}_{22} - \mathbf{f}_{12}^2) = - \left( \frac{\mathbf{f}_q \mathbf{g}_{ss} \mathbf{u}_c \mathbf{h}_{dd}}{\mathbf{f}_{qq} \mathbf{u}_{cc}} \right) > 0,$$

whereas the constant  $K$  is:

$$(A2.6) \quad K = -(\mathbf{f}_{11} \mathbf{g}_{11} + \mathbf{f}_{22} \mathbf{g}_{22}) < 0.$$

For notational ease it is now useful to define  $x = K/2$  and  $y = \det(J)$ . It then follows that for all four eigenvalues to be real it must be true that:

$$(A2.7) \quad x^2 - y > 0 \quad \text{and} \quad \delta^2/4 - Z > 0.$$

From the definitions of  $x$  and  $y$  observe that:

$$\begin{aligned} x^2 - y &= \left( \frac{-(f_{11}g_{11} + f_{22}g_{22})}{2} \right)^2 - g_{11}g_{22}(f_{11}f_{22} - f_{12}^2) \\ &= \left( \frac{f_{11}g_{11}}{2} \right)^2 + \left( \frac{f_{22}g_{22}}{2} \right)^2 - \left( \frac{f_{11}g_{11}f_{22}g_{22}}{2} \right) + g_{11}g_{22}f_{12}^2 \\ &= \left( \frac{f_{11}g_{11} - f_{22}g_{22}}{2} \right)^2 + g_{11}g_{22}f_{12}^2 > 0. \end{aligned}$$

Thus  $x^2 - y > 0$  is satisfied. Note now that it is trivially true that  $x^2 > x^2 - y$  since  $y > 0$ . However values of  $x$  and  $\sqrt{x^2 - y}$  satisfying this inequality may be positive or negative. The possibility  $x > 0$  is ruled out by contradiction, i.e.  $K < 0$ . This must then imply that:

$$(A2.8) \quad x < \sqrt{x^2 - y} \quad \left( \text{and } |x| > \left| \sqrt{x^2 - y} \right| \right).$$

Hence note:

$$(A2.9) \quad Z_1 = x + \sqrt{x^2 - y} < 0 \quad \text{and} \quad Z_2 = x - \sqrt{x^2 - y} < 0.$$

Returning to (A2.7), since all values of  $Z$  are negative, the second condition for real eigenvalues is also satisfied.

Finally, let  $W_{1,2} = (\delta^2/4 - Z_{1,2})^{1/2}$  and observe that  $W_{1,2} > \delta/2 > 0$ . From (A2.3) then note that:

$$(A2.10) \quad \begin{aligned} \lambda_1 = \frac{\delta}{2} + W_1 > 0, \quad \lambda_2 = \frac{\delta}{2} + W_2 > 0, \\ \lambda_3 = \frac{\delta}{2} - W_1 < 0, \quad \lambda_4 = \frac{\delta}{2} - W_2 < 0. \end{aligned}$$

Hence, all eigenvalues of the Jacobian are real; two are positive and two are negative. The equilibrium is thus a saddlepoint with a two-dimensional unstable manifold and a two-dimensional stable manifold. ■

*Proposition 2.* For a given level of resource stock, resource extraction and consumption are respectively increasing and decreasing in the level of indebtedness along the stable manifold of the saddlepoint equilibrium.

*Proof.* From Proposition 1 it follows there exists a two-dimensional stable manifold in the four-dimensional state-costate phase space. To determine the relationship between the control and state variables along this stable manifold define:

$$(A2.11) \quad \begin{bmatrix} \phi - \phi^* \\ \lambda - \lambda^* \end{bmatrix} = \Gamma \begin{bmatrix} s - s^* \\ d - d^* \end{bmatrix}$$

where  $\Gamma$  is a 2 x 2 matrix. Using (A2.11) the linearised dynamic system can be re-written as:

$$(A2.12) \quad \begin{bmatrix} \dot{s} \\ \dot{d} \\ \dot{s} \\ \dot{d} \end{bmatrix} = \begin{bmatrix} \delta I & F\Gamma \\ \Gamma^{-1}G & 0 \end{bmatrix} \begin{bmatrix} s - s^* \\ d - d^* \\ s - s^* \\ d - d^* \end{bmatrix}$$

From (A2.12) it follows that:

$$(A2.13) \quad \delta I + F\Gamma = \Gamma^{-1}G,$$

which can be re-written as:

$$(A2.14) \quad \Gamma F\Gamma + \delta\Gamma - G = 0.$$

Eq. (A2.14) is an algebraic *Ricatti* equation which has two symmetric solutions for  $\Gamma$ ; one positive definite and one negative definite (Barnett, 1971). The latter defines the stable manifold (see Rauscher, 1989). Hence  $\gamma_{11}$  and  $\gamma_{22}$  (where  $\gamma_{ij}$  are elements of  $\Gamma$ ) are known to be negative on the stable manifold and  $\det(\Gamma) > 0$ . Returning to (A2.13), the elements of  $\delta I$ ,  $F$ ,  $G$  and  $\Gamma$  satisfy:

$$(A2.15) \quad \begin{aligned} f_{11}\gamma_{11} + f_{12}\gamma_{21} + \delta &= (\gamma_{11}g_{11} - \gamma_{12}g_{22})/\det(\Gamma) \\ f_{11}\gamma_{12} + f_{12}\gamma_{22} &= (\gamma_{22}g_{12} - \gamma_{12}g_{22})/\det(\Gamma) \\ f_{21}\gamma_{11} + f_{22}\gamma_{21} &= -(\gamma_{21}g_{11} - \gamma_{11}g_{22})/\det(\Gamma) \\ f_{21}\gamma_{12} + f_{22}\gamma_{22} + \delta &= -(\gamma_{21}g_{12} - \gamma_{11}g_{22})/\det(\Gamma). \end{aligned}$$

To determine the effect of changes in debt on resource extraction and consumption define  $d\phi = \phi - \phi^*$ ,  $d\lambda = \lambda - \lambda^*$  and  $dD = d - d^*$ , from which (A2.11) will imply:<sup>32</sup>

$$(A2.16) \quad \begin{bmatrix} d\phi \\ d\lambda \end{bmatrix} = \begin{bmatrix} \gamma_{12} \\ \gamma_{22} \end{bmatrix} dD.$$

It follows that, for given  $s$ ,  $d\lambda/dD < 0$  since  $\gamma_{22} < 0$ . Also  $d\phi/dD = \gamma_{12}$ . The sign of element  $\gamma_{12}$  can be established from the second row of (A2.15). Rearranging gives:

$$(A2.17) \quad \gamma_{12} = \left[ f_{11} + \frac{g_{22}}{\det(\Gamma)} \right]^{-1} \left[ \frac{\gamma_{22}g_{12}}{\det(\Gamma)} - f_{12}\gamma_{22} \right]$$

Note that  $g_{12} = 0$ ,  $\gamma_{22} < 0$ ,  $\det(\Gamma) > 0$  and  $g_{22} > 0$ . (A2.17) therefore simplifies to:

$$(A2.18) \quad \gamma_{12} = \frac{-f_{12}\gamma_{22}}{f_{11} + (g_{22}/\det(\Gamma))} > 0.$$

It is also useful to note that (A2.18) implies  $\gamma_{12} < -f_{12}\gamma_{22}/f_{11}$ . Using the values for  $f_{12}$  and  $f_{11}$  this is equivalently  $pf_q\gamma_{22} + \gamma_{12} < 0$ . Combining (A2.16) with (A2.2), changes in debt imply:

---

<sup>32</sup>Here  $dD$  denotes a change in debt.  $D$  is now used to represent debt to avoid ambiguity with the "d" notation for derivatives.

$$(A2.19) \quad \frac{dc}{dD} = \frac{-\gamma_{22}}{u_{cc}} < 0,$$

$$(A2.20) \quad \frac{dq}{dD} = \frac{(pf_q \gamma_{22} + \gamma_{12})}{u_c pf_{qq}} = \frac{-ve}{-ve} > 0.$$

Thus, for a given resource stock, (A2.19) and (A2.20) show that along the stable manifold increased debt decreases consumption and increases resource extraction. ■

*Proposition 3. If interest payments are determined by the step function (2.53) the state-control sub-system  $(s,q)$  is independent of the  $(d,c)$  sub-system. The  $(s,q)$  phase space can then be characterised in terms of two unique steady-state equilibria which correspond to distinct borrowing regimes.*

*Proof.* Proposition 3 follows immediately from the assumption of the step function which implies  $h_{dd} = 0$ . Consider initially, however, the general case in which  $h_{dd} > 0$ . If the dynamics are represented in state-control space, linearising (2.48), (2.49), (2.50) and (2.51) around the steady-state (2.52) gives:

$$(A2.21) \quad \begin{bmatrix} \dot{s} \\ \dot{q} \\ \dot{d} \\ \dot{c} \end{bmatrix} = \begin{bmatrix} \delta & -1 & 0 & 0 \\ -f_q g_{ss}/f_{qq} & 0 & f_q h_{dd}/f_{qq} & 0 \\ 0 & -pf_q & \delta & 1 \\ 0 & 0 & -u_c h_{dd}/u_{cc} & 0 \end{bmatrix} \begin{bmatrix} s-s^* \\ q-q^* \\ d-d^* \\ c-c^* \end{bmatrix}.$$

Now impose the step function restriction  $h_{dd} = 0$ . Inspection of (A2.21) reveals that this imposes  $\partial \dot{q}/\partial d = f_q h_{dd}/f_{qq} = 0$ . Thus  $\dot{s}$  and  $\dot{q}$  are independent of deviations in  $d$  and  $c$  from their steady-state values. This gives the two dimensional dynamic system.

$$(A2.22) \quad \begin{bmatrix} \dot{s} \\ \dot{q} \end{bmatrix} = \begin{bmatrix} \delta & -1 \\ -f_q g_{ss}/f_{qq} & 0 \end{bmatrix} \begin{bmatrix} s-s^* \\ q-q^* \end{bmatrix}$$

Note also that the nature of the borrowing regime will determine the steady-state equilibrium in  $(s,q)$  space. For debt levels above  $\bar{d}$ , the steady-state requires  $r^h = \delta$ ,

whilst for  $d \leq \bar{d}$   $\delta = r^l < r^h$ . Two steady-states are therefore possible:

$$(A2.23) \quad \begin{array}{l} \delta = r^h: \quad (s^{h*}, q^{h*}) \\ \delta = r^l: \quad (s^{l*}, q^{l*}), \end{array} \text{ with } s^{h*} < s^{l*} \text{ and } q^{h*} < q^{l*} \text{ (see Figure 2.4).} \blacksquare$$

## Chapter 3

### Exhaustible resource extraction by indebted economies: a theoretical model and empirical issues.

#### 3.1 Introduction

This chapter considers from a theoretical perspective the impact of external indebtedness on the extraction of exhaustible natural resources. The classic microeconomic (see Hotelling, 1931) and macroeconomic (see Dasgupta and Heal, 1974) approaches to the problem of exhaustible resource extraction have emphasised that the appropriate framework for analysis is dynamic in nature. In chapter 2 it was shown that the standard approach to the problem of optimal resource depletion at the macroeconomic level has been to incorporate natural resources into models of optimal growth. With respect to the relationship between debt and resource extraction the key result from the previous chapter was that a link between a country's external indebtedness and rate of resource depletion only emerges if international capital markets are *imperfect*.

This chapter presents a theoretical model of resource extraction which like the models discussed in chapter 2 emphasises the importance of imperfections in international lending. However unlike these previous models, e.g. Rauscher (1989, 1990), imperfections in international capital markets are introduced by means of quantity restrictions on available international loans, i.e. credit ceilings. The international finance literature has emphasised that equilibria in international loans markets are typically non-walrasian. If the amount of traded international loans is determined by the demand side then the borrower's



notional demand is equal to effective demand. In short, the country is not constrained in its foreign borrowing. If the quantity of trades is determined by the supply side borrowers will face a divergence between their desired (notional) demand and the actual level of loans available to them. In other words, a borrower is supply constrained.

This approach to imperfections in international lending provides a reasonably straightforward way of deriving testable hypotheses from the theoretical model. These hypotheses are based on the first order conditions - the Euler equations - generated from the solution to an intertemporal choice problem faced by a resource exporter. The introduction of credit ceilings to the optimisation model has the effect of imposing liquidity constraints onto the resource exporter's choice problem. Econometric analyses of the role of liquidity constraints within an Euler equation framework have been evident in other contexts. Zeldes (1989) in a study of household consumption and liquidity constraints tests the hypothesis that the consumption Euler equation can be rejected for liquidity constrained households. Whited (1992) adopts a similar methodology to test for the effect of borrowing constraints on firm investment decisions. More recently, Bond and Meghir (1994) have used the Euler equation approach to investigate the effects of a firm's financial policy on its investment decisions which are derived in an Euler equation framework.

The rest of the chapter is structured as follows. Section 3.2 presents a discrete time theoretical model of a small open economy with three sectors: Non-traded, Traded and Resource, in which decision-makers operate under conditions of uncertainty about the future. In section 3.3 of the chapter the optimisation

problem is outlined and the Euler equations under the assumption of unconstrained foreign borrowing are derived. Section 3.4 considers the effect of binding borrowing constraints on production, consumption and resource extraction. Section 3.5 then discusses an approach which enables econometric estimation and testing of the extraction Euler equations derived in Section 3.3 and 3.4. This methodology provides the framework for the empirical testing of the debt-resources hypothesis considered in chapter 4. Section 3.6 provides a concluding summary.

### **3.2 An intertemporal model of exhaustible resource extraction and foreign borrowing.**

Consider a three sector small open economy producing a non-traded good,  $Y^N$ , a traded good,  $Y^M$ , and a resource good  $Q$  which represents a physical unit of extraction from a stock of exhaustible natural resource denoted by  $S$ . The introduction of non-tradeables represents an extension to earlier models of resource extraction in open economies which have assumed a single consumption good.<sup>1</sup> In models with tradeables and non-tradeables there exists substitution possibilities in terms of production and consumption.<sup>2</sup> Moreover, the relative price of non-traded and traded goods - the real exchange rate - will determine the efficient allocation of mobile factor inputs to non-traded and traded production and the optimal levels of traded and non-traded

---

<sup>1</sup>Mansoorian (1991) does however present an analysis of the impact of natural resource discoveries on external borrowing in a traded / non-traded good framework.

<sup>2</sup>See Martin and Selowsky (1983) for a discussion on this and the associated short-run rationale for foreign borrowing.

consumption.<sup>3</sup> As shown later in this chapter the presence of imperfections in international lending has important implications for this real exchange rate and therefore the production and consumption of traded and non-traded goods. The advantage of this model specification is that it emphasises that the choices available to a borrower facing imperfect lending are wider than those allowed in open economy models with a single imported consumption good and a single exported (i.e. resource) good.

The resource sector is assumed to be an enclave. That is, it is assumed that there are no supply linkages, in terms of outputs or factor inputs, between the resource sector and the non-traded and traded sectors.<sup>4</sup> This is broadly consistent with evidence on mining sectors in developing countries (Looney and Knouse, 1987). Net output (in value terms),  $Y^R$ , from the resource sector is defined as:

$$(3.1) \quad Y_t^R = P_t Q_t - G(Q_t, S_{t-1}),$$

where  $P_t$  is the (given) real price of the resource good in terms of the traded good and total extraction costs are denoted by the function  $G(Q_t, S_{t-1})$ .<sup>5</sup>

Extraction costs are assumed to be a function of current extraction and previous period stocks. Marginal extraction costs are positive and increasing ( $G^Q > 0$ ,  $G^{QQ} > 0$ ), whilst the stock effect on costs is negative ( $G^S < 0$ ). This latter assumption is widely adopted in the natural resources literature and

---

<sup>3</sup>That is, in equilibrium the marginal rate of transformation in production and the marginal rate of substitution in consumption will equal the ratio of the shadow prices for non-traded and traded goods. See eq. (3.20) below.

<sup>4</sup>This will imply that optimal extraction decisions are independent of the real exchange rate (see Gregory, 1976 and van Long, 1984)

<sup>5</sup>Defining resource output in this manner amounts to a dual representation of decisions in the resource sector (Neher, 1990).

presumes depletion begins with more accessible or better quality resource deposits. With no account of exploration or discoveries in the model the stock effect can be equivalently thought of as the impact of cumulative production on extraction costs. Extraction of the resource at any point in the depletion program satisfies the constraint:

$$(3.2) \quad S_t - S_{t-1} = -Q_t.$$

The non-traded and traded sectors use capital and labour in the production of  $Y^N$  and  $Y^M$ , with the marginal products to each factor positive and diminishing. Capital is sector-specific with labour mobile between the non-traded and traded sectors. The production possibility frontier for non-traded and traded goods at time  $t$  is then defined as:

$$(3.3) \quad F(Y_t^N, Y_t^M; L_t, K_t^N, K_t^M) = 0,$$

given an optimal allocation of labour between the two sectors (see Bruno, 1976). The capital stocks in the traded and non-traded sectors are fixed in any given time period, but evolve over time according to the capital accumulation identity:

$$(3.4) \quad K_t^\tau = I_t^\tau + K_{t-1}^\tau \quad \tau = N, M,$$

where  $I_t^\tau$  denotes sectoral gross investment. Note that in (3.4) depreciation in the capital stocks is assumed zero. This has the merit of avoiding unnecessary notation since capital depreciation will have no role to play in the model. <sup>6</sup>

---

<sup>6</sup>Capital accumulation is incorporated into the model to generalise the decisions facing each agent. However, given the enclave assumption about the resource sector the consideration of optimal extraction will be independent of investment in the non-traded and traded sectors. The question of optimal investment is not however divorced from the foreign borrowing

To complete the model, equilibrium in the non-traded and traded good markets are given by the following conditions. For non-traded goods, market clearing requires:

$$(3.5) \quad Y_t^N = C_t^N + I_t^N,$$

where  $C_t^N$  denotes real non-traded consumption. In the case of the traded sector the introduction of foreign borrowing and the presence of the resource sector means that the market in tradeables need not balance in every time period. Thus as noted by Bruno (1976) one role for foreign borrowing in the model is that it replaces period by period constraints on the market for traded goods with a single multi-period foreign currency constraint. For the purposes of simplicity stocks and flows of foreign currency reserves are omitted from the model. The balance of payments therefore comprises flows in traded and resource goods and net foreign capital inflows. Again for simplicity it is assumed that these latter flows are foreign borrowings and repayments. Let  $D_t$  denote the stock of outstanding disbursed foreign debt at the end of period  $t$ . As noted by Eaton (1993) capital account flows for a debtor comprise  $B_t$ , loans disbursed in period  $t$  (or the supply of new gross debt), and  $R_t$ , principal repayments of outstanding debt in period  $t$ . The change in the stock of disbursed debt is then written as:

$$(3.6) \quad D_t - D_{t-1} = B_t - R_t.$$

From balance of payments accounting equilibrium in international flows, given the simplifying assumptions, requires net debt flows to balance trade flows. That is:

---

regime facing each decision-maker, but this chapter will not elaborate on this issue to any great extent.

$$(3.7) \quad B_t - R_t - r_{t-1}D_{t-1} = C_t^M + I_t^M - Y_t^M - Y_t^R,$$

where  $r$  is the real rate of interest payable on foreign borrowings and  $C_t^M$  is real traded good consumption.<sup>7</sup> Using (3.6) the balance of payments constraint in (3.7) can be written as:

$$(3.8) \quad D_t - D_{t-1} = r_{t-1}D_{t-1} + C_t^M + I_t^M - Y_t^M - Y_t^R.$$

The balance of payments constraint as defined in (3.8) would be consistent with a sovereign borrower facing unconstrained lending. The current account determines the demand for new borrowing  $D_t - D_{t-1}$ . In an unconstrained regime observed levels of lending equal the notional demands of the borrower. Thus  $D_t - D_{t-1}$  equals the net supply  $B_t - R_t$  when lending is unconstrained. The contrary case of constrained lending can be introduced by imposing a lender-determined upper limit on  $B_t$ . Let  $B_t^*$  denote this limit on available loans. This additional constraint can be defined as:

$$(3.9a) \quad B_t \leq B_t^*,$$

or using (3.6) and (3.8),

$$(3.9b) \quad R_t + r_{t-1}D_{t-1} + C_t^M + I_t^M - Y_t^M - Y_t^R \leq B_t^*.$$

The constraint defined in (3.9a) and (3.9b) provides a simple but realistic way of introducing imperfections to international capital markets. It is well established that international lending is highly imperfect. The most widely observed manifestation of these imperfections is credit rationing in the form of quantity restrictions on lending (see Hajjivassiliou, 1987 and Lensink and van Bergeijk,

---

<sup>7</sup>In (3.7) net exports in traded goods are given by  $C_t^M + I_t^M - Y_t^M$ . The model also implicitly treats the economy's debt as a single foreign liability serviced with interest  $r_t$ .

1991). Thus observed levels of lending will equal the minimum of either the borrower's demand for new loans or the lender's upper limit. In the case of the former lending is unconstrained in the sense that borrower demand is satisfied and the level of borrowing over time is consistent with a debtor's intertemporal budget constraint. Even if the solvency criteria (i.e. the intertemporal budget constraint) is satisfied a situation where  $B_t = B_t^*$  may face borrowers for a number of reasons. Firstly, credit rationing may be the rational response from lenders to informational imperfections such as adverse selection in credit markets (Stiglitz and Weiss, 1981). Secondly, and of particular relevance for lending to countries, the sovereignty of the borrower introduces additional default risks which can lead to lender restrictions on the flow of new debt (Eaton and Gersovitz, 1981; Sachs and Cohen, 1985; Cohen and Sachs, 1986; see also Kletzer, 1988 and Eaton, 1993 for excellent surveys of the issues concerning sovereign debt).

### 3.3 The optimisation problem with unconstrained borrowing.

The planning problem for each country decision-maker is to choose the consumption levels  $C_k^\tau$  ( $\tau = N, M$ ) and the rates of extraction  $Q_k$  for  $k = 0, \dots, T-t$  which maximise social welfare. More precisely, to maximise the expected discounted future stream of social welfare from non-traded and traded consumption conditional on the information set  $\Omega_t$ . Formally, the problem is:

$$(3.10) \quad \max_{C_k^N, C_k^M, Q_k} E \left\{ \sum_{k=0}^{T-t} \beta^k U(C_{t+k}^M, C_{t+k}^N) \mid \Omega_t \right\},$$

subject to (3.1), (3.2), (3.3), (3.4), (3.5), (3.7), (3.9b) and the initial values  $S_t, D_t, K_t^\tau$  which are assumed given. The aggregate utility function  $U(C_t^M, C_t^N)$

is assumed to be strictly concave and twice differentiable in both arguments and  $\beta$  denotes the discount factor.<sup>8</sup>

To solve the problem stated in (3.10) define the Lagrangian function:

$$(3.11) \quad \Psi = E \left( \sum_{k=0}^{T-t} \beta^k V_{t+k} \mid \Omega_t \right),$$

where,

$$(3.12) \quad \begin{aligned} V_t = & U(C_t^M, C_t^N) + \lambda_t^N (K_{t-1}^N + Y_t^N - C_t^N - K_t^N) \\ & + \lambda_t^M ((1 + r_{t-1})D_{t-1} + C_t^M - Y_t^M + K_t^M - K_{t-1}^M - P_t Q_t \\ & + G(Q_t, S_{t-1}) - D_t) \\ & + \phi_t (S_{t-1} - Q_t - S_t) \\ & + \lambda_t^Y F_t(Y_t^M, Y_t^N; L_t, K_t^N, K_t^M) \\ & + \mu_t (B_t^* - R_t - r_{t-1}D_{t-1} - C_t^M + Y_t^M - K_t^M + K_{t-1}^M \\ & + P_t Q_t - G_t(Q_t, S_{t-1})) \end{aligned}$$

The variables  $\lambda_t^M$ ,  $\lambda_t^N$ ,  $\phi_t$  and  $\mu_t$  are Lagrangian multipliers and can be interpreted as the shadow prices of traded and non-traded goods, the rent on resource stock and the shadow marginal benefit of access to capital markets. Note also in the context of foreign borrowing that  $\lambda_t^M$  represents the shadow cost of borrowing and so strictly the shadow price of traded goods is denoted by  $-\lambda_t^M$ . An alternative to the resource rent interpretation of  $\phi_t$  is the view that

---

<sup>8</sup>The usual non-negativity constraints have been omitted for convenience. It is therefore assumed that the choice variables are strictly positive and there exists an interior solution to this problem.

this multiplier measures the shadow opportunity cost of current period extraction, i.e. the user cost of resource use.

For the moment assume  $\mu_t = 0$  and by complementary slackness  $B_t < B_t^*$ . With respect to traded consumption and extraction the first order conditions are given by:<sup>9</sup>

$$(3.13) \quad \frac{\partial U}{\partial C_t^M} + \lambda_t^M = 0,$$

$$(3.14) \quad \phi_t + \lambda_t^M \left( P_t - \frac{\partial G}{\partial Q_t} \right) = 0.$$

Equation (3.13) indicates that at the optimum marginal utility from traded consumption equals the shadow cost of foreign borrowing, whilst (3.14) notes that the resource rent equals the marginal net benefits (in terms of traded consumption) of extraction.<sup>10</sup>

The shadow price of traded goods and the resource rent also obey the following equations of motion which define the conditions for intertemporal equilibrium:

$$(3.15) \quad \lambda_t^M = \beta(1 + r_t)E_t(\lambda_{t+1}^M),$$

or equivalently using (3.13),

<sup>9</sup>For ease of exposition the first order conditions are hereafter written for  $k=0$ . In addition the transversality conditions are assumed to hold.

i.e.

$$E_t(\beta^{T-t}\lambda_t^\tau) \geq 0; E_t(\beta^{T-t}\lambda_t^\tau K_T^\tau) = 0 \quad (\tau = N, M) \text{ and } E_t(\beta^{T-t}\phi_T) \geq 0; E_t(\beta^{T-t}\phi_T S_T) = 0.$$

<sup>10</sup>Alternatively, (3.14) indicates that extraction incurs two type of cost: the cost of physically extracting the resource and the user cost. Thus at the margin the real price of the resource is equated with total marginal cost, i.e. marginal extraction cost plus the real (i.e. relative to shadow price of traded goods) user cost of extraction.

$$(3.16) \quad \frac{\partial U}{\partial C_t^M} = \beta(1+r_t)E_t\left(\frac{\partial U_{t+1}}{\partial C_{t+1}^M}\right),$$

and

$$(3.17a) \quad \phi_t = \beta E_t(\phi_{t+1}) + \beta E_t\left(\lambda_{t+1}^M \frac{\partial G}{\partial S_t}\right).$$

Equation (3.16) is the familiar condition required for optimal consumption decisions.<sup>11</sup> In the present context (3.16) implies that at the optimum expected lifetime utility cannot be increased by foregoing one unit of future consumption and borrowing to enjoy an extra unit of current consumption. Equivalently, marginal utility in the current period should equal the discounted value of marginal utility in some future period. Equation (3.17a) contains a generalisation of the Hotelling rule for extraction over time, namely that the expected real resource rent should grow by an amount equal to the interest rate less the expected marginal saving in future extraction costs from deferring current extraction weighted by expected marginal utility of consumption. That is, rearranging (3.17a):

$$(3.17b) \quad \frac{\hat{\phi}_{t+1} - \hat{\phi}_t}{\hat{\phi}_t} = r_t + \hat{\phi}_t^{-1} \frac{E_t(\partial U / \partial C_{t+1}^M \cdot \partial G / \partial S_t)}{E_t(\partial U / \partial C_{t+1}^M)},$$

where  $\hat{\phi}_{t+1} = E_t(\phi_{t+1}) / -E_t(\lambda_{t+1}^M)$  and  $\hat{\phi}_t = \phi_t / \lambda_t^M$ . Note also that the depletion effect on costs  $\partial G / \partial S_t < 0$  ensures that the second terms on the right hand side of (3.17b) is negative.<sup>12</sup> An alternative interpretation of this condition for dynamic efficiency is given by (3.17c) which results from simple rearrangement of (3.17b) and noting (3.13):

<sup>11</sup> See for example Hall (1978).

<sup>12</sup> Note that the relevant interest rate in (3.17b) is the interest payable on foreign borrowings and not the rate used to discount the expected stream of future utilities. This reflects the standard open economy result that production decisions are independent of preferences and are instead determined by world prices. Recall the discussion from chapter 2.

$$(3.17c) \quad \hat{\phi}_{t+1} - \hat{\phi}_t - \left[ E_t(\lambda_{t+1}^M \partial G / \partial S_t) / E_t(\lambda_{t+1}^M) \right] = r_t \hat{\phi}_t.$$

Eq. (3.17c) equates the return to investing in resource stock and the cost associated with such investment. The term  $\hat{\phi}_{t+1} - \hat{\phi}_t$  denotes the expected (real) capital gain from investing in period  $t+1$  resource stock or equivalently from deferring period  $t$  extraction. The second term on the left hand side,  $-\left[ E_t(\lambda_{t+1}^M \partial G / \partial S_t) / E_t(\lambda_{t+1}^M) \right] > 0$ , can be interpreted as the (utility) weighted "dividend" from investing in resource stock. In other words, the weighted marginal cost saving that arises from a higher resource stock at the beginning of period  $t+1$ . The right hand side of (3.17c) can be interpreted as the opportunity cost of investing in resource stock, i.e. the foregone liquidity which arises if extraction is deferred to the future.

### 3.4 Production, consumption and resource extraction with constrained borrowing.

Now consider the case where  $\mu_t > 0$  which implies  $B_t = B_t^*$ . The optimal conditions for traded consumption are now given by:

$$(3.18) \quad \frac{\partial U}{\partial C_t^M} + \lambda_t^M - \mu_t = 0,$$

with the equation of motion for traded consumption under constrained borrowing given by:

$$(3.19) \quad \frac{\partial U}{\partial C_t^M} = \beta(1 + r_t) E_t \left( \frac{\partial U}{\partial C_{t+1}^M} \right) - \beta E_t(\mu_{t+1}) + \mu_t.$$

The multiplier  $\mu_t$  measures the additional utility which is possible if the borrowing constraint were to be relaxed by one unit. Comparing (3.18) and (3.13), note that both conditions require that marginal utility from traded consumption at an optimum equals the shadow cost of borrowing. However the levels of traded consumption at these optima will clearly be different since (3.18) contains  $\mu_t$  indicating that the shadow cost of borrowing is greater at the point where borrowing constraints bind. This suggests that current period marginal utility (from traded consumption) for constrained borrowers is always greater than or equal to current period marginal utility for unconstrained borrowers. From the concavity of the utility function the corollary of this is that current levels of traded consumption for constrained borrowers are always less than or equal to those of unconstrained borrowers. It will also be the case that a borrower facing constraints on lending will have the incentive to devote more resources to the production of traded goods. Since labour is the only mobile factor this would imply a fall in non-traded output. The key here is the effect of borrowing constraints on the relative price of non-tradeables. In the unconstrained case the traded / non traded optimum is characterised by:

$$(3.20) \quad \left( \frac{\partial U / \partial C_t^N}{\partial U / \partial C_t^M} \right) = \left( \frac{\partial F / \partial Y_t^N}{\partial F / \partial Y_t^M} \right) = \left( \frac{\lambda_t^N}{-\lambda_t^M} \right) = q_t,$$

where  $q_t$  is the relative (shadow) price of non-tradeables or the real exchange rate. Equation (3.20) states the condition that the marginal rate of substitution in consumption should equal the marginal rate of transformation in production at the prevailing shadow relative price. With constraints on foreign borrowing it has been observed that marginal utility from current traded consumption is higher which given the definition of the real exchange rate indicates that traded

good production and non-traded consumption are relatively more attractive in a constrained borrowing regime. Figure 3.1 overleaf illustrates.

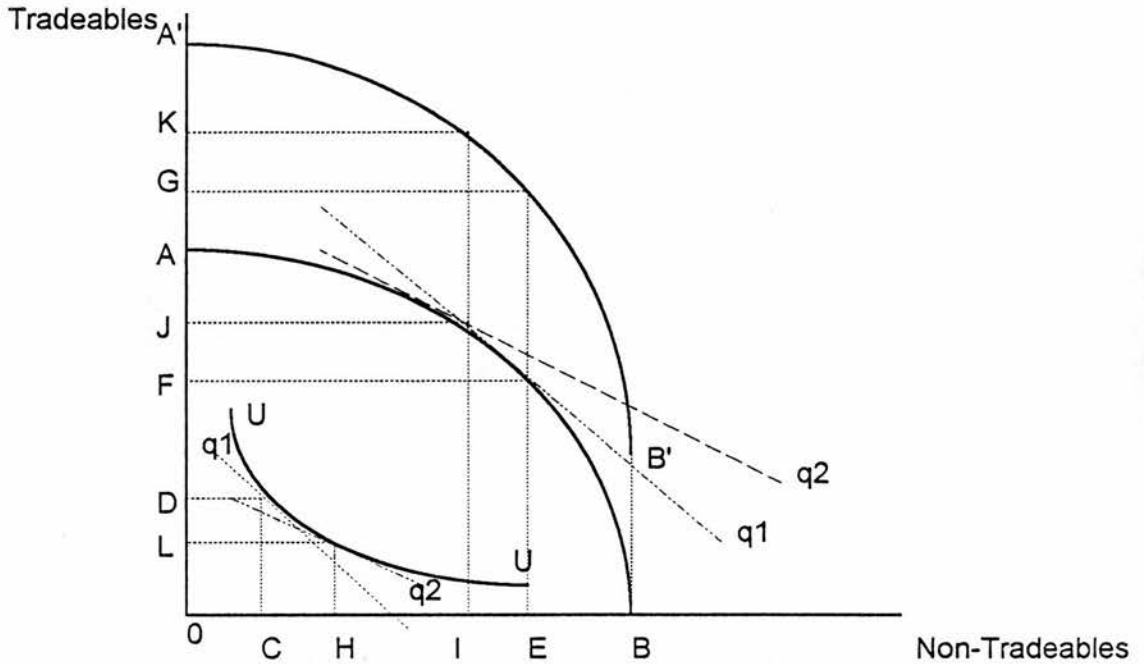
In Figure 3.1 AB denotes the production possibility frontier defined by (3.3) and A'B' is obtained from adding net resource output  $Y^R$  to this frontier. The vertical axis then defines the total level of traded goods. The equilibrium under no borrowing constraints is given by the points where the real exchange rate schedule  $q_1$  is tangential to the production possibility frontier AB and the indifference curve UU. That is, the production and consumption combinations FE and DC. Distance OE is non-traded production and OC non-traded consumption under this borrowing regime. By identity (3.5) the distance CE then measures the level of non-traded investment consistent with  $\mu_t = 0$ . On the tradeables side, OF and FG are traded good production and net resource output respectively with OD equal to traded good consumption.

If borrowing constraints are strictly binding then the relevant shadow price ratio becomes  $(q_t | \mu_t > 0)$  which is represented in Figure 3.1 by  $q_2$ . For equilibrium at this set of (shadow) prices production moves leftwards up the possibility frontier to the combination JI and consumption shifts down the indifference curve to combination LH. Traded good consumption has fallen by DL and total tradeables output increases by GK, of which FJ represents the increase in  $Y^m$ . However, the proportion of non-traded goods consumed must rise markedly since non-traded production is lower by the amount IE. Clearly then investment in the non-traded sector under a constrained borrowing regime is lower since distance  $CE > HI$ .<sup>13</sup>

---

<sup>13</sup>This is an interesting outcome in itself given suggestions that the debt problems of the 1980s have led to an "investment crisis" in many developing countries. This is especially true

**Figure 3.1: Production and consumption of tradeables and non-tradeables with constrained and unconstrained borrowing.**



In sum the static optimality conditions (3.13), (3.18) and (3.20) indicate that imperfections in international lending provide an incentive for greater net export of traded goods and consumption of non-traded goods than would be optimal without such constraints. The resource sector as an exportable sector provides another means by which current account flows can adjust to constrained lending regimes and in static terms it is easy to show that extraction will be greater, *ceteris paribus*, for a country faced with a binding borrowing constraint. The first order condition for extraction under the two cases  $\mu_t = 0$  and  $\mu_t > 0$  can be written as:

$$(3.21) \quad \mu_t = 0: \quad P_t = \frac{\partial G}{\partial Q_t} + \frac{\phi_t}{-\lambda_t^M},$$

---

of infrastructural developments typical of non-traded sectors such as construction. See Warner (1992) for a discussion.

$$(3.22) \quad \mu_t > 0: \quad P_t = \frac{\partial G}{\partial Q_t} + \frac{\phi_t}{-\lambda_t^M + \mu_t}.$$

The small open economy assumption implies  $P_t$  is given and therefore invariant to the foreign borrowing regime faced by an individual country. From (3.21) and (3.22) it can be seen that under constrained borrowing the real resource rent (or real user cost of current period extraction) is lower. Moreover for the equalities in (3.21) and (3.22) to hold it must be the case that the marginal cost of extraction is higher in the constrained case. Since extraction costs are assumed convex in extraction, this implies that the extraction rate is similarly higher.<sup>14</sup> This result has a simple intuition. The marginal benefit of an extra unit of traded goods increases relative to the marginal benefit of an extra unit of resource stock with supply-side constraints on foreign borrowing. Thus, the opportunity cost of current extraction decreases as the natural resource in its "liquid" form has the additional benefit of easing borrowing constraints through the balance of payments.

Countries which face credit rationing in international lending will thus hold a different "portfolio" of capital stocks since greater benefit is to be gained from capital in the form of traded goods rather than a stock of natural capital. Natural resources, in constrained borrowing regimes, are more important as a source of international liquidity than as capital assets. This proposition holds with one important proviso. That is, the lending constraints are themselves exogenous to the borrower's extraction decisions. Mohr (1988) addresses the question of debt repudiation by debtors whose sole source of national income is from the export of an exhaustible natural resource. When extractors can pre-commit themselves

---

<sup>14</sup>An alternative way of expressing this is that the first order condition in (3.21) cannot be satisfied by constrained borrowers. If  $Q_t^*$  denotes the optimal value of extraction which satisfies (3.21), this will not be the value which satisfies (3.22).

to an extraction program creditors will determine the credit line as a function of future resource stocks.<sup>15</sup> To avoid the repudiation of sovereign debt lenders ensure credit contracts are self-enforcing. As noted by Sachs and Cohen (1985) if a borrower can subject itself to higher repudiation costs, a higher credit line may be forthcoming as creditworthiness is augmented by the higher costs of default to the borrower. In the context of a resource exporter Mohr suggests this self imposed sanction would take the form of investment in resource stock or in other words, a resource conserving policy. Thus the level of  $B_t^*$  is likely to be endogenous rather than exogenous in a resource exporting debtor. Binding borrowing constraints and their effects can therefore be avoided by a resource-conserving and not resource depleting policy which results in a higher  $B_t^*$ . Resource conservation acts as an investment in creditworthiness. However, Mohr also notes that the creditworthiness benefits of resource conservation will conflict with the liquidity role of resource extraction. This conflict will be greater the tighter is the squeeze on the balance of payments. During the 1980s many developing countries faced this kind of squeeze as real interest rates rose and resource prices fell (for non-oil mineral producers). These exogenous factors in turn proved detrimental to creditworthiness and the ability to borrow, thereby worsening the liquidity position. Consequently, it could be argued that it is the *severity* of a constrained liquidity situation which will lead to increased resource depletion not the existence of such constraints per se.

To see this possibility in the model above the effects of lender constraints on the *intertemporal* choices of resource extractors must be considered. The conflict

---

<sup>15</sup>Mohr presents a simple 2-period model. Thus the credit available in period 1, under pre-commitment, is a function of the remaining stock in period 2, since for the resource exporter this determines their ability to repay period 1 borrowing.

between creditworthiness and liquidity is in essence an intertemporal conflict: the ability to borrow in the future depends on maintaining collateral in the form of resource capital whereas the ability to finance current account flows in the present depends on the rate of resource extraction.

Consider the equation of motion for the resource rent in the presence of a binding constraint on borrowing. This is written as:

$$(3.23) \quad \phi_t = \beta E_t(\phi_{t+1}) + \beta E_t \left( \lambda_{t+1}^M \frac{\partial G}{\partial S_t} \right) - \beta E_t \left( \mu_{t+1} \frac{\partial G}{\partial S_t} \right).$$

By comparison with (3.17a), (3.23) illustrates that with binding constraints on borrowing introduce the additional term  $\beta E_t(\mu_{t+1} \partial G / \partial S_t)$  which is necessarily negative. However, from (3.23) it can be shown that the effect of binding credit ceilings on the allocation of extraction over time will in fact be ambiguous. To see this consider the constrained regime equivalent to (3.17c). Substituting (3.18) into (3.19) gives  $\lambda_{t+1}^M = \beta(1 + r_t)E_t(\lambda_{t+1}^M) - \beta r_t E_t(\mu_{t+1})$  and dividing (3.23) by  $-\lambda_{t+1}^M$  gives:

$$(3.24) \quad \hat{\phi}_{t+1} - \hat{\phi}_t - \left[ E_t(\lambda_{t+1}^M \partial G / \partial S_t) - E_t(\mu_{t+1} \partial G / \partial S_t) / E_t(\lambda_{t+1}^M) \right] \\ = \left( 1 - E_t(\mu_{t+1}) / E_t(\lambda_{t+1}^M) \right) r_t \hat{\phi}_t,$$

where  $\hat{\phi}_{t+1}$  and  $\hat{\phi}_t$  are defined as above. (3.24) equates for the constrained borrower the return to investing in resource stock and the cost associated with such investment. This expression indicates that the stock effect "dividend" is greater in the constrained case. Since the current period incentive to liquidate resource stock is greater for the constrained debtor (recall eq. 3.22), current period extraction, *ceteris paribus*, is greater for such a debtor. Assuming the resource stock at the beginning of period  $t$  is the same under the

unconstrained and constrained scenarios, it is implied that end of period stocks are lower for the constrained debtor. The stock effect on next period costs is therefore larger. As a corollary, if current extraction is deferred the period  $t+1$  cost saving in the constrained case is larger. Hence, for constrained debtors the extra "dividend" implies a higher return at the margin to investing in resource stock. In sum, there is an incentive for "problem" (i.e. constrained) debtors to defer rather than increase current extraction. However, the right hand side of (3.24) highlights that constrained debtors also face a higher cost to investing in next period resource stock. Since  $E_t(\mu_{t+1})/E_t(\lambda_{t+1}^M) < 0$ , the debtor faced with a binding credit ceiling incurs a higher marginal opportunity cost of investing in  $t+1$  resource stock. By deferring period  $t$  extraction, the debtor forgoes the opportunity to generate liquidity made more valuable by the binding ceiling on borrowing. The overall effect of borrowing constraints on extraction will therefore depend on the relative magnitudes of the stock effect dividend and the increase in the marginal opportunity cost of resource stock investment; in the terms of Mohr there is a creditworthiness / liquidity conflict. If the stock effect on costs is relatively unimportant then such ambiguity will clearly be resolved in favour of increased extraction arising from borrowing constraints. If stock effects cannot be ignored then the marginal opportunity cost of deferring extraction to the future is required to be relatively high. In other words, the need for international liquidity in the present must dominate extraction decisions.

To develop this further it is useful to substitute out of (3.23) the terms  $\phi_t$  and  $E_t(\phi_{t+1})$ . Assuming (3.18) holds at time  $t+1$  and recalling (3.19) the equation of motion for the resource rent (3.23) can be re-written as:

$$\begin{aligned}
(3.25) \quad & (1 + r_t)(P_t - G^{Q_t}) - \left[ \frac{E_t(\mu_{t+1}) - \beta^{-1}\mu_t}{E_t(U^{C_{t+1}})} \right] (P_t - G^{Q_t}) \\
& = E_t \left[ U^{C_{t+1}} (P_{t+1} - G^{Q_{t+1}} + G^{S_t}) \right] / E_t(U^{C_{t+1}}),
\end{aligned}$$

where  $G^{Q_t} = \partial G / \partial Q_t$ ,  $G^{S_t} = \partial G / \partial S_t$ ,  $U^{C_{t+1}} = \partial U / \partial C_{t+1}^M$ . The interpretation of the Euler equation expressed by (3.25) is not obvious given the interaction between the expected terms. It is useful therefore to rewrite (3.25) in terms of expectational errors rather than the conditional expectations operator.<sup>16</sup> This is also a key feature of the econometric methodology which can be employed to empirically test the propositions of this chapter (see 3.5 below). If expectations are rational (3.25) can be re-expressed as:

$$\begin{aligned}
(3.26) \quad & (1 + r_t)(P_t - G^{Q_t}) - \left[ \frac{(\mu_{t+1}) - \beta^{-1}\mu_t}{U^{C_{t+1}}} \right] (P_t - G^{Q_t}) \\
& - \left[ U^{C_{t+1}} (P_{t+1} - G^{Q_{t+1}} + G^{S_t}) \right] / (U^{C_{t+1}}) = \xi_{t+1},
\end{aligned}$$

where  $\xi_{t+1}$  is a composite expectational error reflecting uncertainty about future prices, extraction costs, traded consumption and the borrowing constraint multiplier. By assumption  $\xi_{t+1}$  satisfies the orthogonality property  $E(\xi_{t+1} | \Omega_t) = 0$ .

(3.26) can be further re-arranged to give:

$$\begin{aligned}
(3.27) \quad & G^{Q_{t+1}} - G^{Q_t} = P_{t+1} - P_t - r_t(P_t - G^{Q_t}) - G^{S_t} \\
& + (g_\mu - \rho)\hat{\mu}_{t+1}(P_t - G^{Q_t}) - \xi_{t+1},
\end{aligned}$$

where the term  $(g_\mu - \rho)\hat{\mu}_{t+1}$  is obtained by noting:

---

<sup>16</sup>See Zeldes (1989) for a similar approach.

$$(3.28) \quad \left( \frac{\mu_{t+1} - \beta^{-1}\mu_t}{U^{C_{t+1}}} \right) \Leftrightarrow \left( \frac{\left[ \frac{\mu_{t+1} - (1+\delta)\mu_t}{\mu_t} \right]}{\left[ \frac{U^{C_{t+1}}}{\mu_t} \right]} \right),$$

$\rho$  is the discount *rate*,  $g_\mu$  is the rate of growth in the borrowing constraint multiplier and  $\hat{\mu}_{t+1}$  denotes  $\mu_t/U^{C_{t+1}}$ . Note that in (3.27) the left hand side term  $(G^{Q_{t+1}} - G^{Q_t})$  represents the discrete time change in marginal extraction costs. This implies (3.27) can be interpreted in terms of the rate of change in extraction along the optimal path.<sup>17</sup> In the case of binding borrowing constraints (3.27) therefore suggests that along the optimal path extraction is determined by price movements, the depletion effect on costs, the interest rate (i.e. marginal cost of borrowing), uncertainty (about future prices, costs, marginal utility of traded consumption, the borrowing constraint multiplier) and of note the term  $(g_\mu - \rho)\hat{\mu}_{t+1}$ . In the unconstrained case it can be equivalently shown that extraction along the optimal path is governed by an extraction Euler equation of the form:

$$(3.29) \quad G^{Q_{t+1}} - G^{Q_t} = P_{t+1} - P_t - r_t(P_t - G^{Q_t}) - G^{S_t} - \zeta_{t+1},$$

where  $\zeta_{t+1}$  is a expectational error satisfying  $E(\zeta_{t+1}|\Omega_t) = 0$ . Note however that this expectational error must differ from that in (3.27) since it excludes uncertainty about the future borrowing constraint multiplier. Given this and on the basis of (3.27) and (3.29) it is then possible to state:

<sup>17</sup>That is  $G^{Q_{t+1}} - G^{Q_t} = \Delta G^{Q_{t+1}}$ . For  $\Delta \rightarrow 0$ , this becomes the continuous time change in marginal extraction cost  $dG^Q(Q, S)/dt = G^{QQ}(dQ/dt) + G^{QS}(dS/dt) = G^{QQ}\dot{Q} - G^{QS}Q$ .

If i)  $\mu_t > 0$ , ii)  $P > G^Q$  and iii)  $g_\mu > \rho$  are satisfied then along optimal path the expected change in extraction under a constrained lending regime is greater than expected change in extraction under an unconstrained regime.

The necessary conditions i) and ii) are in some ways trivial. i) states the obvious requirement that borrowing constraints must be strictly binding, whereas ii) indicates that extraction only occurs (irrespective of borrowing constraints) when the rent on the resource stock (in real terms) is positive or in other words, extraction is feasible in an economic sense. The steady state of zero extraction will therefore be consistent with  $P_T = G_T^Q$ , i.e. the point where the marginal resource rent is zero. This emphasises that the steady-state is consistent with economic rather than physical exhaustion of the resource stock (see Sweeney, 1993).

Condition iii) is clearly of most interest. It suggests that only if the rate of increase in future marginal utility losses arising from constraints on borrowing is greater than the rate at which those losses would be discounted is there any incentive to increase the rate of extraction (relative to the unconstrained case).<sup>1819</sup> Thus the need to "cash in" resource stocks only arises if the net present value of future utility losses from borrowing constraints is positive. It

<sup>18</sup>Note also that the discount rate now plays a role in optimal extraction decisions which reflects the effect of imperfections in international capital markets represented here by binding credit ceilings.

<sup>19</sup>An alternative way of thinking about this is to note that  $(g_\mu - \rho)\hat{\mu}_{t+1}$  may be equivalently written as  $(\mu_{t+1} - (1 + \rho)\mu_t) / (\partial U / \partial C_{t+1}^M)$ . So if the borrowing constraint multiplier in present value terms is a constant, i.e.  $\mu_{t+1} = (1 + \rho)\mu_t$ , then the constrained Euler equation will reduce to that for the unconstrained case. In other words the condition for dynamic optimality is the same under either regime, *if this condition holds*. Only if the rate of increase in  $\mu$  is greater than the discount rate do the conditions for dynamic efficiency differ in the two case. Of course this does not imply that the time paths will be identical since each type of debtor must satisfy different conditions for static efficiency, i.e. eqs. (3.21) and (3.22).

would seem reasonable to presume that this rate of growth in marginal utility losses would be an increasing function of the severity of borrowing constraints. This idea parallels to a degree some of the stylised facts concerning the debt crisis period in the 1980s. Increases in the debt repayment burden coupled with falling commodity prices meant many developing countries faced chronic balance of payments difficulties. Creditworthiness consequently fell which was reflected in the marked fall in private lending to developing countries. Allsopp and Joshi (1985) highlight this collapse noting that new private lending in 1981 amounted to US\$ 80 billion, but by 1985 was only US\$ 10 billion. Thus developing countries in this period were increasingly constrained in their ability to borrow foreign capital. Concurrent with these economic difficulties, investment by debtor countries has been shown to have fallen during this period. This fall in investment could be interpreted as one source of the future marginal utility losses mentioned above as it would feed through to lower income and consumption growth in future periods.<sup>20</sup> Increased resource extraction provides one avenue for offsetting these negative effects of constrained international liquidity.

To sum up so far, it has been shown that in the presence of supply-side constraints on foreign borrowing, there will be an incentive to increase current extraction of an exhaustible natural resource. However, the existence of constrained borrowing per se does not guarantee this possibility. The extent to

---

<sup>20</sup> The preceding discussion has already pointed to lower (non-traded sector) investment in a constrained borrowing regime. At the empirical level, the precise extent to which the debt crisis directly contributed to the fall in investment is a matter which remains uncertain. What is known with greater certainty is that investment as a percentage of national income did fall in this period for many indebted developing countries. Warner (1992) quotes a fall of 22.5 % for the highly indebted countries and 10.9 % for all developing countries over the period 1982-86.

which this incentive exists depends on the growth in the marginal cost of constrained borrowing relative to the discount rate, which can be interpreted as indicating the incentive will be determined by the severity of the liquidity "squeeze" facing constrained borrowers. Thus it can be suggested that under these conditions the creditworthiness-liquidity conflict which Mohr (1988) argues faces exporters of exhaustible resources will be resolved in favour of the need for international liquidity. Section 3.5 discusses some general empirical issues raised by this chapter's theoretical model prior to an econometric analysis of the extraction Euler equations in chapter 4.

### **3.5 Econometric estimation and testing of the extraction Euler equations.**

A basic premise of this chapter's theoretical model (and those presented in chapter 2) is the assumption that resource extractors behave efficiently. More generally, it assumes that resource use decisions can be modelled within a capital theory framework. So assuming decisions makers regard the natural resource as a capital asset, the theoretical model describes necessary and sufficient conditions for optimal resource use over time. Within this framework the theoretical model has examined these conditions when the resource extractor in question is a small open economy which exports a natural resource and has access to international capital markets. More precisely, the theoretical model has been used to identify the effect that constrained international liquidity has on decisions with regard to resource extraction.

The debt crisis of the 1980s represented a severe liquidity squeeze for many developing economies producers, who are reliant on foreign exchange earnings from the export of natural resources / primary commodities. The actual resource

use decisions of these economies thus provides an opportunity to test the predictions from theory. However, it is clear that any empirical analysis will represent a joint test of whether resource use within developing economies is consistent with the efficient paths described by the model and conditional on this consistency, whether periods of constrained international liquidity are observed to result in higher resource extraction.

Thus in the remainder of this chapter two general issues are considered. Firstly, existing empirical evidence on the efficiency of resource extraction is reviewed. This review will emphasise that Euler equation models, whilst having received considerable attention at the level of firms and resource markets, have not received the same level of attention when resource use is considered at an aggregate level. This is particularly the case with respect to resource use in developing economy contexts.<sup>21</sup> This lack of attention is perhaps surprising for two reasons. Firstly, there is now a wealth of theoretical literature on the optimal use of resources by closed and open economies, recall for example the discussions in chapter 2. A second, and related, reason is the growing theoretical literature on the issue of sustainable development; see Toman, Pezzey and Krautkraemer (1995) for an overview. In this literature a basic premise is again the efficiency of resource use within a capital theory framework. Thus empirically testing whether observed rates of resource use in developing economies are consistent with a theoretical and efficient path for resource use is of interest from the point of view of assessing the applicability of these theoretical models.

---

<sup>21</sup>Questions concerning resource use within developing economies have tended to be addressed within the framework of macro-econometric models which incorporate ad-hoc specifications for resource supply. An example is Nziramasanga and Obideguu (1981).

The second general issue concerns the econometric methods employed to estimate the extraction Euler equations and to test the prediction that resource extraction is higher in constrained economies. A particular concern will be to consider how this main hypothesis of interest can be tested whilst controlling for the auxiliary hypotheses concerning the dynamic efficiency of resource use.

### *3.5.1 Resource use and dynamic efficiency : a review of empirical evidence.*

The empirical literature in resource economics can be classified into three main areas: (a) the literature on economic indicators of resource scarcity, (b) tests of arbitrage behaviour in resource markets and (c) econometric tests of the theory of exhaustible resources. Each is considered in turn.

#### (a) Economic indicators of resource scarcity

Theoretical models of resource use to paraphrase Norgaard (1990) derive time paths for net resource prices and extraction costs which are necessary conditions for the efficient allocation of scarce natural resources over time. It would appear logical then to argue that observing the actual behaviour of resource prices and costs should provide information on the long-run availability or scarcity of natural resource stocks. This logic lies behind a considerable empirical literature on the measurement of resource scarcity. Indirectly, this logic also provides a test of the theory of resource use: scarcity will be reflected in rising costs or rising prices, both of which are predicted in the theoretical literature.

In a seminal work Barnett and Morse (1963) examined unit costs of extraction and the relative price of resource in the U.S. over the period 1870 to 1957. Both indicators were observed to *fall* leading to the conclusion that technological change, new discoveries, substitution and economies of scale had more than offset any effect of resource depletion. Barnett (1979), in a re-assessment of these conclusions, continued to find no evidence of any upturn in unit costs or relative prices and hence maintained scarcity was not increasing.

The appropriate choice of scarcity indicator has been a particular focus in this literature. Brown and Field (1978) criticise the Barnett and Morse focus on unit cost as backward looking and argue for in situ prices (i.e. price net of marginal extraction cost or  $\hat{\phi}$  in the context of the model presented earlier in this chapter) as the preferred indicator since they are forward looking. This has a theoretical appeal since it is easy to demonstrate that the resource rent is equivalent to the discounted value of future extraction costs associated with current extraction; see for example Levhari and Liviatan (1977) and Bohi and Toman (1984). Smith (1978, 1979) prefers a relative output price measure since the rate of price change is equal to a weighted average of the rate of interest (a pure scarcity rent) and the rate of change in marginal extraction costs (interpreted as a differential quality rent).<sup>22</sup> The advantage of the latter, of course, is that it is easily observed whereas in situ prices are typical not. The findings from Smith (1979) based on data in Manthy (1978) provide evidence of

---

<sup>22</sup>This is easy to show in a model with extraction costs, but no stock effect on costs. Static efficiency requires  $\phi = P - C_Q$ , where  $C_Q$  is marginal extraction cost. Differentiating with respect to time gives  $\dot{\phi} = \dot{P} - \dot{C}_Q$ , which when combined with the simple Hotelling rule  $\dot{\phi}/\phi = r$  gives  $\dot{P}/P = (P - C_Q/P)r + (C_Q/P)\dot{C}_Q/C_Q$ .

negative time trend coefficients for relative prices, but importantly, these coefficients exhibit structural breaks. Notably the negative coefficients are observed to increase (i.e. move towards zero) towards the end of the sample period (1870-1972) which weakens support for the hypothesis of no increase in resource scarcity. This evidence could be taken to indicate that "ultimately the exhaustibility underlying Hotelling's model should re-assert itself". (Slade, 1991, p. 11).

Slade (1982) attempts to show models of the Hotelling type can in fact be consistent with price paths which are U-shaped, thus reconciling theory with the observation of falling relative prices for resources. The key is the effect of technological progress on extraction costs.<sup>23</sup> A sufficiently high rate of technical progress can offset any depletion effect on marginal extraction costs implying such costs fall over time. If this decline outweighs the discounted increase in resource rents, then resource price will be predicted to fall, not rise. However, if technical progress itself is subject to diminishing returns, i.e. the cost reducing impact of technical change declines over time, eventually prices should begin to rise. Slade examines this hypothesis by estimating quadratic time trends for 12 metal commodities with annual time series data covering 1870-1978 and finds the parameter on the quadratic term to be positive in all cases and statistically significant in 11 of the commodities (lead is the exception). This implies price movements consistent with the U-shaped hypothesis for the majority of metals considered. It also provides some insight into the instability found by Smith (1979) who estimated linear time trend models. If the underlying price path is

---

<sup>23</sup>There are alternative explanations which can reconcile theory with falling prices. For example new discoveries as in Pindyck (1980) and the introduction of a new backstop technology as in Heal (1976).

non-linear then the slope of a linear approximation will vary according to the sample period chosen for estimation. In other words the parameters of the linear model will vary according to the time period. A final conclusion to be taken from Slade's findings relates to the turning point in the fitted quadratic curves. By the 1970s prices of every commodity has passed the minimum of the estimated convex relationships, indicating that scarcity as measured by relative price was increasing. These findings receive further support from Hall and Hall (1984) who estimate linear time trends models for unit cost and relative price indices of scarcity, but also allow for structural breaks in the estimated coefficients. Market interventions, primarily the impact of OPEC post 1974, are controlled for with crude dummy variables. Their findings find qualitative differences between the 1960s and 1970s. with the conclusion being that the data no longer supports the Barnett and Morse view that scarcity is either static or diminishing.

The focus on relative prices rather than the more appropriate resource rent reflects, as noted above, the greater difficulties associated with observing rents. A number of studies have however proposed ways of measuring indirectly or estimating rents. Since the marginal benefit from exploration is represented by the in situ value of any discovery and the optimal level of exploration equates marginal benefits and costs, Devarajan and Fisher (1982) argue that unit exploration costs provide an indirect way of measuring rents and therefore scarcity. They present figures on average real exploration costs for U.S. oil and gas for the period 1946-71 which show unit costs to have increased at an annual average rate of 5.7 %. Leaving aside the use of average rather than marginal exploration costs and the approximate nature of the measure, Devarajan and

Fisher are still inclined to conclude that the trend is of increasing scarcity.<sup>24</sup> Halvorsen and Smith (1984) argue in favour of econometric estimates of resource rents. They present a model of a vertically integrated natural resource firm which extracts and processes mineral ores. Assuming the firm maximises its discounted flow of profits they show that the shadow price of ore in situ can be estimated from the firm's cost function.<sup>25</sup> They estimate a translog cost function with data on the Canadian metal mining industry and the parameter estimates are then used to construct the estimated in situ price. Over the period 1956-74 the estimated price of unextracted ore is observed to decline markedly, whereas the relative price of metal output has been relatively unchanged. Resource scarcity appears then to have declined.

It would seem then that economic indicators provide no conclusive evidence with respect to resource scarcity either way. Given the logic which lies behind the measurement of scarcity it would also seem unclear whether this evidence provides support for or against the underlying theoretical models of resource use. However, even if the evidence was conclusive in either direction, it is equally unclear whether this empirical literature provides any test whatsoever of the theoretical literature for as Norgaard (1990) outlines "the logic behind the arguments that economic indicators can inform us of whether resources are scarce are not is fallacious." (Norgaard, 1990, p. 19). The logical fallacy of the scarcity literature is illustrated by reducing the theoretical models to the following deductive reasoning which paraphrases Norgaard:

---

<sup>24</sup>Devarajan and Fisher highlight for example that with uncertainty in exploration marginal exploration cost need no longer equate with the in situ price at optimal levels of exploration.

<sup>25</sup>Formally, the in situ price is the negative of the partial derivative of the cost function for reproducible inputs used in processing and extraction with respect to the level of extraction.

Major Premise: If resources are scarce, and

Minor Premise: If resource extractors, knowing resources to be scarce, behave efficiently,

Conclusion: Then economic indicators (e.g. in situ prices) will reflect this scarcity.

Norgaard's fundamental criticism is that the empirical scarcity literature attempts to determine whether resources are scarce (the major premise) by observing economic indicators (the conclusion). In other words they attempt to run the reasoning in reverse and in doing so ignore the minor premise. Consequently, a refutation of scarcity may actually be explained by a violation of the minor premise and not a fall in scarcity itself. This clearly highlights the need to investigate this minor premise.

#### (b) Arbitrage Behaviour in Resource Markets.

One test of this minor premise is to examine the simple Hotelling prediction that in equilibrium the rate of increase in resource prices should equal the rate of interest, recall eq. (2.39). This can be interpreted as an arbitrage condition which views the rate of price appreciation as the capital gain from holding resource assets and leads to the prediction of a close association between rates of change in resource prices and the rate of return on other capital assets (i.e. the rate of interest). Heal and Barrow (1980) provide the first empirical tests of this interpretation of the Hotelling theoretical framework. Since the focus is on arbitrage behaviour Heal and Barrow do not outline an explicit model of resource extraction. Instead they specify log-linear demand and supply functions for a given resource and introduce arbitrage to the model through the demand

function. Specifically, resource demand is a function of the ratio of the expected rate of capital gain from the resource (measured by price appreciation) to the expected capital gain in addition to the standard price and income arguments. With market clearing and expectations generated by a distributed lag of past values the basic model specification is represented by:

$$(3.30) \quad (\Delta P/P)_t = \sum_{k=1}^K \alpha_k (\Delta P/P)_{t-k} + \sum_{j=0}^J \beta_j r_{t-k} + \sum_{j=0}^J \gamma_j g_{t-k} + \varepsilon_t,$$

where  $r$  is the rate of return on alternative assets,  $g$  is the rate of income growth and  $\varepsilon$  is a stochastic error.

Heal and Barrow (1980) examine monthly price data for copper, lead, tin and zinc with the resource price defined by the 3-month forward price. The interest rate is the return to maturity of a 91 day UK treasury Bill and income growth is derived from the OECD Index of Industrial production. The findings in Heal and Barrow (1980) offer some general support for the view that resource price movements are related to the returns on other assets. However, they are keen to stress " [the] conclusions we reach are very tentative, but suggest that the matter is considerably more complex than simple equilibrium theory [i.e. Hotelling] would suggest." (Heal and Barrow, 1980, p. 161). More specifically, their empirical results establish a statistical relationship between resource price movements and *changes* in rates of return on alternative assets which leads to the unsatisfactory "...implication that if interest rates are constant then the rate of change of resources prices must be zero, a conclusion which contradicts the simple asset market equilibrium [i.e. Hotelling] argument." (Heal and Barrow, 1980, p. 175).

A subsequent analysis by the same authors, Heal and Barrow (1981), of long term price movements reached similar conclusions in that their results were not supportive of the simple Hotelling predictions. More recently, Agbeyegbe (1989) has provided further evidence on the relationship between interest rates and resource price movements with an examination of quarterly data between 1968 and 1982 on prices for copper, lead, zinc and silver. The conclusion once again is supportive of a statistical relationship between changes in resource prices and *changes* in interest rates.<sup>26</sup>

Smith (1981) examines the performance of the Heal-Barrow specification of the arbitrage model relative to a number of competing specifications since the Heal-Barrow reduced form is consistent with a number of different structural specifications for the underlying supply and demand model. These competing models are distinguished by rates of return (i.e. single / multiple; short-term / long-term) and assumptions with respect to expectations (i.e. perfect expectations / current values ; imperfect expectation / lag function of past values).<sup>27</sup> Examined on their out-of-sample forecasting the arbitrage models are assessed relative to an first order autoregressive time series model. Smith finds that the arbitrage models are *not* uniformly superior to the AR(1) model. However, where the arbitrage models do dominate the AR(1) model (anthracite coal, copper and lead) the preferred specification is that of Heal and Barrow.

---

<sup>26</sup>Further insight into this finding is available from the stationarity properties of the Agbeyegbe data. Resource price changes are  $I(0)$ , whilst interest rates are only stationary after first differencing.

<sup>27</sup>The simple equilibrium Hotelling model is specified with price movements a function of a single interest rate in the current period and extraction costs assumed to be zero.

Two points are worth noting with respect to this limited support for arbitrage models of resource prices. The first is with respect to the role of uncertainty. The Heal and Barrow approach assumes under uncertainty the expected rate of increase in resource prices will equal the expected rate of interest. Gaudet and Howitt (1989) show that such an equivalence is generally not valid. Using capital asset pricing theory they show that the return to resource assets under uncertainty must differ from returns on other assets. Specifically, if risk aversion is assumed, the analog of the Hotelling rule will show that expected growth in resource prices differs from expected returns by an amount determined by the covariance between the marginal utility of consumption and the difference between the rate of increase in resource prices and the interest rate. The negative of this covariance provides a measure of the riskiness of resource assets. If resources are riskier then the negative of this covariance is positive and the expected gain to resource assets must in equilibrium be higher than alternative expected returns.

The second point relates to an observation by Smith (1981). He notes that by focusing on movements in output prices for resources, the Heal and Barrow model ignores potentially important aspects of the arbitrage process, e.g. movements in extraction costs. The underlying arbitrage condition in Heal and Barrow is only consistent with the efficiency predictions of Hotelling type models under the special conditions of constant marginal extraction costs and no stock depletion effect. With the introduction of increasing marginal extraction costs and depletion effects, as with the theoretical model presented above, the link between prices and interest rates is broken (Levhari and Liviatan, 1977). Related to this point is the observation that the behaviour of

resource producers on the supply side are effectively ignored in the arbitrage models of Heal and Barrow. Thus the results of the arbitrage models cannot be used to assess whether actual extraction decisions are consistent with the dynamic efficiency conditions predicted by Hotelling models which incorporate extraction costs in their general sense, i.e. with stock effects in addition to costs associated with physical extraction. Also, as noted for example by Miller and Upton (1985), Hotelling type models provide decision rules for the optimal management of stock resources and not, except indirectly, resource prices. An optimising resource extractor will choose its path of extraction and therefore marginal extraction costs, so that the path of price net of extraction cost satisfies the Hotelling dynamic efficiency condition. This is irrespective of the path for market prices.<sup>28</sup>

The empirical literature has examined this direct dynamic efficiency proposition with respect to resource extraction in one of two ways. The most prevalent has been to estimate and test empirical specifications of the dynamic efficiency condition. However, before assessing this literature in section (c) below it is worth noting the findings from the only example to date of the second approach. Miller and Upton (1985) present an alternative to the time series tests employed in the arbitrage models of Heal and Barrow. Their analysis is motivated by their demonstration that if the in situ price of a resource is expected to follow the Hotelling rule then the asset value of remaining reserves depends primarily on current period product price and extraction. This proposition is termed the Hotelling valuation principle and if valid implies asset values are homogenous of degree one in current output price net of current

---

<sup>28</sup>This describes of course the analysis presented earlier in this chapter.

extraction cost and orthogonal to possible explanatory variables such as interest rates or expected future resource prices. Their empirical evidence based on a cross-section of U.S. oil and gas companies is strongly supportive of their interpretation of the standard Hotelling model. Furthermore, their Hotelling valuation principle is shown to explain a higher proportion of the variance in reserve asset values compared to alternative non-Hotelling valuation methods.

(c) Econometric tests of the theory of exhaustible resources

A weakness of the arbitrage approach is that it is by its construction a reduced form approach which could be consistent with any number of underlying theoretical models. Empirical testing of the optimality of resource extraction should ideally entail econometric estimation of a structural model of extraction and an investigation of whether this model satisfies the restrictions implied by the dynamic efficiency condition for in situ prices. A difficulty encountered with this approach is the unobserved nature of the key variable. Two distinct approaches have been employed to overcome this.

The first is to directly estimate the production technology used in extraction. Stollery (1983) adopts this approach in an analysis of the extraction of nickel by the dominant producer INCO (International Nickel Company). Annual data from 1952 to 1973 is used to estimate a log-linear demand function and a Cobb-Douglas production function. Resource rents are then estimated as the difference between estimated values for marginal revenue and cost. These estimated resource rents in turn are used to estimate a dynamic efficiency condition which explains changes in the in situ price. Stollery obtains a

reasonable estimate of 0.15 for the firm's discount rate and concludes that extraction by this dominant producer has been consistent with a Hotelling type model. These results are dependent, however, on interpreting the difference between firm marginal revenue and cost as an estimate of the resource rent. Farrow (1985), for example, notes that this difference could equally represent the change in profit margin arising from a dynamic limit pricing policy on the part of the dominant producer. Similarly Cairns (1985, 1986) presents a critique of the Stollery analysis with the argument that a myopic pricing rule (i.e. a fixed mark-up on extraction costs) fits the nickel supply data equally well. Stollery (1985) in a response to Cairns tests this myopic pricing rule against his preferred Hotelling model. The in situ resource price is found to be statistically significant when included in a nickel price equation. With myopic pricing this variable would have an expected coefficient of zero, but should be included under a Hotelling interpretation.

Stollery's analysis relies on a Cobb-Douglas specification for the production technology. Two other studies employing the dual approach, i.e. estimation of the extraction cost function, are less supportive of Stollery's evidence in favour of the Hotelling model. Farrow (1985) examines the efficiency of extraction with monthly data on prices and costs for a competitive mining firm in the period 1975:1 to 1981:12. The tests are based on estimation of:

$$(3.31) \quad \Delta\phi_t = \delta\phi_{t-1} + \partial C/\partial X_t,$$

where  $\phi$  is the resource rent,  $\delta$  is the discount rate to be estimated and  $\partial C/\partial X$  is the depletion effect on costs (modelled here in terms of cumulative extraction). Testing for efficiency is then based on obtaining a reasonable estimate for the

discount rate and a coefficient of unity on the depletion term. It is important to note in (3.31) that neither the dependent variable nor the explanatory variables are directly observable. To implement (3.31) Farrow estimates a translog cost function which is then used to compute the marginal cost effect of cumulative extraction and to compute  $\phi$ . Given the competitive market structure this is estimated as the difference between market price and estimated marginal extraction cost which follows from the standard condition for static efficiency in Hotelling models. As Farrow recognises such a procedure is not without consequence for the empirical testing which follows. Specifically, since the static and dynamic conditions are *both* necessary for efficient resource extraction, imposing by assumption one condition to test the other biases any test towards a finding of efficiency. This being said, the results obtained by Farrow strongly reject the condition of dynamic efficiency. The estimated discount rates are consistently found to be negative, as is the coefficient on the depletion cost term. Both are contrary to the predictions of (3.31). Moreover, these findings are robust to variations of the basic model, i.e. time-varying discount rates, uncertainty about future prices and capacity constraints on extraction.

Halvorsen and Smith (1991) provide the other example of duality theory applied to the estimation of the extraction production technology and a test of dynamic efficiency. By contrast to Farrow (1985), Halvorsen and Smith do not attempt to directly estimate the condition for dynamic efficiency. Instead, the conditions required for efficient extraction are used to impose parametric restrictions on a restricted extraction function which is jointly estimated with a cost shares equation. A Hausman test is then constructed using two sets of estimates

obtained with and without the restrictions implied by the condition for dynamic efficiency. Annual time series data (1954 to 1974) for the Canadian metals industry is used to estimate the system of equations. For a range of assumed constant and variable discount rates, the evidence provided by Halvorsen and Smith rejects strongly the restrictions implied by dynamic efficiency. However, they insist on being tentative about rejecting the Hotelling model given the high level of aggregation in the data.

The optimality of resource extraction in Canada receives further attention in Young (1992). She examines the extraction behaviour of a panel of Canadian copper mining firms over the period 1956-82 in two steps. First a variety of cost functions are investigated to determine an appropriate specification for extraction costs. Once this is established the relevant marginal cost expressions are substituted into an Euler equation for extraction which derives from the condition for dynamic efficiency. This approach has the two notable advantages over earlier studies, for example Farrow (1985). First, it permits allowing direct estimation of the structural Euler equation parameters and second, it avoids difficulties which arise when estimating with "generated" regressors, i.e. computing valid standard errors for the estimates, see Pagan (1984, 1986). As with Halvorsen and Smith, the extraction Euler equation is estimated jointly with the preferred cost function specification. The parameter restrictions implied by this joint estimation are rejected given an increase in implausible estimates for price and output elasticities compared to the same estimates obtained without the cross-equation restrictions. Thus, at the level of individual firms the evidence in Young substantiates the earlier findings of Farrow which reject Hotelling explanations for observed resource extraction.

The studies considered up to now have focused solely on the consistency between the production behaviour of resource extractors and conditions for dynamic efficiency. However as noted by Bohi and Toman (1984) the resource supply process involves three interconnected stages: exploration, development and extraction. The related studies by Pesaran (1990) and Favero (1992) adopt the Euler equation framework to examine oil exploration and extraction decisions in the U.K. continental shelf. Pesaran elaborates the basic framework in which a representative price-taking firm operating under uncertainty chooses the rates of extraction and exploratory effort which will maximise the discounted future stream of profits. Necessary conditions for optimal extraction and exploration are derived and then specified for empirical analysis by assuming functional forms for extraction costs and the discovery function. In general the extraction model performs poorly with Pesaran noting "an important trade-off between statistical fit and the plausibility of the estimates" (Pesaran, 1990, p. 379). In particular estimation of the extraction model with the assumption of rational expectations obtains an estimate for the discount rate of around 1 % which is considered too low in an industry as unpredictable as the oil industry. The cost function parameter estimates also imply implausible (i.e. negative) estimates of in situ resource prices. Plausible estimates for resource rents are only obtained by imposing a zero discount factor or infinite discount rate.<sup>29</sup>The investigation in Favero (1992) examines the sensitivity of this result to the inclusion of the UK tax regime for the oil sector. As in Pesaran the results favour a zero discount factor. The implication is that U.K. oil producers operate under very short time horizons which are difficult to reconcile with an

---

<sup>29</sup>It is also notable that residual serial correlation is observed. This violates the rational expectations assumption.

intertemporal model of extraction along Hotelling lines. However, as Favero notes these findings may reflect the high degree of uncertainty generated by instability in oil prices, the unpredictable nature of the tax regime and by the high technical costs of production associated with off-shore platforms.

In summary, the empirical evidence from estimation of structural models of extraction suggest little compelling support for the view that observed resource extraction has been consistent with the efficiency predictions of intertemporal allocation models. The evidence from the arbitrage literature is no more compelling. In combination this evidence would seem to find favour with Norgaard (1990) who was so critical of the empirical literature on resource scarcity. Equally however, as Miller and Upton (1985) note, "the role of the Hotelling principle as the central proposition of resource economics is unlikely to be much affected by "mere" empirical testing. No viable alternative paradigm exists." (Miller and Upton, 1985, p. 24)

### *3.5.2 Econometric estimation and testing of the extraction Euler equation under unconstrained and constrained foreign borrowing regimes.*

The econometric analysis presented in the next chapter represents a contribution to the literature on the estimation of structural extraction Euler equations reviewed in (c) of 5.3.1 above. This analysis specifically aims to test the prediction that resource extractors faced with constraints on their ability to borrow international liquidity will, as a consequence increase their rate of resource depletion. Sections 5.2 to 5.4 have outlined a theoretical rationale for this hypothesis and since the theoretical model is premised on efficient

behaviour the econometric analysis can also be viewed as presenting a test of the dynamic efficiency of resource use. It is implied therefore, as noted above, that the econometric analysis of the debt-resources hypothesis involves the testing of joint hypotheses. However, as outlined below, the theoretical framework permits a testing procedure which allows some distinction to be made between these hypotheses.

The econometric analysis, as outlined in the next chapter, is conducted in the context of mineral production in a sample of developing countries. This is of interest from the perspective of both the indebtedness and efficiency aspects of the theoretical Euler conditions presented in this chapter. Clearly the possibility of constrained international lending is of most relevance to economies, which given their stage of economic development, are typically net debtors rather than creditors. This relevance is greatly enhanced by the macroeconomic circumstances of the 1980s which for many developing economies are characterised by increased debt servicing burdens and a reduced ability to borrow on international capital markets. With respect to efficiency, it is of interest to assess the extent to which the "positive" intertemporal allocation approach is useful in modelling resource extraction in developing economies. Given the novelty of this application of this approach to resource use decisions the econometric analysis is of interest in its own right. However, as noted earlier, with the emergence of literatures on sustainability and sustainable development which use the tools of intertemporal allocation, the testing of such models in the context of developing economies has even greater significance.

Estimation and testing of theoretical Euler equations is now standard in a wide variety of contexts. For example the approach has been widely adopted in the literatures on intertemporal consumption, investment and labour supply decisions (e.g. Hansen and Singleton, 1982; Bond and Meghir, 1994; Hotz, Kydland and Sedlacek, 1988.). This approach has also been adopted in structural modelling of resource extraction. For example the studies by Pesaran (1990), Favero (1992) and Young (1992) reviewed earlier are all based on the direct estimation of Euler equations.

In the present context the Euler equations (3.27) and (3.29) would provide the basis for econometric analysis. In general notation these Euler equations defines the first order condition:<sup>30</sup>

$$(3.32) \quad E_t h(x_{t+1}, \beta) = 0,$$

where  $x_{t+1}$  is a  $k$  dimension vector of variables observed at time  $t+1$ ,  $\beta$  is an unknown parameter vector of dimension  $l$  and  $h$  is a (possibly) non-linear function.<sup>31</sup>  $E_t$  denotes the expectations operator conditioned on information available in period  $t$ . Under the assumption of rational expectations (3.32) is written as:

$$(3.33) \quad h(x_{t+1}, \beta) = \varepsilon_{t+1},$$

---

<sup>30</sup>This brief exposition follows Hansen and Singleton (1982).

<sup>31</sup>The specification of  $h(\cdot)$  is obviously important to the empirical testing of the model. The advantage of the econometric approach outlined here is that estimation of the model only requires specification of the extraction cost function. Closed form solutions for equations (3.27) or (3.29) are not required. The issue of extraction cost specification has been widely discussed in the empirical natural resources literature. See for example Bohi and Toman (1984), Young (1992) and Epple and Londregan (1993).

which implies  $E_t(\varepsilon_{t+1}) = 0$ . Thus in the present context the function  $h(x_{t+1}, \beta)$  under unconstrained borrowing is given by:

$$(3.34) \quad h_u(x_{t+1}, \beta) = G^{Q_{t+1}} - G^{Q_t} - P_{t+1} + P_t + r_t(P_t - G^{Q_t}) + G^{S_t}$$

whilst for the case of constrained borrowing:

$$(3.35) \quad h_c(x_{t+1}, \beta) = h_u(x_{t+1}, \beta) + (g_\mu - \rho)\hat{\mu}_{t+1}(P_t - G^{Q_t})$$

If  $z_t$  denotes a  $q$  dimension vector of variables that are observed in the period  $t$  information set then a set of  $r$  population orthogonality conditions implied by the Euler equations can be defined by:

$$(3.36) \quad E(g(x_{t+1}, z_t, \beta)) = 0,$$

where  $g(x_{t+1}, z_t, \beta) = h(x_{t+1}, \beta) \otimes z_t$  and  $E$  now denotes the unconditional expectations operator. Estimation of the parameter vector  $\beta$  can be obtained from Generalised Methods of Moments (GMM) using the sample moments:<sup>32</sup>

$$(3.37) \quad m(\beta) = \frac{1}{T} \sum_{t=1}^T g(x_{t+1}, z_t, \beta).$$

The natural choice for the estimator of  $\beta$  is the vector which minimises the criterion function:

$$(3.38) \quad J = m(\tilde{\beta})' W m(\tilde{\beta}),$$

where  $W$  is a symmetric positive definite matrix of dimension  $r \times r$  and  $\tilde{\beta}$  is an initial consistent estimate of  $\beta$ . Hansen (1982) has shown that the optimal choice of  $W$ , judged in terms of the efficiency of the GMM estimator, is the asymptotic variance-covariance matrix of  $m(\beta)$ . In addition to providing an

<sup>32</sup>Note that identification of the parameter vector requires  $r \geq 1$ .

estimate of the parameter vector  $\beta$ , the GMM approach also provides a test of any over-identifying restrictions implied by the theoretical Euler equation (see Hansen, 1982; Hansen and Singleton, 1982). This feature can be exploited to provide a test of the debt-resources hypothesis.

An established approach to estimating and testing Euler equations with liquidity constraints has been to impose extra over-identifying restrictions onto the Euler equation and then test the validity of these restrictions. This would be equivalent to imposing the restriction that  $(g_u - \rho)\hat{\mu}_{t+1}(P_t - G^{\alpha}) = 0$  onto (3.35). Zeldes (1989) and Whited (1992) provide examples of this approach.<sup>33</sup> Estimation and testing in both papers proceeds with the assumption that the standard (i.e. unconstrained) Euler equation is satisfied when liquidity constraints do not bind, whereas, to the contrary, the standard Euler equation should be rejected when constraints are binding. Thus in the present context this corresponds to (3.34) being an appropriate specification for unconstrained borrowers, but this specification being rejected for constrained borrowers. Thus the liquidity constraint hypothesis can be tested by stating the standard Euler equation as the null model specification. If  $\Lambda$  denotes a matrix of instruments correlated with borrowing constraints (in Zeldes' paper household income is used) the null model imposes the over-identifying restrictions  $E(\Lambda'\varepsilon) = 0$ , where  $\varepsilon$  denotes the null model expectational error. The validity of these restrictions can then be tested (as in Zeldes' paper) by including  $\Lambda$  as regressors in the model and testing their statistical significance or by using Hansen's test of over-

---

<sup>33</sup>Bond and Meghir (1994) use similar methods to investigate the effect of financial policies on firm level investment.

identifying restrictions to test the null model specification (as in White).<sup>34</sup> If the regressors are statistically significant the restrictions  $E(\Lambda'e) = 0$  and the null model are rejected. Alternatively, the Hansen test should reject the null model if it is true that  $E(\Lambda'e) \neq 0$ .

This testing procedure in essence involves testing the validity of the null extraction Euler equation on two sub-samples of observations: an unconstrained sub-sample and a constrained sub-sample. For the first group extraction should be observed to be orthogonal to a vector of instruments which correlate with the presence of binding credit ceilings. For the constrained group theory predicts that extraction *may* also be a function of the multiplier on the credit ceiling constraint and as consequence the orthogonality conditions valid for the unconstrained group should, in contrast, be violated for the constrained group. Note extraction *may* be a function of the credit constraint multiplier for constrained economies. From the previous section it was suggested that the condition  $g_\mu > \rho$  was required to hold for the rate of extraction to increase under constrained borrowing. If  $\alpha = g_\mu - \rho$  then the null specification of the extraction Euler equation is obtained by the over-identifying restriction  $\alpha = 0$ . If this restriction is valid, then extraction decisions are independent of constraints on international lending, irrespective of whether they bind or not. Thus it might be expected that the null extraction Euler model should be rejected for resource exporters which can be classed as *severely constrained*.

---

<sup>34</sup>This is usually referred to as the J statistic. See Hansen (1982) for details of the test. There are also other moment specification tests as detailed in Newey (1985). These are discussed further in chapters 4 and 6.

Testing the validity of the extraction Euler equations for two distinct sub samples has a further advantage. The approach is able to distinguish between the failure of auxiliary assumptions and the presence of binding borrowing constraints. Zeldes makes a similar point in the context of his investigation of liquidity constrained consumption:

"While the failure of any of auxiliary assumptions ...could lead to a rejection of the Euler equation, it seems unlikely that such a failure would lead to a rejection for low-asset consumers, but not high asset consumers. However, we would expect to see this pair of results if the rejection of the Euler equation is due to liquidity constraints." (Zeldes, 1989, p. 322)

In the present context the auxiliary assumptions can be interpreted as the efficiency of resource use and the Euler equation in question is that consistent with no binding credit ceiling. Moreover, for "low-asset consumer" read "constrained debtor" and for high asset consumer read "unconstrained debtor". In short if the intertemporal allocation model of efficient resource extraction is inappropriate for modelling resource use in developing economies then data on both unconstrained and constrained observations should reject the restrictions implied by dynamic efficiency. A rejection of the null Euler equation for only constrained observations would give stronger credence to the view that the extraction of resources is higher in "problem" debtor economies.

### **3.6 Concluding summary.**

To conclude, this chapter has presented a discrete time theoretical model of a small open economy exporting an exhaustible natural resource. It was shown that under certain conditions the economy, when faced with constraints on its ability to borrow international capital, will have an incentive to increase the rate of resource extraction. A key point is that binding borrowing constraints are in

themselves not sufficient to encourage the increase in extraction during constrained periods. It is also required that the "cost" of lending constraints to the borrower be, in present value terms, positive. This indicates that there exists an underlying economic rationale for the idea that problem indebtedness (interpreted as severely constrained borrowers) can lead to the increased extraction of natural resources as a means of generating scarce international liquidity. This chapter has also briefly outlined an approach which enables econometric testing of the theoretical model and the debt-resources hypothesis. This approach proceeds by imposing over-identifying restrictions onto the theoretical Euler equation for extraction which holds under the presence of binding borrowing constraints. A rejection of these over-identifying restrictions indicates that extraction is not orthogonal to these constraints and such a rejection can be interpreted as being supportive of the debt resources hypothesis. These econometric tests are pursued further in chapter 4.

## Chapter 4

### **Exhaustible resource extraction by indebted economies: an econometric analysis.**

#### **4.1 Introduction and related literature.**

This chapter presents an econometric analysis of the debt-resources hypothesis in the context of developing country mineral producers. The analysis, as outlined at the end of chapter 3, employs Generalised Method of Moments (GMM) estimation techniques. These methods, since Hansen and Singleton (1982), have been extensively employed in the estimation and testing of stochastic Euler equations generated by dynamic optimisation problems. A distinguishing feature of the empirical analysis presented in this chapter, therefore, is the derivation of the econometric model from the theoretical framework presented in chapter 3. Epple and Hansen (1981) note the advantage of this approach to the econometric modelling of exhaustible resource supply. In particular a theoretical basis allows for a clear economic interpretation of the parameters in any empirical resource supply equation, including restrictions on sign and magnitude. Furthermore, this approach to modelling should permit an explicit treatment of stochastic factors which give rise to the error term in the econometric model. In addition to these general points, the theoretical model presented in chapter 3 suggests an explicit interpretation of the debt-resources hypothesis which as already noted is particularly amenable to the GMM estimation framework.

The use of the GMM approach to the econometric estimation and testing of a theoretical model of resource extraction by an indebted economy is distinct from previous empirical studies which have investigated or alluded to this issue, e.g.

Gilbert (1986,1989), Chang (1987) and Sen (1993). The studies presented by Gilbert and Chang are motivated by a desire to provide empirical explanations for the observation of excess volatility during the 1980s in the long run elasticity of U.S. dollar commodity prices with respect to changes in U.S. dollar exchange rates. Within the context of a general equilibrium model of the determination of international commodity prices, Gilbert is able to show that given gross substitutability in the production and consumption of a vector of traded commodities dollar commodity price elasticities are predicted to lie in the interval  $[-1,0]$ . Most econometric evidence in the 1980s as noted by Gilbert suggested elasticities which in absolute terms exceeded unity.

One of the explanations proposed for this observation is based on the effect of developing country indebtedness on commodity prices. The rationale for this relationship lies with the supply responses of developing country primary commodity producers faced with a "target revenue" constraint for foreign exchange. This constraint exists, it is argued, because of the financial pressures of high external debt burdens which are magnified by appreciations of the dollar since this increases the value of dollar denominated foreign liabilities. Consequently individual debtor countries reliant on primary commodity export for their foreign exchange earnings will, given this constraint, shift their commodity supply curve to the right or even operate on a negatively sloped supply schedule. Both of these potential effects imply producers increasing supply at lower prices in the attempt to maintain foreign exchange revenues. The effect at the aggregate level is to create excess commodity supply leading to further downward pressure on commodity prices. Given this debt effect a greater than proportionate response of commodity prices to dollar appreciations can then be rationalised. Chang (1987) in a response to Gilbert (1986) presents econometric evidence which is unable to substantiate the basic hypothesis of

debt service induced changes in commodity supply curves. Even the evidence from Gilbert himself is not convincing as the finding of a negative relationship between debt servicing and commodity prices is only statistically significant for agricultural foods. For metals and minerals the estimated negative relationship between debt servicing and price is not statistically different from zero implying that "target revenue" constraints on the supply of this group of commodities are at best unsubstantiated.

The empirical results presented by Sen (1993) focus entirely on the export supply behaviour of a number of Latin American metals / minerals producers with the hypothesised debt link motivated by an argument similar to the "target revenue" constraint. The model estimated by Sen specifies the level of metals or mineral export as a linear function of the contemporaneous level of price and debt servicing. In all cases the debt servicing coefficient is positive and in most cases statistically different from zero. It is difficult to know, however, the degree to which these findings would be robust to the inclusion of variables purposely ignored by Sen, e.g. an index of OECD industrial production, or a more explicit treatment of the dynamics in the estimated models. With respect to the latter the reported Durbin Watson statistics indicate first order autocorrelation cannot be rejected. This may indicate the need to model more explicitly the dynamics of export supply.<sup>1</sup>

Two observations can be made about these empirical studies. Firstly, the focus on a link between exports and indebtedness means that the question of whether indebtedness is a relevant determinant in the depletion of exhaustible natural resources, interpreted in this context as mineral production, cannot be assessed.

---

<sup>1</sup>A more general econometric issue associated with omitted variables is that the OLS estimator of the coefficient variance-covariance matrix is biased if the omitted variables are correlated with the included regressors (see Greene, 1990). If so in this case, this would preclude any valid statistical inferences to be made from Sen's reported estimates.

Moreover the ambiguous nature of the findings in the studies by Gilbert and Chang may be a reflection of the "world" level of analysis which obscures possible debt effects on mineral supply at the level of individual countries. A second point alluded to by Chang is that the explanations offered in these studies for a debt effect on commodity supply ignore the possibility that debtors can adjust to temporary shocks, e.g. to price or dollar exchange rates, through short-term borrowing. In other words these studies fail to control for the distinction between constrained and unconstrained periods of international lending which the analysis of chapter 3 has emphasised.

In addition to the testing of an explicit theoretical model the econometric analysis presented in the rest of this chapter attempts to provide some insight on these two issues. To address the first the empirical model is specified in terms of mineral extraction / production and then estimated using panel data on mineral production in a sample of developing countries. With respect to the second issue the approach adopted in this analysis exploits the distinction between unconstrained and constrained debtors to construct tests of the debt-resources hypothesis.

The rest of the chapter is outlined as follows. Section 4.2 discusses issues of specification which permit the derivation of an econometric model from the theoretical Euler equations considered in chapter 3. The data-set used in the analysis is described in section 4.3 along with a discussion of the econometric methods used in the analysis. The issue of specification testing is also considered at this point. Empirical results are presented in section 4.4. Section 4.5 provides a concluding summary to the chapter.

## 4.2 Specification issues.

### 4.2.1 The extraction cost function

The starting point for the empirical analysis is the null specification of the extraction model given by the Euler equation (3.29) in the previous chapter. Simple rearrangement allows this condition to be written thus:

$$(4.1) \quad G^{Q_{t+1}} = P_{t+1} - P_t + G^{Q_t} - r_t(P_t - G^{Q_t}) - G^{S_t} - \zeta_{t+1}.$$

Given a specification for the extraction cost function (4.1) will yield a resource supply equation derived from economic theory and which can be consistently estimated. However, one difficulty with this model is that extraction costs are defined by a function which has levels of extraction and remaining stocks / reserves as its arguments. It is the latter which gives rise to the expected marginal stock effect on costs denoted by  $G^{S_t}$ .<sup>2</sup> The difficulty associated with defining extraction costs in this way is that with most functional forms the specified model of supply will include a stock or reserves variable for which data, particularly at an aggregated level, may not be available.<sup>3</sup> In an attempt to overcome this data problem the standard approach

---

<sup>2</sup>Recall from chapter 3 that this stock effect was negative reflecting the idea that the cost of extraction increases as the stock is depleted. Standard justifications for this assumption include the view that as depletion progresses mining operations move further down the mine which increases the cost of bringing ore to the surface. A second view is that higher grade ores are depleted first implying remaining ores are more costly to extract. Recall Solow and Wan cited in chapter 2, Norgaard (1990) is critical of this assumption and refers to the Mayflower problem. He claims that if the Pilgrims on the Mayflower had known the location of the highest quality agricultural land, Plymouth Rock would not have been the destination of choice. In short there is no way of knowing where high quality resources are to be found beforehand. In the context of mineral extraction this view may be countered by geological surveys of resource deposits which can reveal thickness of seams etc. Additionally, evidence in Livernois and Uhler (1987) from individual oil pools in Alberta, Canada indicates that extraction costs are increasing in the order of discovery which counters the Norgaard view that "The history of North America...is a history of using low quality resources before learning led to the exploitation of higher quality, less costly resources." (Norgaard, 1990, p.23)

<sup>3</sup>Exceptions in recent literature are the related studies by Pesaran (1990) and Favero (1992) which are able to employ UK Department of Energy data on proven oil reserves in the UK continental shelf. See

which is employed in the empirical resource supply literature is to specify extraction costs in terms of levels of extraction and *cumulative extraction* with the latter acting as a proxy for the stock effect on costs. The intuition for this approach is straightforward. If  $S_0$  denotes the initial (known and unknown) stock and  $X_t = \sum_{s=1}^t Q_s$  defines cumulative extraction to period  $t$  then the level of remaining stock at the end of period  $t$  is given by the identity  $S_t = S_0 - X_t$ . This identity relationship will ensure equivalence between a stock based cost function and a cumulative extraction specification for extraction costs (Epple and Londregan, 1993). More precisely if the former is denoted by  $G^1(Q, S)$  and the latter by  $G^2(Q, X)$ , then the two cost functions are related by the identity  $G^1(Q, S_0 - X) \equiv G^2(Q, X)$ . In terms of the marginal effect on costs this equivalence between the two specifications simply implies that the marginal effect of cumulative extraction is the minus of the marginal stock effect.<sup>4</sup> For the data-sets employed in this empirical analysis stock data was unavailable and so the cumulative extraction approach is used which allows (4.1) to be re-written as:

$$(4.2) \quad G^{Q_{t+1}} = P_{t+1} - P_t + G^{Q_t} - r_t(P_t - G^{Q_t}) + G^{X_t} - \zeta_{t+1}.$$

The discussion so far has focused on costs associated with physically removing stock from the ground. Adjustment costs are also a typical feature of extraction activities. Pesaran (1990) for example cites adjustment costs in oil production arising from the need to maintain reservoir pressure. More generally, the presence of adjustment costs can be justified with the argument that any deviation of actual extraction from the desired level (in the sense, say, of the optimal response to a change in demand conditions) will reflect the economic costs which adjustment to extraction levels may

---

Harris (1993) for a detailed discussion of the geology and estimation of exhaustible resource stocks / proven reserves.

<sup>4</sup>That is given  $S_t = S_0 - X_t$ ,  $G^{X_t} \equiv \partial G / \partial X_t = \partial G / \partial S_t \cdot \partial S_t / \partial X_t = -\partial G / \partial S_t$ .

entail. The relatively high capital intensity of mining activities and the long "gestation" periods for mining projects would be relevant factors in this respect.<sup>5</sup> In an optimising framework it would be possible to incorporate these adjustment costs into the objectives of economic agents deciding upon an optimal extraction program.<sup>6</sup> Frank and Babunovic (1984) follow this approach in an effort to model the slow supply adjustments evident in mineral markets. They adopt a simple adjustment cost formulation which they argue captures the lags in extraction adjustments associated with the exploration and development process. This provides a simple way to implement analyses such as Pindyck (1978). Results from their empirical analysis reveal strong support for the presence of adjustment costs in the model of mineral supply they consider. It would be appropriate therefore to allow for the possibility of adjustment costs in the extraction model of (4.2). For ease of exposition it is assumed that the marginal extraction cost expressions in (4.2) are inclusive of adjustment costs which avoids any undue complication of the analysis. The empirical specification of the Euler extraction equation thus employs an extraction cost function of the form:

$$(4.3) \quad G(Q_t, X_{t-1}, Q_{t-1}) = (\delta_0 + (\delta_1/2)Q_t + \delta_2 X_{t-1})Q_t + AC_t.$$

(4.3) is a simple linear-quadratic functional form which has been extensively employed in the literature on resource supply (see Epple and Hansen, 1981; Bohi and Toman, 1984; Epple, 1985 and Epple and Londregan, 1993).<sup>7</sup> The dependence of extraction costs on lagged extraction  $Q_{t-1}$  reflects the presence of the adjustment cost

<sup>5</sup> Capital set-up costs for large-scale mining ventures can be considerable. For example in the case of the Carajas mineral complex in the Brazilian Amazon they are estimated to be of the order of 5-6 billion U.S. dollars (Siebert, 1985). Another example is the Selebi-Phikwe nickel-copper mine in Botswana with estimated capital expenditure of 304 million U.S. dollars by 1983 (O'Faircheallaigh, 1985).

<sup>6</sup>The adjustment cost models in the literature on firm level investment provide an obvious parallel.

<sup>7</sup>Pesaran (1990) and Favero (1992) are again perhaps an exception. Their functional form allows for a non-linearity not considered here which is that the rate of increase in marginal extraction costs is increasing in reserves. With (4.3) this second order condition is constant. The general properties of (4.3) are however, with appropriate restrictions on the cost parameters, the same as the functional form employed by Pesaran and Favero.

term  $AC_t$  which like Frank and Babunovic is specified with the quadratic term  $(\delta_3/2)(Q_t - Q_{t-1})^2$ .

The marginal cost terms with respect to  $Q_t$  using (4.3) are then specified as:

$$(4.4) \quad \begin{aligned} \partial G / \partial Q_t &= \delta_0 + (\delta_1 + \delta_3)Q_t + \delta_2 X_{t-1} - \delta_3 Q_{t-1} > 0, \\ \partial^2 G / \partial Q_t^2 &= \delta_1 + \delta_3 > 0. \end{aligned}$$

With respect to cumulative extraction:

$$(4.5) \quad \partial G / \partial X_{t-1} = (-\partial G / \partial S_{t-1}) = \delta_2 Q_t > 0.$$

The restrictions required of the marginal conditions are also indicated by the expressions given in (4.4) and (4.5). These ensure that the cost function satisfies the properties  $\partial G / \partial Q_t > 0$ ,  $\partial^2 G / \partial Q_t^2 > 0$ ,  $\partial G / \partial S_{t-1} < 0$  which were assumed in the previous chapter. Increasing marginal extraction costs thus require  $\delta_1 + \delta_3 > 0$  and the restriction  $-\delta_2 < 0$  is consistent with the anticipated effect that depletion (i.e. declining stocks) has on costs. The parameter  $\delta_3$  captures the dependence of marginal extraction costs on the speed of adjustment and is expected to be positive. The constant  $\delta_0$  would also be expected to be positive to ensure non negative marginal extraction costs at low levels of extraction. Epple (1985) however notes that relaxing this restriction on  $\delta_0$  may be needed to improve the fit of estimated models.<sup>8</sup> One final point concerning the structural cost parameters is that in standard linear-quadratic specifications  $\delta_1$  measures economies of scale in current extraction with  $\delta_1 > 0$  consistent with decreasing returns to scale (i.e. increasing marginal cost) and increasing returns to scale indicated by  $\delta_1 < 0$ . With (4.3) incorporating quadratic adjustment costs in extraction increasing marginal cost with respect to current

---

<sup>8</sup>Most empirical studies which have adopted the linear-quadratic functional form for costs have obtained negative estimates for this parameter. An example is Epple (1985). See also Epple and Londregan (1993) for an overview of some econometric findings.

extraction is observed with  $\delta_1 + \delta_3 > 0$ . Note also that  $\delta_3 > |\delta_1|$  is a sufficient condition for  $\delta_1 + \delta_3 > 0$  to hold. Given that the primary hypothesis of interest in this analysis concerns the effect of indebtedness on extraction estimation of the cost parameters is perhaps of secondary importance. Thus in the econometric analysis estimates of the structural parameters are inferred from reduced form parameters rather than estimated directly.<sup>9</sup> Using the cost function derivatives the null Euler equation (4.2) can now be specified as the econometric model:

$$(4.6) \quad \begin{aligned} Q_{t+1} = & \theta^{-1}(\delta_1 + 2\delta_3 - \delta_2)Q_t - \theta^{-1}\delta_3Q_{t-1} + \theta^{-1}P_{t+1} - \theta^{-1}P_t \\ & - \theta^{-1}r_t[P_t - \delta_0 - (\delta_1 + \delta_3)Q_t - \delta_2X_{t-1} + \delta_3Q_{t-1}] + \varepsilon_{t+1}, \end{aligned}$$

where  $\theta = \delta_1 + \delta_3 - \delta_2$  and  $\varepsilon_{t+1}$  is a random disturbance defined as  $-\theta^{-1}\zeta_{t+1}$  which satisfies the orthogonality condition  $E(\varepsilon_{t+1}|\Omega_t) = 0$ .

#### 4.2.2 Constrained and unconstrained foreign borrowing regimes.

The extraction model specified in (4.6) represents the null specification considered in the econometric estimation and testing presented below. The term null is used here in the sense that (4.6) corresponds to the extraction Euler equation which holds if extraction is independent of the foreign borrowing constraint multiplier. It was noted at the end of chapter 3 that a test of this independence or orthogonality property of the null Euler equation provides one approach to the testing of the debt-resources hypothesis. More specifically, such orthogonality is expected to be violated for observations which correspond to periods of constrained borrowing.<sup>10</sup>

<sup>9</sup>The estimates are of course not unimportant since they will provide some indication of how well the Euler equation model specification fits the mineral production data.

<sup>10</sup>Recall however one of the important results from the previous chapter which suggested it is the "severity" of binding constraints rather than a strictly positive borrowing constraint multiplier per se which distinguishes the unconstrained and constrained Euler equations. This was the interpretation that was offered of the finding that the unconstrained Euler equation (3.26) holds even if  $\mu_1 > 0$ , but  $g_\mu = \rho$ .

Testing these hypotheses requires a method for identifying periods in which constraints are binding. The approach adopted in this empirical analysis is based on defining a dummy variable indicator of binding borrowing constraints. More precisely define:

$$\begin{aligned} D_t^\mu &= 1 \text{ if } \hat{\mu}_{t+1} > 0 \Leftrightarrow \mu_t > 0, \\ &= 0 \text{ if } \hat{\mu}_{t+1} = 0 \Leftrightarrow \mu_t = 0. \end{aligned}$$

The construction of this dummy variable follows the International Debt literature which has identified debt arrears as an important indicator of constrained borrowing. Debt arrears information, as noted by Hajivassiliou (1987), provides an observable indication of the *severity* of lending constraints. The role of arrears in identifying constrained lending can be demonstrated from simple manipulation of the definitions for the change in debt and the balance of payments given in section 2 of chapter 3. Recall (3.6) which defined the change in the stock of disbursed debt. This total stock figure can be decomposed into two components: the stock of borrowing falling due for repayment in the present or future and a stock of arrears which represents deferment of principal due in previous periods and / or capitalisation of unpaid interest.<sup>11</sup> For convenience it was implicitly assumed that this latter stock was zero in (3.6). Relaxing this assumption gives  $D_t = \bar{D}_t + A_t$ , where  $\bar{D}_t$  is the stock of outstanding debt due for repayment and  $A_t$  denotes the stock of outstanding debt due to accumulated principal and interest arrears. The change in the total outstanding stock of debt stock as given in (3.6) was defined as net capital flows in a given period: the balance between the supply of new debt  $\bar{B}_t$  and principal repayments  $R_t$  due in that period. This balance as defined ignores any element of arrears in the outstanding stock of disbursed debt since it only constitutes net new borrowing in

---

<sup>11</sup>The element of arrears and its role in the total debt stock was evident from the debt reschedulings of the 1980s. To ease repayment pressures lenders would negotiate the deferment of debt repayments usually by extending the repayment schedule. As a consequence despite a substantial fall in the availability of new (voluntary) lending particularly by private lenders, for many developing countries the total stock of debt outstanding increased.

period  $t$ . Thus  $\bar{D}_t - \bar{D}_{t-1} = B_t - R_t$ . The total change in the stock of outstanding debt will then equal this change plus any change in debt arrears. More explicitly, total indebtedness evolves according to:

$$(4.7) \quad D_t - D_{t-1} = \bar{D}_t - \bar{D}_{t-1} + \Delta A_t = B_t - R_t + \Delta A_t.$$

The total demand for new borrowing given by  $D_t - D_{t-1}$  will be determined by the current account defined earlier by (3.8). In an unconstrained borrowing regime observed net lending is equal to the demand for new funds, i.e.  $B_t = R_t + D_t - D_{t-1}$  and further by implication  $R_t + D_t - D_{t-1} < B_t^*$ . Given (4.7) it must also be true that the change in arrears is zero. Hence when  $\mu_t = 0$ , then  $\Delta A_t = 0$ . In the contrary case of constrained lending the observed level of lending is determined by the credit ceiling. In this regime the (voluntary) supply of new loans is less than the borrower's desired demand. This implies:  $R_t + D_t - D_{t-1} - B_t^* > 0$ . This condition corresponds to the borrower's excess demand for new loans in a constrained regime. Balance of Payments equilibrium considerations require this excess demand to be matched by an offsetting "excess supply" which in this context can be interpreted as debt arrears. The accumulation of principal and interest arrears effectively represent an alternative source of lending. A balance of payments equilibrium in a constrained regime will therefore entail  $R_t + D_t - D_{t-1} - B_t^* = \Delta A_t > 0$ . The dummy variable  $D_t^{\mu}$  can then be defined as:

$$\begin{aligned} D_t^{\mu} &= 1 && \text{if } \Delta A_t > 0 \Leftrightarrow \mu_t > 0, \\ &= 0 && \text{if } \Delta A_t \leq 0 \Leftrightarrow \mu_t = 0. \end{aligned}$$

In practice a positive change in arrears may be observed in situations of relatively severe liquidity constraints. Running down currency reserves would provide an obvious alternative for financing any "excess demand" on the balance of payments. Nunnenkamp (1990) has observed that low stocks of currency reserves are indeed a characteristic of severely constrained borrowers indicating perhaps that the

opportunity cost of foregone currency reserves is probably less than the cost of accumulating arrears *up to a certain point*.<sup>12</sup> One reason for this might be that arrears carry more weight than currency reserves in the determination of a borrower's creditworthiness. Hajivassiliou (1987) for example presents evidence showing past arrears to be a significant determinant of levels of new loan supply (the relationship is negative as expected), whilst levels of reserves are shown not to be significant. However, as reserves tend towards zero borrowers who still face lending constraints must inevitably turn to arrears to satisfy any excess demand.

One issue which arises from this discussion of arrears as an indicator of constrained lending concerns the role of the current account. In a situation of excess demand why are arrears accumulated instead of adjustments to the trade flow component of the current account, (i.e. net trade in trade goods and resource exports in the context of the model presented in chapter 3) ? One explanation, suggested by Hajivassiliou is that deviations from current account targets may involve high costs (relative presumably to the costs associated with arrears accumulation). These may be due to domestic political concerns linked to the maintenance of living standards. A further reason is that adjusting levels of export will typically involve lags, whereas arrears by definition are the consequence of a non-action. Such lags are a feature of the above model. In the model a constraint which binds in period  $t$  is hypothesised to lead to an increase in extraction (i.e. an adjustment to a component of the flow in tradeables) during the period  $t+1$ . Thus it is binding constraints in a previous period which, under certain circumstances, influence extraction of the resource. This is important because it means any possible simultaneity problem is avoided: the

---

<sup>12</sup>This point may be when reserves are zero, but could also be at some low level of positive reserves. In the limit, as reserves tend to zero it could be argued that the opportunity cost of foregone reserves tends to infinity. It will then be rational for a borrower to accumulate arrears where the marginal costs of doing so are less than the marginal costs of reducing reserves (marginal benefits of accumulating arrears).

accumulation of arrears in  $t$  is exogenous with respect to extraction in  $t+1$  (though such accumulation beyond  $t+1$  may not be exogenous).

### 4.3 Data, econometric estimation and specification testing.

#### 4.3.1 Data

The econometric model outlined in Section 4.2 is estimated with panel data on mineral extraction in a sample of developing countries over the period 1968-89 (22 annual observations). The cross-sectional dimension of the panel is defined in terms of country-mineral combinations.<sup>13</sup> A total of 89 cross-sectional units are obtained from 33 developing countries and the minerals Bauxite, Copper, Iron, Lead, Tin and Zinc giving a total sample of 1958 observations. The structure of the data-set is detailed in a data appendix to this chapter along with summary characteristics of external indebtedness and export status as defined by World Bank classifications.

Data for the extraction and cumulative extraction variables are based on mine production data available in the British Geological Survey's *World Mineral Statistics*. Given the small open economy assumption of the theoretical model, real prices for the minerals included in the sample are based on world prices (in U.S. dollars) published in *International Financial Statistics*. It can be noted that defining the price variable in terms of foreign currency (i.e. U.S. dollars) would imply the assumption that producer costs are similarly denominated in US dollars (see Chang, 1987). For capital intensive activities such as mining reliant on imported technology this

---

<sup>13</sup>Chang (1987) also adopts the approach of considering country-mineral combinations, but does not pool over these combinations as considered in this empirical analysis. An alternative to defining the panel in terms of country-mineral combinations would be to consider individually sub-panels defined by mineral type (or indeed country). However, as Table IV.10 in the data appendix indicates, either of these approaches would imply  $N$  (the cross-sectional dimension of the panel) is small. The estimation methods employed in the analysis are based on large  $N$  and fixed time dimension asymptotics which means pooling across countries and minerals has the advantage of consistent econometric estimation.

assumption can be considered a reasonable approximation. In addition, the price variable is defined in real terms with traded goods treated as the numeraire. The empirical version of the model defines real price as nominal price relative to an index of export unit values for industrial (OECD) countries provided again in *International Financial Statistics*. This variable acts as a general price deflator in the empirical model and is treated as a proxy for the world price of traded (manufactured) goods.<sup>14</sup> The World Bank's *World Debt Tables* provide the data for the interest rate variable and the construction of the dummy variable indicator of foreign borrowing constraints. The data appendix at the end of this chapter provides further details of the variable definitions and sources.

#### 4.3.2 Econometric estimation and specification tests.

##### a) Econometric methods for dynamic panels.

In the following discussion of the econometric methods employed in estimation  $j$  is used to notate countries,  $m$  minerals and  $t$  the time period. Guided by (4.6) the basic empirical specification to be estimated can be written as:

$$(4.8) \quad \begin{aligned} Q_{jm,t} = & \beta_0 Q_{jm,t-1} + \beta_1 Q_{jm,t-2} + \beta_2 P_{m,t} + \beta_3 P_{m,t-1} + \beta_4 r_{j,t-1} \\ & + \beta_5 (r_{j,t-1} P_{m,t-1}) + \beta_6 (r_{j,t-1} Q_{jm,t-1}) + \beta_7 (r_{j,t-1} X_{jm,t-2}) \\ & + \beta_8 (r_{j,t-1} Q_{jm,t-2}) + f_{jm} + \varepsilon_{jm,t}, \end{aligned}$$

where  $jm$  denotes the combination of country  $j$  and mineral  $m$ .<sup>15</sup> The errors in the model (4.8) are assumed to satisfy  $E(\varepsilon_{jm,t}) = 0$ ,  $E(\varepsilon_{jm,t} \varepsilon_{jm,s}) = 0$  for  $t \neq s$  and  $E(\varepsilon_{h,t} \varepsilon_{jm,s}) = 0$  for  $h \neq jm$  and  $t \neq s$ . In addition orthogonality conditions of the form:

<sup>14</sup>Pesaran (1990) and Favero (1992) adopt the same price deflator to obtain their real dollar price (of oil).

<sup>15</sup>Note also that the dependent variable in the empirical model is now written in terms of period  $t$  rather than  $t+1$  as in the theoretical model. All explanatory variables are correspondingly "lagged" one period. This is done merely to retain consistency with standard notation.

$$(4.9) \quad E(Q_{jm,s} \varepsilon_{jm,t}) = E(w_{jm,s} \varepsilon_{jm,t}) = E(f_{jm} \varepsilon_{jm,t}) = 0, \quad (s < t)$$

where  $w_{jm,t}$  denotes  $(P_{m,t}, P_{m,t-1}, r_{j,t-1}, r_{j,t-1} P_{m,t-1}, r_{j,t-1} Q_{jm,t-1}, r_{j,t-1} X_{jm,t-2}, r_{j,t-1} Q_{jm,t-2})'$ , are assumed. The reduced form parameters  $\beta = (\beta_0, \beta_1, \dots, \beta_8)'$  are defined by:

$$\begin{aligned} \beta_0 &= \theta^{-1}(\delta_1 + 2\delta_3 - \delta_2), \beta_1 = -\theta^{-1}\delta_3, \beta_2 = \theta^{-1}, \beta_3 = -\theta^{-1}, \beta_4 = \theta^{-1}\delta_0, \\ \beta_5 &= -\theta^{-1}, \beta_6 = \theta^{-1}(\delta_1 + \delta_3), \beta_7 = \theta^{-1}\delta_2, \beta_8 = -\theta^{-1}\delta_3. \end{aligned}$$

Note therefore that the restrictions  $\beta_1 = \beta_7$ ,  $\beta_2 = -\beta_3$ ,  $\beta_2 = -\beta_4$  and  $\beta_3 = \beta_4$  are implied in (4.8). In addition, the structural cost parameters  $\delta = (\delta_0, \delta_1, \delta_2, \delta_3)'$  can be identified from the reduced form parameters as follows:  $\delta_0 = \beta_4/\beta_2$ ,  $\delta_1 = \beta_6/\beta_2 - \beta_8/\beta_2$ ,  $\delta_2 = \beta_7/\beta_2$  and  $\delta_3 = \beta_8/\beta_2$ .<sup>16</sup>With respect to the anticipated signs of the structural cost parameters it was noted in section 4.2 that  $\delta_1 + \delta_3 > 0$  and  $\delta_2 > 0$  would be consistent with marginal extraction costs increasing in extraction and cumulative extraction. For the reduced form parameters it is therefore expected that  $0 < \beta_2, -\beta_3, -\beta_5, \beta_6, \beta_7 < 1$  and  $-1 < \beta_1, \beta_8 < 0$ . If  $\delta_2$  is small relative to  $\delta_1 + \delta_3$  then note that  $\beta_0 > 1$  is not ruled out.<sup>17</sup>

Two further observations may be made about the empirical model. The first point concerns the error term in (4.8). The error in the econometric model recall is a composite random disturbance which arises from amongst other things uncertainty about extraction costs and prices. In a panel model these shocks need not be independently distributed over  $j$ ,  $m$  or  $t$ . This will be particularly true of the price shocks since the assumption that prices are determined on the demand side will imply that producers of mineral  $m$  experience the same shock. Moreover, historically commodity prices have tended to move together; note for example the respective

<sup>16</sup>These structural cost function parameters can be uniquely identified only if the reduced form restrictions noted previously cannot be rejected.

<sup>17</sup>One advantage of the panel model is that the stationarity assumption  $|\beta_0| < 1$  is not required where the time dimension of the panel is fixed. This arises because the properties of panel estimators for models such as (4.10) are based on semi-asymptotics, i.e. only the cross-sectional dimension of the panel is allowed to tend to infinity.

commodity price boom and slump of the mid 1970s and early 1980s, suggesting correlation of price shocks across minerals. To account for these potential correlations the error term in (4.8) can be more fully specified in terms of the error components:

$$(4.10) \quad \varepsilon_{jm,t} = \varphi_m + \lambda_t + \omega_{jm,t},$$

where  $\lambda_t$  is an aggregate time shock and  $\varphi_m$  is a mineral specific component in the error which may account for shocks to extraction costs or indeed prices which are specific to  $m$ .<sup>18</sup> The aggregate time component to the error term shock can be thought of as general commodity price shocks which affect all  $j$  and  $m$ .

The second observation with respect to (4.8) concerns the term  $f_{jm}$ . This denotes a fixed cross-sectional unit effect which has been introduced to control for heterogeneity in the marginal cost intercept  $\delta_0$ . (see Eq. (4.4)) One rationale for this can be seen by recalling from section 4.2 the equivalence between stock and cumulative extraction cost functions. To illustrate, if the depletion effect on costs is specified in terms of stocks rather than cumulative extraction then (4.3) (ignoring adjustment costs for the purposes of the illustration) could be written as:

$$(4.11) \quad G(Q_{jm,t}, S_{jm,t-1}) = (\delta_0 + (\delta_1/2)Q_{jm,t} - \delta_2 S_{jm,t-1})Q_{jm,t}.$$

The constraint on resource use implies  $S_{jm,t-1} = S_{jm,0} - X_{jm,t-1}$  where  $S_{jm,0}$  denotes the initial resource stock. The corresponding expression for marginal extraction cost is then given by:

$$(4.12) \quad \partial G / \partial Q_{jm,t} = \delta_0 - \delta_2 S_{jm,0} + \delta_1 Q_{jm,t} + \delta_2 X_{jm,t-1}.$$

---

<sup>18</sup>An example of the latter would be the unanticipated fall in tin prices in 1985 which arose from the collapse of the International Tin Council.

In the context of a panel model of resource supply defining  $-\delta_2 S_{jm,0}$  as the fixed effect  $f_{jm}$  provides a method which controls for unobserved characteristics which give rise to heterogeneity in marginal extraction costs across cross-sectional units. One obvious characteristic is the initial level (and possibly quality) of the resource stock.<sup>19</sup> A further point is that assuming the marginal cost intercepts equal  $\delta_0 - \delta_2 S_{jm,0}$ , it is easily seen that they are not guaranteed to be positive if (as expected)  $\delta_2 > 0$ . It was noted above that in much of the empirical literature which has employed cumulative extraction cost specifications negative estimates are often obtained for the marginal cost intercepts. However the view that this is contrary to expectation (e.g. see Epple, 1985) overlooks the point that the intercept in a reduced form supply equation does not uniquely identify the parameter  $\delta_0$ . In particular the use of cumulative extraction rather than remaining stocks to measure depletion must imply the omission of a relevant variable; namely initial stocks. Since this variable is fixed its effect will be proxied by the intercept in a regression model.

The estimation of dynamic panel models such as (4.8) has been the subject of a recent and expanding econometric literature. One well established finding in this literature is the (semi-) inconsistency of the Within (or Least Squares Dummy Variables) estimator. That is for an econometric model of the form:

$$(4.13) \quad y_{it} = f_i + \alpha y_{i,t-1} + x'_{it} \beta + v_{it} \quad i=1, \dots, n; t=1, \dots, T,$$

where  $v$  is an i.i.d error with constant variance then estimates of  $\alpha$  and the vector  $\beta$  are obtained from OLS estimation of (4.13) expressed as deviations from time means which "sweeps" out the fixed effect  $f_i$ . That is,

$$(4.14) \quad y_{it} - \bar{y}_i = \alpha (y_{i,t-1} - \bar{y}_{i,-1}) + (x_{it} - \bar{x}_i)' \beta + (v_{it} - \bar{v}_i).$$

<sup>19</sup>This initial level of stock is also clearly correlated with explanatory variables such as extraction and cumulative extraction levels which is a further reason to view the individual heterogeneity as being a fixed rather than random characteristic.

Assuming  $T$  to be fixed (as with most panels) this OLS estimator is inconsistent since it can be shown that (see Nickell, 1981; Hsiao, 1986; Sevestre and Trognon, 1992):

$$(4.15) \quad \begin{aligned} & \text{plim}_{N \rightarrow \infty} NT^{-1} \sum_i \sum_t (y_{it-1} - \bar{y}_{i,-1})(v_{it} - \bar{v}_{i,-1}) \\ & = -\frac{\sigma_v^2}{T^2} \cdot \frac{T-1-T\alpha+\alpha^T}{(1-\alpha)^2} \neq 0, \end{aligned}$$

given the asymptotic correlation between the transformed lagged endogenous variable and disturbance term.<sup>20</sup>

Consistent estimation of the parameters of interest in dynamic panel models has therefore relied on alternatives to the within transformation. The commonest approach is to first difference the econometric model. Thus estimation of  $\beta = (\beta_0, \dots, \beta_8)'$  in (4.8) is obtained from the model:

$$(4.16) \quad \begin{aligned} \Delta Q_{jm,t} &= \beta_0 \Delta Q_{jm,t-1} + \beta_1 \Delta Q_{jm,t-2} + \beta_2 \Delta P_{m,t} + \beta_3 \Delta P_{m,t-1} \\ &+ \beta_4 \Delta r_{j,t-1} + \beta_5 \Delta(r_{j,t-1} P_{m,t-1}) + \beta_6 \Delta(r_{j,t-1} Q_{jm,t-1}) \\ &+ \beta_7 \Delta(r_{j,t-1} X_{jm,t-2}) + \beta_8 \Delta(r_{j,t-1} Q_{jm,t-2}) + \Delta \varepsilon_{jm,t} \end{aligned}$$

where  $\Delta \varepsilon_{jm,t} = (\omega_{jm,t} - \omega_{jm,t-1}) + (\lambda_t - \lambda_{t-1})$ . For notational purposes it is more succinct hereafter to define  $i = jm$  and recalling the vector  $w_{jmt}$  from (4.9), the transformed model can be written as:

$$(4.17) \quad \Delta Q_{it} = \beta_0 \Delta Q_{it-1} + \beta_1 \Delta Q_{it-2} + \Delta w_{it}' \tilde{\beta} + \Delta \varepsilon_{it}, \quad i=1, \dots, N; t=1, \dots, T$$

where  $\tilde{\beta} = (\beta_2, \beta_3, \beta_4, \beta_5, \beta_6, \beta_7, \beta_8)'$ .<sup>21</sup>

<sup>20</sup>Note in addition if  $T \rightarrow \infty$  then (4.15) does tend to zero.

<sup>21</sup>Note therefore that (4.17) is written without the reduced form parameter restrictions being imposed. In the empirical analysis below this unrestricted specification is estimated initially with the restrictions then being tested. The results below suggest these restrictions cannot be rejected.

Estimation of (4.17) by OLS would lead to inconsistent estimates given correlation between  $\Delta Q_{it-1}$  and  $\Delta \varepsilon_{it}$ . An instrumental variables approach to estimation is therefore appropriate. One possibility as suggested in Anderson and Hsaio (1982) is to instrument  $\Delta Q_{it-1}$  with either  $\Delta Q_{it-2}$  or  $Q_{it-2}$ . Sevestre and Trognon (1992) note however that it should be possible to obtain more efficient instrumental variable estimators than that proposed by Anderson and Hsiao.<sup>22</sup> Asymptotically efficient IV estimators of the type analysed by Hansen (1982) within a Generalised Method of Moments (GMM) framework have been extended to dynamic panel models by, for example, Holtz-Eakin et. al. (1988), Keane and Runkle (1990) and Arellano and Bond (1991).

The orthogonality properties of the error term imply that with first differencing a valid set of instruments for identifying the parameters in (4.17) contains values of  $Q_{it}$  and  $w'_{it}$  lagged two or more time periods. Thus following Arellano and Bond (1991) the valid instrument set for each  $i$  can be denoted by:

$$(4.18) \quad Z_i = \text{diag}(Q_{i1}, \dots, Q_{is}; w'_{i1}, \dots, w'_{is}) \quad (\text{for } s < T-1),$$

which defines  $Z_i$  as a  $(T-2) \times r$  block diagonal matrix with the  $s$ th block given by  $(Q_{i1}, \dots, Q_{is}; w'_{i1}, \dots, w'_{is})$ . The orthogonality properties of the error in (4.8) can then be expressed in terms of a  $r \times 1$  vector of moment restrictions defined by  $E(Z_i' \bar{\varepsilon}_i) = 0$  where  $\bar{\varepsilon}_i = (\varepsilon_{i3} - \varepsilon_{i2}, \dots, \varepsilon_{iT} - \varepsilon_{iT-1})'$ .<sup>23</sup> However, a GMM estimator which exploits sample equivalents of these moment restriction, i.e.  $N^{-1} \sum_{i=1}^N Z_i' \bar{\varepsilon}_i$ , will not give consistent parameter estimates given the presence of a time-specific component in the first differenced error. As noted by Chamberlain (1984), these sample orthogonality conditions will only to converge to zero as  $T \rightarrow \infty$  with the presence of

<sup>22</sup>The Anderson and Hsiao estimator, for example, takes no account of the MA(1) structure of the first differenced error term.

<sup>23</sup>This vector would be equivalent to the population orthogonality conditions defined in (3.32) of chapter 3.

aggregate shocks. One option as employed in Keane and Runkle (1990) is to use a long panel to ensure the GMM estimator has the desired properties. In the context of large N fixed T panels however it is evident that the typical time dimension will be insufficient to guarantee this consistency. An alternative which is more widely employed in practice therefore is to use time dummy variables as a way of controlling for aggregate shocks in the model and thus eliminate its effect from the error term (e.g. Hotz, Kydland and Sedlacek, 1988 and Whited, 1992). Thus following this latter approach the model in (4.17) stacked over each i now becomes in matrix form:

$$(4.19) \quad Y = W\beta + D_\lambda \lambda + V,$$

where:

$$\begin{aligned} Y &= (Y_1', \dots, Y_N')' & Y_i &= (\Delta Q_{i3}, \dots, \Delta Q_{iT})' \\ W &= (W_1', \dots, W_N')' & W_i &= (\Delta Q'_{i,-1}, \Delta Q'_{i,-2}, \Delta w'_i)' \\ V &= (V_1', \dots, V_N')' & V_i &= (\Delta \omega_{i3}, \dots, \Delta \omega_{iT})' \\ D_\lambda &= (I_{1,T-2}, \dots, I_{N,T-2})' & I_{1,T-2} & \text{is a } (T-2) \times (T-2) \text{ identity matrix} \\ \beta &= (\beta_0, \dots, \beta_8)' \\ \lambda &= (\lambda_3 - \lambda_2, \dots, \lambda_T - \lambda_{T-1})' \end{aligned}$$

and the orthogonality conditions are now expressed as:

$$\text{plim}_{N \rightarrow \infty} N^{-1} \sum_{i=1}^N Z_i' V_i = \text{plim}_{N \rightarrow \infty} N^{-1} Z' V = 0,$$

where Z is the  $N(T-2) \times r$  instrument matrix  $(Z_1', \dots, Z_N')'$  with  $Z_i$ , now defined as  $Z_i = \text{diag}(Q_{i1}, \dots, Q_{i5}; w'_{i1}, \dots, w'_{i5}; 1)$ .

The GMM estimator for  $\gamma = (\beta, \lambda)'$  can then be obtained by minimising the criterion:

$$(4.20) \quad (N^{-1} Z' V)' A_N (N^{-1} Z' V) = \left( N^{-1} \sum_{i=1}^N V_i' Z_i \right) A_N \left( N^{-1} \sum_{i=1}^N Z_i' V_i \right),$$

which in the linear case implies the estimator:

$$(4.21) \quad \hat{\gamma}_{\text{GMM}} = (X'ZA_NZ'X)^{-1}(X'ZA_NZ'Y) \\ = \left( \left( \sum_{i=1}^N X_i'Z_i \right) A_N \left( \sum_{i=1}^N Z_i'X_i \right) \right)^{-1} \left( \left( \sum_{i=1}^N X_i'Z_i \right) A_N \left( \sum_{i=1}^N Z_i'Y_i \right) \right),$$

where  $X = (W D_\lambda)$ .

The efficiency of the GMM estimator (4.21) depends on the choice of  $A_N$ . A necessary condition for efficiency (see Davidson and MacKinnon, 1993; Theorem 17.3) is that as  $N \rightarrow \infty$  the matrix  $A_N$  should tend to a matrix proportional to  $\Phi^{-1}$  which denotes the inverse of the average covariance matrix of the empirical moments  $Z_i'V_i$ , i.e.  $\Phi = N^{-1} \sum_{i=1}^N E(Z_i'V_iV_i'Z_i)$ . Using  $A_N = \Phi^{-1}$  the asymptotic variance-covariance matrix of (4.21) can thus be denoted by (see for example Arellano and Bond, 1991):

$$(4.22) \quad \text{a var}(\hat{\gamma}_{\text{GMM}}) = N \cdot (X'Z\Phi^{-1}Z'X)^{-1}.$$

The computation of (4.21) and (4.22) thus requires a consistent estimator for  $\Phi$ . Under the assumptions of conditional homoscedasticity and serial independence of the errors a suitable choice for  $A_N$  would be  $(N^{-1} \sum_{i=1}^N Z_i'Z_i)^{-1}$ .<sup>24</sup> The latter assumption of serial independence would not be appropriate in the present context, however, since the first differenced error implies within group errors are MA(1). If conditional homoscedasticity can still be retained then a consistent estimate of  $E(Z_i'V_iV_i'Z_i)$  may be obtained using  $Z_i'H_iZ_i$  where  $H_i$  is a  $(T-2)$  square matrix with twos on its main diagonal elements and minus ones on the first sub-diagonals.<sup>25</sup> When, however, the true structure of the error variances is unknown it may be more appropriate to relax conditional homoscedasticity and allow for conditional heteroskedasticity over both  $i$  and  $t$  dimensions. With the Euler equation errors in

<sup>24</sup>This would give the two-stage least squares or ordinary IV estimator.

<sup>25</sup>Note that with the first difference error  $\text{var}(\omega_{it} - \omega_{it-1}) = 2\sigma_\omega^2$  and  $E((\omega_{it} - \omega_{it-1})(\omega_{it-s} - \omega_{it-s-1})) = -\sigma_\omega^2$  for  $s=1$  and zero for  $s > 1$ .

chapter 3 it was clear that these composite errors were heteroscedastic given the interaction between variables and random forecast errors. A consistent estimator for  $\Phi$  can then be obtained from (see Holtz-Eakin et. al., 1988 and Arellano and Bond, 1991):<sup>26</sup>

$$(4.23) \quad \hat{\Phi}_{rs} = N^{-1} \sum_{i=1}^N \hat{v}_{ir} \hat{v}_{is} (Z'_{ir} Z_{is}),$$

where  $\hat{v}_{it}$  ( $t = r, s$ ) is an initial consistent estimate of element  $t$  in  $V_i$  and  $Z_{it}$  denotes row  $t$  of  $Z_i$ .<sup>27</sup>

### *b) Specification Tests.*

The discussion so far has concentrated on the estimation of the empirical specification of the Euler equation model. As outlined at the end of chapter 3 one approach to the testing of the debt-resources hypothesis is to test the validity of the over identifying restrictions exploited in this GMM estimation, i.e. the sample moment restrictions  $N^{-1} \sum_{i=1}^N Z'_i V_i$ . It is anticipated under the maintained hypothesis, furthermore, that these restrictions are valid for unconstrained observations, but rejected for those which are classed as constrained.

Two specification tests can be employed to test the validity of these over-identifying restrictions. The first is the standard test for mis-specification or validity of the instrument set employed in estimation; see for example Sargan (1958).<sup>28</sup> Hansen (1982) extends this test to GMM estimators and shows that  $N$  times the minimised

<sup>26</sup>This estimator is analogous to the heteroskedasticity consistent covariance estimator due to White (1980). It is appropriate where the error terms for different cross-sectional units are uncorrelated. Errors within units may however be correlated, e.g. as with the first differenced error.

<sup>27</sup>The initial estimates of  $v_{it}$  can be computed using an initial consistent estimate of  $\gamma$  which itself can be obtained using  $\hat{\Phi} = N^{-1} \sum_{i=1}^N Z'_i H_i Z_i$ .

<sup>28</sup>Validity of the instrument set here refers to the orthogonality property of the instruments which is required for consistent IV estimation. This property is simply the moment restrictions  $E(Z'_i V_i) = 0$  referred to above.

value of the criterion (4.20) is asymptotically distributed as a Chi square variable with  $r - k$  degrees of freedom where  $r$  is the number of instruments (orthogonality conditions) and  $k$  the number of parameters estimated. This test, referred hereafter to as the J-Statistic, is of particular relevance to the testing of Euler equation specifications. The moment restrictions used to construct the GMM estimator are implied by the underlying theoretical model (recall for example the discussion in section 3.5.2 of chapter 3). The J-Statistic can therefore be interpreted as a test of the Euler equation specification.

This test is however only a general specification test. It could be argued that the main feature of the debt-resources hypothesis is that it implies a test of whether extraction is orthogonal to a particular set of variables. More specifically, if  $\Lambda$  denotes variables correlated with the presence of constrained borrowing the null Euler equation for extraction implies the additional moment restrictions  $E(\Lambda'_i V_i) = 0$ . If valid, these restrictions would suggest extraction is indeed orthogonal to these variables. Thus it is also of interest to test the validity of moment restrictions which can a priori be considered "suspect" or "contaminated".

Following Newey (1985), suppose the set of instruments used in estimation,  $Z_i$ , can be partitioned into  $(Z_{i1}, Z_{i2})$  which implies a corresponding partition of the vector of moments  $Z'_i V_i$  into  $(Z'_{i1} V_i, Z'_{i2} V_i)'$ . If only the instruments  $Z_{i2}$  are considered to be "contaminated", then the mis-specification may be parameterised as the expectation of  $Z'_{i2} V_i$  with the restrictions  $E(Z'_{i1} V_i) = 0$  satisfied under the mis-specification. Thus the alternative hypothesis is stated as:

$$(4.24) \quad E(Z'_{i1} V_i) = 0, \quad E(Z'_{i2} V_i) \neq 0.$$

Clearly in the context of the debt-resources hypothesis the vector of suspect moments  $Z'_{i2}V_i$  can be interpreted as the vector  $\Lambda'_iV_i$ . Thus in terms of the definitions above:

$$(4.25) \quad \begin{aligned} Z_{i1} &= \text{diag}(Q_{i1}, \dots, Q_{is}; w'_{i1}, \dots, w'_{is}; 1), \\ Z_i &= (Z_{i1}; \text{diag}(\Lambda_{i1}, \dots, \Lambda_{is})), \end{aligned}$$

and under the alternative the sample moments  $N^{-1} \sum_{i=1}^N \Lambda'_iV_i$  are considered "suspect", i.e. under the alternative hypothesis  $\Lambda_i$  covaries with the error from the null specification of the Euler equation model.

In related econometric analyses, e.g. Zeldes (1989) and Whited (1992), the testing of equivalent moment restrictions, with for example the J statistic, has exploited differences between unconstrained and constrained sub-samples which are predicted by theoretical Euler equations. For example, in the context of Zeldes' investigation of the permanent income / life cycle model (with rational expectations) of household consumption, the standard Euler equation of consumption which equates marginal utility from current consumption with the present value of future marginal utility is predicted to hold only for households who do not face liquidity constraints.<sup>29</sup> The equivalent Euler equation for constrained households will contain an additional variable which is the lagrange multiplier on the liquidity constraint. To the extent that this variable covaries with current household income, Zeldes argues that disposable income levels should be a determinant of consumption in constrained households. Thus in Zeldes' analysis defining  $\Lambda$  in terms of observations on household income should imply rejection of the restrictions  $E(\Lambda'e)=0$  for constrained households, but not unconstrained households. Whited (1992) employs similar reasoning in the context of firm level investment by arguing that the lagrange multiplier from a

---

<sup>29</sup>That is households who do not face binding borrowing constraints. In Zeldes model this constraint is defined in terms of a non-negativity constraint on household assets.

constraint on a firm's debt accumulation will covary with indicators of financial "distress", e.g. the ratio of debt service to cash flow.

This approach is repeated in the present analysis. More specifically, the Euler equation model is estimated using unconstrained and constrained sub-samples of data. For the unconstrained group it is anticipated that the "suspect" moment restrictions will not be rejected since the theoretical model indicates no role for the borrowing constraint multiplier in the Euler equation. The converse may be expected for the constrained group. The tests statistics outlined in Newey (1985) for testing hypotheses such as (4.24) are employed in the analysis, with the matrix of suspect instruments  $\Lambda$  specified in a number of ways (see section 4.4 below for details).<sup>30</sup>

So far testing of the debt-resources hypothesis has been discussed in terms of "suspect" moment restrictions which involve instruments correlated with constrained borrowing. This testing also exploits information, in this case on debt arrears, to examine these restrictions with samples of unconstrained and constrained observations. An alternative approach to the testing of similar hypotheses is provided by Bond and Meghir (1994) in an investigation of the effect of financial constraints on investment decisions with a panel of U.K. companies. The approach used by Bond and Meghir is to interact the explanatory variables suggested by a basic (i.e. unconstrained) Euler equation for optimal investment with a dummy indicator of financial constraints which is defined in terms of whether firms issue shares and pay dividends. For firms where the former is zero and the latter positive the inference is that a firm has sufficient internal finance to fund investment plans and is therefore unconstrained. The tests conducted by Bond and Meghir are then based on the

---

<sup>30</sup>These tests simply involve computing the usual chi-square test statistic from the subset of "contaminated" sample moment restrictions, i.e.  $N^{-1} \sum_i Z'_{i2} V_i$ , and the associated variance-covariance matrix, see Newey (1985) for details.

estimated coefficients on the explanatory variables interacted with the dummy indicator which measure differences between unconstrained and constrained firms. Thus the estimated parameters are expected to reveal systematic differences between unconstrained and constrained groups of firms. Another way of investigating such systematic differences between groups of observations with respect to the estimated parameters is to directly test for parameter constancy / stability. Such tests have been developed in the GMM context by Hoffman and Pagan (1989) and Ghysels and Hall (1990). These tests are applied to the testing of the debt-resources hypothesis in the following manner.

If there are no systematic differences between the unconstrained and constrained sub-samples it would be reasonable to hypothesise that the parameter estimates from one of the sub-samples can be used to predict over the other sub-sample. The absence of any such differences suggesting that the error terms in each sub-sample are drawn from the same underlying distribution. To illustrate more formally, assume the unconstrained sub-sample of size  $N_1$  is used to compute predictions for extraction in the constrained sub-sample of size  $N_2$ . It is then possible to test for parameter stability by examining the average prediction error over the constrained sub-sample. In the GMM context this extends to examining the expectation of a vector of predicted moment functions. More precisely, let the average prediction error be denoted by  $N_2^{-1} \sum_i^{N_2} \hat{V}_i$  where  $\hat{V}_i$  is the constrained sample prediction error evaluated at estimates obtained from the unconstrained sample. For a GMM test these prediction errors are generalised to the predicted sample moments  $N_2^{-1} \sum_i^{N_2} Z_i' \hat{V}_i$  and to test the null hypothesis that they equal zero. Technical details on the econometrics of the test statistic are reserved for an appendix to this chapter.

Some general tests of model adequacy are also reported with the empirical results presented in Section 4.4. The first is a test of second order serial correlation in the estimated residuals. The consistency of the GMM estimators outlined above depends crucially on the assumption of serial independence in the levels equation error term. Equivalently for the first differenced model consistency hinges on the assumption  $E(v_{it}v_{it-2})=0$ , since with the first difference of serially uncorrelated errors  $E(v_{it}v_{it-1})$  need not be zero. Section 4.4 reports the test statistic presented in Arellano and Bond (1991) which is asymptotically distributed  $\mathcal{N}(0,1)$  under the null of serial independence. Tests of appropriate functional form are also reported, with the statistics computed as a GMM equivalent of the conventional RESET test (see Pagan and Vella, 1989). As with the tests for parameter stability noted earlier, technical details on these specification tests are left to the chapter appendix. Finally a measure of goodness of fit appropriate in the context of IV estimation is also reported, see Pesaran (1990) for details.

#### **4.4 Empirical results.**

The empirical results presented below were obtained with two modifications to the estimators discussed in 4.3. The first modification concerns the actual set of instruments used in  $Z_i$  or equivalently, the actual moment restrictions exploited to construct the GMM estimators. The optimal instrument set as defined in (4.18) is impractical in practice even for panels with only a reasonably sized time dimension. For this reason all available moment restrictions are not exploited in estimation, but it could be argued, as in Bond and Meghir (1994), that remote lags are unlikely to be useful instruments.

The second modification concerns the estimator used to construct  $\Phi$  which is essential for the GMM estimator (4.21) and its covariance matrix (4.22). In initial investigations the use of the estimator (4.23) did not prove very successful in the sense that the matrix  $\hat{\Phi}$  was not guaranteed to be semi-positive definite.<sup>31</sup> A further issue with the choice of (4.23) to estimate  $\Phi$  is that it does not allow for the possibility that the moments  $Z_i'V_i$  are unlikely to be independent of the moments  $Z_{i,-\tau}'V_{i,-\tau}$  for  $\tau = 1$  given  $V_i$  is a vector of first differenced errors.<sup>32</sup> This would suggest in the present framework an estimator for  $\Phi$  of the form:

$$(4.26) \quad \hat{\Phi} = N^{-1} \sum_{i=1}^N \hat{\Phi}_i = N^{-1} \sum_{i=1}^N \left( \sum_{-\tau}^{\tau} Z_i' V_i V_{i,\tau}' Z_{i,\tau} \right),$$

or equivalently for  $\tau = 0, 1$ :

$$(4.27) \quad \hat{\Phi} = N^{-1} \sum_{i=1}^N \left( \hat{\Phi}_{i,0} + \left( \hat{\Phi}_{i,1} + \hat{\Phi}_{i,1}' \right) \right).$$

The estimators (4.26) and (4.27) are analogous to the covariance matrix estimators outlined by Newey and West (1987a) and employed in the panel studies of Keane and Runkle (1990) and Young (1992). It is well established, however, that the estimator (4.27) which corresponds to the truncated kernel estimator is not guaranteed to be positive definite (see Newey and West, 1987a). To avoid this possibility is it standard to impose a weighting structure on (4.27) to ensure the estimator is positive definite. This gives:

---

<sup>31</sup>This was found with a variety of instrument sets. As a check on the computations which were obtained using Shazam 7.0, the DPD program written by Arellano and Bond was also used to estimate the extraction Euler equation. In some cases estimates could not be computed because the  $\Phi$  matrix was not positive definite. In others the reported standard errors were incredibly small indicating possible singularity problems. Of note is the finding by Arellano and Bond (1991) of downward bias in their estimated GMM standard errors. They suggest as a result alternative estimators of  $\text{avar}(\hat{\gamma})$  which really implies different estimators for  $\Phi$ . One possibility which was investigated was to restrict to zero elements not on the main diagonal and the first sub-diagonal of the matrix  $V_i V_i'$  which reflects the MA(1) structure. The resulting matrix for  $\Phi$  remained non positive definite.

<sup>32</sup>Note that given earlier assumptions about the error terms it can be assumed that  $Z_i'V_i$  are independent of  $Z_h'V_h$  and  $Z_{h,-\tau}'V_{h,-\tau}$  for  $i \neq h$ .

$$(4.28) \quad \hat{\Phi} = N^{-1} \sum_{i=1}^N \left( \kappa_0 \hat{\Phi}_{i0} + \kappa_1 (\hat{\Phi}_{i1} + \hat{\Phi}_{i1}') \right),$$

where  $\kappa_\tau$  denotes a series of weights such that  $\kappa_\tau = 1$  for  $\tau = 0$  and less than 1 for  $|\tau| > 0$ . The reported results use the Parzen kernel for  $\kappa_\tau$ . In addition the eigenvalues for the estimators of  $\Phi$  computed using (4.28) were used as a test of positive definiteness. In all cases these were positive as required.<sup>33</sup>

#### *4.4.1 Estimation and testing of the extraction Euler equation with unconstrained and constrained sub-samples.*

Tables IV.1 to IV.3 report the estimation results obtained from splitting the data-set into the unconstrained and constrained sub-samples. The interest here, recall, is to observe whether the extraction Euler equation is rejected for constrained observations, but not for those classed as unconstrained.

The estimations in Table IV.1 do not provide a direct test of this hypothesis since OLS and LSDV estimates are reported here. The earlier discussion in section 4.3.2 noted the inconsistency of these estimation methods and the results are detailed primarily for the purposes of comparison with the GMM estimates outlined in Tables IV.2 to IV.3. A number of observations on Table IV.1 are however worthy of note.

---

<sup>33</sup>Andrews (1991) provides discussion of different kernel estimators. He recommends the use of a quadratic spectral kernel given its asymptotic optimality. However it is complicated and time-consuming to compute. Easier computationally are the Parzen and Bartlett kernels. The Monte Carlo evidence in Andrews suggests the Parzen weights may be preferable to the Bartlett kernel. This evidence though is in the context of time series models.

**Table IV.1**  
*Estimation of the Extraction Euler Equation with Unconstrained and Constrained Sub-Samples*

Estimation Method:	OLS		LSDV	
	Unconstrained	Constrained	Unconstrained	Constrained
$\beta_0$	1.0732 (0.0337)	0.9684 (0.0415)	1.0180 (0.0351)	0.8699 (0.0420)
$\beta_1$	-0.0943 (0.0388)	0.1091 (0.0466)	-0.0794 (0.0389)	0.0990 (0.0433)
$\beta_2$	0.0004 (0.0006)	0.0024 (0.0120)	0.0005 (0.0007)	0.0019 (0.0012)
$\beta_3$	-0.0005 (0.0007)	-0.0013 (0.0014)	0.0002 (0.0008)	-0.0012 (0.0013)
$\beta_4$	-0.6143 (1.921)	2.2171 (3.331)	0.0628 (3.105)	-0.2192 (4.779)
$\beta_5$	0.0021 (0.0034)	0.0043 (0.0061)	0.0052 (0.0034)	0.0006 (0.0060)
$\beta_6$	1.2116 (0.3534)	1.5136 (0.5574)	2.4875 (0.3908)	1.2051 (0.5134)
$\beta_7$	0.2021 (0.0780)	-0.3090 (0.0646)	0.2234 (0.0800)	-0.3169 (0.0651)
$\beta_8$	-1.9850 (0.4077)	-0.2398 (0.6805)	-3.1867 (0.4396)	-0.0898 (0.6267)
Sample Period	1972-89	1972-89	1972-89	1972-89
No. of Observations	975	627	975	627
$\bar{R}^2$	0.895	0.945	0.808	0.837

*Notes: Standard errors of estimates in parentheses.*

First, the OLS estimates of  $\beta_0$  for each sub-sample when compared with the GMM (and LSDV) results are suggestive of the upward bias usually associated with the presence of fixed effects. Compared to the GMM results in Table IV.2 to IV.3, this upward bias in the OLS estimates is marked. Relative to the LSDV estimates in Table IV.1 the bias is less marked which is surprising since it is well established that LSDV estimates of the first order autoregressive coefficient are themselves biased downwards, see Nickell (1981), Hsiao (1986).<sup>34</sup> Indeed, the LSDV estimates are substantially greater than those obtained by GMM. This finding replicates similar

<sup>34</sup>Though the extent of the bias is smaller as T increases. The panel used in this analysis has a relatively large T dimension.

results in Arellano and Bond (1991) obtained from the estimation of dynamic employment equations and as suggested there, may be explained by the possible endogeneity of included variables assumed to be strictly exogenous (in this case current prices).

A second point to note about the results in Table IV.1 concerns the degree to which the Euler equation model explains variation in the dependent variable. The  $\bar{R}^2$  measure suggests between 81-90 % is explained in the unconstrained sub-sample, with a corresponding 84-95 % for the constrained sub-sample. Although it is not possible to lay much stress on results obtained by these estimation methods, it might have been anticipated that the explanatory power of the Euler equation model would be lower for the constrained sub-sample given the omission of variables correlated with the borrowing constraint multiplier. A further point of note is with respect to the estimates for  $\beta_4$  which corresponds to the coefficient on the interest rate variable. This variable of any in the Euler equation model might possibly pick up the influence of indebtedness on extraction. Notably of all the parameter estimates  $\beta_4$  is the most poorly determined and its sign changes with estimation method and sub-sample. This evidence would cast doubt on any notion that interest rates on foreign debt should be regarded as a determinant of extraction, though see following discussion of the GMM results.

The GMM results for each sub-sample are detailed in Tables IV.2 and IV.3. Four distinct specifications of the instrument set were employed in obtaining these estimates; respectively A, B, C and D. The basic instrument set is defined by A. Here the instrument matrix  $Z_i$  is given by:

$$(4.29) \quad Z_i = \left[ \text{diag}(Q_{it-4}, Q_{it-3}, Q_{it-2}, r_{it-2} Q_{it-2}, 1) : (w'_{i3} \dots w'_{iT-2}) \right] \quad t=5, \dots, T.$$

In addition to the instruments specified by (4.29), a set of mineral dummies variables are included to control for any potential mineral specific effects.

The three remaining specifications of the instruments provide alternative ways of specifying the sub-set of instruments which define  $\Lambda_i$ . Testing the moment restrictions associated with this subset of instruments, recall the discussion in 4.3.2, is of particular interest. These additional instruments are included in  $Z_i$  as single column vectors implying that not all moment restrictions available under the null hypothesis of exogeneity are exploited.<sup>35</sup>

The additional instruments in sets B, C and D are chosen on the basis of variables which are considered to correlate with terms included in the Euler equation for extraction obtained with the binding constraint on foreign borrowing. Recalling the model from chapter 3 and eq. (3.27), these are the lagrange multiplier on the borrowing constraint and the marginal utility of (traded) consumption. Instrument set B is restricted to incorporating variables which proxy the role of the marginal utility of consumption in (3.27). The additional instruments are defined by the t-2 values of the aggregate consumption / GDP ratio (CGDP) and its interaction with other Euler equation variables, i.e. price, extraction and cumulative extraction. One motivation for focusing solely on these consumption instruments is to test whether consumption and extraction are independent for constrained observations. By examining the over-identifying restrictions imposed on these extra instruments, it can be established whether the prediction that the separation theorem is violated for such borrowers is valid.

---

<sup>35</sup>This is for computational reasons since the relatively large T dimension of the data-set means the variance-covariance matrices obtained from the optimal instrument sets are particularly difficult to invert within Shazam 7.0.

Instrument sets C and D extend the analysis conducted with instrument set B by including variables which may correlate with the credit ceiling multiplier. Two approaches are adopted as a check for robustness. The first, which defines the additional instruments in C, follows the related analysis in Whited (1992) with the implicit assumption that the constraint multiplier can be modelled as a convex function of the debt to export ratio (DTX) and the debt interest to export ratio (DIX). These variables are traditionally employed as indicators of a debtor's ability to borrow and service debt obligations respectively. The instrument set is accordingly extended to include these variables and their squared terms.

Instrument set D provide an alternative specification of the variables which are thought to correlate with the credit ceiling multiplier. In this case a vector of macroeconomic variables and creditworthiness indicators are employed and are chosen on the basis of evidence presented from previous econometric analyses of the debt repayment problems of developing country borrowers and their ability to borrow on international capital markets, see for example McFadden et. al. (1985), Hajivassiliou (1987) and Lensink and van Bergeijk (1991). For reasons of parsimony, the vector of chosen variables is restricted those which have received some statistical support in these previous analyses. That is: real GDP growth (RGDPG), real GDP per capita (RGDPC), the investment / GDP ratio (IGDP), the debt to income ratio (DTY), the debt service to export ratio (DSX), the reserves to import ratio (RESM), a cumulative indicator of IMF history (IMF) and a cumulative indicator of debt reschedulings (RESCH).

The results of the GMM estimation and testing are presented in Tables IV.2 to IV.3.

**Table IV.2**  
*GMM Estimation and Testing of the Extraction Euler Equation  
 with Unconstrained and Constrained Sub-Samples: I*

Estimation Method:	GMM-A Unconstrained	GMM-A Constrained	GMM-B Unconstrained	GMM-B Constrained
$\beta_0$	0.4393 (0.0898)	0.3348 (0.0828)	0.4385 (0.0829)	0.1058 (0.1238)
$\beta_1$	0.0351 (0.0566)	0.1349 (0.0737)	-0.0130 (0.0829)	-0.0428 (0.0454)
$\beta_2$	0.0035 (0.0019)	0.0059 (0.0044)	0.0034 (0.0040)	0.0036 (0.0048)
$\beta_3$	-0.0036 (0.0023)	-0.0039 (0.0022)	-0.0009 (0.0048)	-0.0095 (0.0060)
$\beta_4$	3.3590 (6.1003)	-11.670 (8.5937)	3.1245 (13.947)	19.468 (23.723)
$\beta_5$	-0.0019 (0.0070)	-0.0039 (0.0091)	0.0096 (0.0152)	-0.0381 (0.0250)
$\beta_6$	1.6667 (0.6469)	0.1130 (0.9275)	1.3004 (0.9466)	-0.8306 (1.6342)
$\beta_7$	0.0711 (0.1202)	-0.0643 (0.1406)	0.0939 (0.1755)	-0.1783 (0.2303)
$\beta_8$	-2.6253 (0.6471)	0.3296 (1.2269)	-2.2957 (1.0102)	1.7124 (0.7883)
Specification Tests:				
J-Statistic: $\chi^2(df)$	15.07 (65)	21.77 (65)	17.69 (70)	23.33 (70)
Newey Test: $\chi^2(df)$	-----	-----	0.124 (5)	0.262 (5)
Serial Correlation	-1.468 (P=0.142)	-1.365 (P=0.172)	-1.467 (P=0.142)	0.084 (P=0.932)
Functional Form	2.666 (P=0.264)	1.338 (P=0.512)	2.033 (P=0.362)	0.693 (P=0.707)
$\hat{\rho}$	0.810	0.684	0.427	0.454
Sample Period	1973-89			
No. of Observations	918                      595                      918                      595			

*Notes: Cols (ii) and (iii) give GMM estimates of the first differenced equation using instrument set A with heteroskedasticity and autocorrelation (MA(1)) consistent asymptotic standard errors in parentheses. Cols (iv) and (v) report results for instrument set B. See main text and chapter appendix for details on reported specification tests.  $\hat{\rho}$  is a IV goodness of fit measure and is computed as the minimised value of the GMM criterion divided by the sum of squared residuals (see Pesaran, 1990) and then multiplied for reporting purposes by N, the number of cross-sectional units. Values closer to zero are interpreted as higher goodness of fit.*

Concentrating initially on the results obtained with the basic instrument set (A), it is noteworthy that for the unconstrained sub-sample all the estimates are correctly signed. This contrasts both the constrained sub-sample estimates with GMM-A and

the OLS and LSDV results in Table IV.1. Of these correctly signed parameters the estimates of  $\beta_0$ ,  $\beta_2$ ,  $\beta_6$ ,  $\beta_8$  are statistically significant at less than the 5 % level which suggests a dominate role for lagged extraction and its interaction with the interest rate in explaining current levels of extraction. The interest rate in of itself appears to have no role, whilst the anticipated stock depletion effect is not supported since  $\beta_7$  is not statistically different from zero. With regard to the specification tests, the over-identifying restrictions imposed in estimating the model are overwhelmingly not rejected by the chi-squared statistic (J-statistic = 15.07 (65), whilst the diagnostic tests for serial correlation and functional form indicate the respective nulls cannot be rejected.

One indication that the unconstrained Euler equation is inappropriate for the constrained sub-sample would be an observation of incorrectly signed parameter estimates with higher standard errors. This would suggest correlation between the instruments used in estimation and the error residuals. With GMM-A for the constrained sub-sample there is some evidence of this with  $\beta_1$ ,  $\beta_4$ ,  $\beta_7$  and  $\beta_8$  all signed contrary to expectation. Moreover, again with reference to a 5 % level, only the autoregressive parameter  $\beta_0$  can be regarded as statistically significant ( t-ratio > 2.00). Any basis for interpreting these observations as a rejection of the orthogonality of the instruments is undermined, however, by the J-statistic. Although higher than the corresponding figure for the unconstrained sub-sample, the value of 21.77 is again overwhelmingly within the acceptance region for the null. Like the unconstrained sub-sample the diagnostics for serial correlation and functional form are acceptable.

**Table IV.3**  
*GMM Estimation and Testing of the Extraction Euler Equation  
 with Unconstrained and Constrained Sub-Samples: II*

Estimation Method:	GMM-C Unconstrained	GMM-C Constrained	GMM-D Unconstrained	GMM-D Constrained
$\beta_0$	0.4366 (0.1021)	0.1116 (0.1208)	0.4331 (0.0790)	0.3667 (0.0671)
$\beta_1$	0.0003 (0.0817)	-0.0414 (0.0435)	0.0563 (0.0538)	0.0487 (0.0420)
$\beta_2$	0.0025 (0.0039)	0.0018 (0.0042)	0.0022 (0.0016)	0.0036 (0.0172)
$\beta_3$	-0.0010 (0.0047)	-0.0069 (0.0048)	-0.0020 (0.0020)	-0.0051 (0.0023)
$\beta_4$	-2.9272 (12.719)	22.936 (20.344)	-0.8641 (4.3519)	19.660 (8.2550)
$\beta_5$	0.0069 (0.0147)	-0.0312 (0.0229)	0.0008 (0.0064)	-0.0132 (0.0101)
$\beta_6$	1.3318 (0.9313)	-0.6664 (1.6130)	1.8028 (0.5615)	-0.6342 (1.5780)
$\beta_7$	0.0906 (0.1724)	-0.1613 (0.2293)	0.0754 (0.6255)	-0.4470 (0.1182)
$\beta_8$	-2.2978 (0.9997)	1.47406 (2.1397)	-2.7349 (0.5632)	2.04174 (0.8098)
Specification Tests:				
J-Statistic: $\chi^2(df)$	18.62 (74)	23.84 (74)	18.85 (78)	25.36 (78)
Newey Test: $\chi^2(df)$	1.554 (4)	0.777 (4)	1.664 (8)	1.912 (8)
Serial Correlation	-1.455 (P=0.146)	0.081 (P=0.934)	-1.478 (P=0.138)	0.028 (P=0.978)
Functional Form	2.010 (P=0.366)	1.258 (P=0.533)	2.260 (P=0.322)	3.520 (P=0.172)
$\hat{\rho}$	0.484	0.482	0.484	0.532
Sample Period				
No. of Observations	1973-89 918	1973-89 595	1973-89 918	1973-89 595

*Notes: Cols (ii) and (iii) give GMM estimates of the first differenced equation using instrument set C with heteroskedasticity and autocorrelation (MA(1)) consistent asymptotic standard errors in parentheses. Cols (iv) and (v) report results for instrument set D. See also notes to Table IV.2.*

Turning now to the estimates once the instrument set is extended to include "debt" instruments, Tables IV.2 and IV.3 indicate the theoretical prediction that the unconstrained Euler equation should be rejected for constrained observations is not supported. For each of the instrument sets B, C and D a chi-square test of the moment restrictions (denoted as Newey test) imposed on the debt instruments does

not reject the null of orthogonality for either the unconstrained or constrained sub-samples. In Table IV.2 for GMM-B this statistic tests restrictions on CGDP and four interaction terms, in Table IV.3 the statistic for GMM-C tests the validity of overidentifying restrictions imposed on DTX, DIX and their squared terms. whilst for GMM-D the Newey test is defined in terms of the vector defined above. As with GMM-A the diagnostic tests with these extended instrument sets indicate no problems with serial correlation or functional form.

One interesting consequence of introducing the "debt" instruments is with regard to the constrained sub-sample estimate of  $\beta_4$ . With the basic instrument set this parameter is negatively signed, but positively signed for instrument sets B, C and D. Indeed with this latter set of instruments the interest rate parameter becomes statistically significant at the 5 % level. Thus by extending the set of debt instruments used in estimation it appears that an interest rate effect is observed, reflecting perhaps the greater information content provided by a wider set of creditworthiness indicators which are correlated with the interest rates offered to problem debtors. Interpreting this evidence as support for the basic hypothesis under investigation would however be unwise given the greater balance of evidence which provides little basis for concluding that the unconstrained Euler equation represents a mis-specified model for constrained observations.

Table IV.4 presents additional information on the adequacy of the Euler equation model with the results from tests of parameter restrictions for both sub-samples.

**Table IV.4**  
*Tests of Parameter Restrictions with GMM Estimates: Unconstrained and Constrained Sub-Samples*

Parameter Restriction:	Unconstrained		Observations	
	(i) GMM - A	(ii) GMM - B	(iii) GMM - C	(iv) GMM - D
$\beta = 0$	83.88 (9) (P=0.000)	30.82 (9) (P=0.000)	31.49 (9) (P=0.000)	88.28 (9) (P=0.000)
$\beta_4 = \beta_5 = \beta_6 = \beta_7 = \beta_8 = 0$	39.55 (5) (P=0.000)	11.02 (5) (P=0.051)	11.73 (5) (P=0.039)	51.44 (5) (P=0.000)
$\beta_5 = \beta_6 = \beta_7 = \beta_8 = 0$	38.56 (4) (P=0.000)	10.70 (4) (P=0.030)	10.56 (4) (P=0.032)	48.63 (4) (P=0.000)
$\beta_2 = -\beta_3 = -\beta_5$	0.20 (2) (P=0.906)	0.78 (2) (P=0.678)	0.50 (2) (P=0.777)	0.40 (2) (P=0.817)
$\beta_1 = -\beta_7, \beta_2 = -\beta_3 = -\beta_5$	17.22 (3) (P=0.000)	5.63 (3) (P=0.131)	5.64 (3) (P=0.131)	25.26 (3) (P=0.000)
Time Dummies	12.21 (17) (P=0.787)	3.86 (17) (P=0.999)	3.16 (17) (P=0.999)	12.95 (17) (P=0.740)
Time Dummies: 82 - 89	9.32 (8) (P=0.316)	2.24 (8) (P=0.972)	1.57 (8) (P=0.992)	7.85 (8) (P=0.448)
Mineral Dummies	1.24 (5) (P=0.941)	0.774 (5) (P=0.979)	1.02 (5) (P=0.961)	1.47 (5) (P=0.916)
Parameter Restriction:	Constrained		Observations	
	(i) GMM - A	(ii) GMM - B	(iii) GMM - C	(iv) GMM - D
$\beta = 0$	89.94 (9) (P=0.000)	16.04 (9) (P=0.066)	13.78 (9) (P=0.130)	107.30 (9) (P=0.000)
$\beta_4 = \beta_5 = \beta_6 = \beta_7 = \beta_8 = 0$	5.41 (5) (P=0.368)	3.61 (5) (P=0.607)	3.32 (5) (P=0.651)	16.93 (5) (P=0.005)
$\beta_5 = \beta_6 = \beta_7 = \beta_8 = 0$	2.88 (4) (P=0.578)	3.56 (4) (P=0.469)	3.13 (4) (P=0.537)	16.21 (4) (P=0.003)
$\beta_2 = -\beta_3 = -\beta_5$	0.44 (2) (P=0.801)	1.91 (2) (P=0.386)	1.56 (2) (P=0.458)	0.98 (2) (P=0.614)
$\beta_1 = -\beta_7, \beta_2 = -\beta_3 = -\beta_5$	1.31 (3) (P=0.726)	2.62 (3) (P=0.454)	2.17 (3) (P=0.539)	6.44 (3) (P=0.092)
Time Dummies	7.36 (17) (P=0.978)	7.61 (17) (P=0.974)	7.24 (17) (P=0.980)	14.77 (17) (P=0.612)
Time Dummies: 82 - 89	6.62 (8) (P=0.578)	3.69 (8) (P=0.884)	3.45 (8) (P=0.903)	10.62 (8) (P=0.224)
Mineral Dummies	1.93 (5) (P=0.859)	1.30 (5) (P=0.935)	1.18 (5) (P=0.953)	1.74 (5) (P=0.884)

*Notes: All reported statistics are computed as GMM wald tests distributed  $\chi^2$  with degrees of freedom in parentheses. See Newey and West (1987b) for details.*

Common to both the unconstrained and constrained sets of observations is the failure to reject zero restrictions on the time-specific and mineral-specific dummy variables. The latter finding with respect to mineral group effects would suggest that controlling for general fixed effects by first differencing eliminates (as expected) any differences in intercept terms associated with mineral groupings. With respect to time effects, Table IV.4 also indicates that a zero restriction on year effects post 1982, i.e. the "debt crisis" period, is likewise not rejected.

A test of the joint significance of  $\beta$  rejects the null of a zero restriction on all parameters, though the rejection is strongest for the unconstrained sample. For constrained observations joint significance is weaker, particularly with instrument set C. This accords with the observation from Tables IV.2 and IV.3 that the Euler equation parameters are relatively less well determined with constrained observations.

Two further sets of restrictions on the parameters were also considered. The first is a test of a zero restriction on the coefficient vector  $(\beta_4, \beta_5, \beta_6, \beta_7, \beta_8)'$  which correspond to the rate of interest on foreign debt and its interactions with other Euler equation variables. Table IV.4 also reports a test of the significance of the interaction terms alone. Testing the significance of these variables provides one indication of the extent to which the intertemporal approach to the modelling of resource supply is appropriate. In the case of unconstrained observations these parameters are always statistically significant at the 5 % level or less, though it is evident from Table IV.4 that this statistical significance is determined primarily by the interaction terms. The role for the interest rate itself as noted above is generally weak. Of further note, the estimated signs on the unconstrained group coefficients imply the expected negative relationship between extraction and the interest rate along the optimal path.<sup>36</sup> The

---

<sup>36</sup>Recall for instance some of the discussion in chapters 2 and 3.

significance of these parameters is not evident with the constrained sub-sample, except in the case of GMM-D where as noted previously from Table IV.3 the interest rate parameter is itself strongly significant. In general the signs on these parameters for the constrained group are not entirely consistent with expectation.

The second set of restrictions of interest are those that can be placed on the reduced form parameters; recall the discussion in 4.3.2. The restrictions on the parameters associated with prices and the interaction with the interest rate, i.e.  $\beta_2 = -\beta_3 = -\beta_5$ , are not rejected for either sub-sample. However, these restrictions when considered jointly with the restriction  $\beta_1 = -\beta_7$  can be rejected for the unconstrained sample with instrument sets A and D. Rejection for B and C is only possible at the weaker p-value of 0.13. In combination these findings indicate that there are grounds for rejecting the restriction  $\beta_1 = -\beta_7$  which is suggested by the Euler equation model. For the constrained sample the corresponding parameter restrictions cannot be rejected, but any support this may provide for the Euler equation model is tempered by the general observation that most of the relevant constrained parameter estimates are not statistically different from zero.

The discussion to date has noted that the estimates for the unconstrained and constrained samples provide only very weak support for any rejection of the Euler equation model in the case of constrained observations. The J-statistics and, more notably, the results of the Newey test, clearly support the orthogonality of the "debt instruments" for both samples. The only contrary evidence is perhaps the generally poorer performance of the model with the constrained group of observations, particularly with regard the sign and statistical significance of the parameter estimates. Table IV.5 presents the results from formal testing of parameter constancy between the two sub-samples as outlined in 4.3.2. It is clear that the null of stability

in the coefficients over the two sub-samples is easily accepted. In short, there is no reason to presume structural differences between the two samples.

**Table IV.5**  
*GMM Tests of Parameter Stability:  
Unconstrained v Constrained Sub-Samples*

Instrument Set	$\chi^2(\text{df})$
GMM - A	19.25 (96)
GMM - B	20.56 (101)
GMM - C	22.44 (105)
GMM - D	24.62 (109)

*Notes: See main text and chapter appendix for details on test statistic.*

To summarise, the evidence presented above strongly supports the conclusion that the Euler equation model cannot be rejected for constrained observations. In light of this, and to assess to the general adequacy of the model further, the Euler equation was re-estimated using the full sample of observations. These results are presented and discussed below.

#### *4.4.2 Estimation and testing of the extraction Euler equation with the full sample.*

Tables IV.6 to IV.8 present the estimation results and Wald tests of parameter restrictions obtained with the full sample. In Table IV.6 the results of the OLS and LSDV estimations reveal similar findings to those obtained with the sub-samples. For example, the OLS estimate of  $\beta_0$  is consistent with the upward bias associated with this estimation method, whilst the LSDV estimate does not indicate the expected downward bias.

**Table IV.6**

*Estimation and Testing of the Extraction Euler Equation: Full Sample*

Estimation Method:	(i) OLS - Levels	(ii) LSDV - Levels	(iii) GMM - A
$\beta_0$	1.0435 (0.0257)	0.9504 (0.0258)	0.4938 (0.0718)
$\beta_1$	0.0068 (0.0281)	-0.0002 (0.0273)	0.0947 (0.0467)
$\beta_2$	0.0010 (0.0006)	0.0010 (0.0006)	0.0126 (0.0035)
$\beta_3$	-0.0005 (0.0007)	-0.0002 (0.0007)	-0.0148 (0.0041)
$\beta_4$	1.0853 (1.7650)	-0.2233 (2.6530)	8.4508 (8.2825)
$\beta_5$	0.0038 (0.0032)	0.0039 (0.0031)	-0.0245 (0.0116)
$\beta_6$	2.0554 (0.3014)	2.2363 (0.3046)	0.1725 (0.5170)
$\beta_7$	-0.0814 (0.0456)	-0.0949 (0.0458)	0.2652 (0.1169)
$\beta_8$	-1.8118 (0.3578)	-2.1015 (0.3579)	-0.5698 (0.5871)
<b>Specification Tests:</b>			
J-Statistic: $\chi^2(\text{df})$	-----	-----	19.29 (65)
Serial Correlation	-----	-----	-1.561 (P=0.108)
Functional Form: $\chi^2(2)$	-----	-----	5.220 (P=0.074)
$\hat{\rho}$			0.3026
Sample Period	1972-89	1972-89	1973-89
No. of Observations	1602	1602	1513
$\bar{R}^2$	0.926	0.820	-----

*Notes: Col. (i) reports OLS estimates of levels equation. Col. (ii) reports LSDV estimates of levels equation. Col (iii) gives GMM estimates of the first differenced equation using instrument set A with heteroskedasticity and autocorrelation (MA(1)) consistent asymptotic standard errors in parentheses. See main text for details on reported specification tests.*

In general the GMM estimation results suggest an improved performance for the Euler equation model with the full sample. In Table IV.6 the results with instrument set A indicate the majority of the parameter estimates to be statistically significant, with only  $\beta_1$  incorrectly signed. Notably the coefficients on the price variables are well determined, as is  $\beta_7$  which corresponds to the stock depletion effect. Of further note, the interest rate parameter is positively signed, but is not statistically different from zero. With regard to the reported specification tests the J-statistic and the Newey test respectively support the validity of the over-identifying restrictions used in estimation and the moment restrictions imposed on the sub-set of debt instruments. The tests for serial correlation and adequate functional form, as with the

unconstrained and constrained sub-samples, indicate the respective nulls cannot be rejected. In terms of goodness of fit the  $\hat{\rho}$  measure indicates a substantial improvement when the Euler equation model is estimated with the full sample of observations. These findings are similarly observed when the instrument set includes additional debt instruments, see Table IV.7. In addition Table IV.7 also reveals better determined estimates of  $\beta_8$ .

**Table IV.7**  
*GMM Estimation and Testing of the Extraction Euler Equation with Debt Instruments: Full Sample*

Instrument set:	(i) GMM - B		(ii) GMM - C		(iii) GMM - D	
	coef.	s.e.	coef.	s.e.	coef.	s.e.
$\beta_0$	0.6057	(0.0688)	0.6320	(0.0695)	0.6527	(0.0732)
$\beta_1$	0.0204	(0.0284)	0.0159	(0.0271)	0.0119	(0.0269)
$\beta_2$	0.0102	(0.0030)	0.0094	(0.0028)	0.0096	(0.0027)
$\beta_3$	-0.0115	(0.0033)	-0.0105	(0.0031)	-0.0105	(0.0030)
$\beta_4$	2.7405	(8.3466)	4.1716	(7.8122)	6.7649	(6.3638)
$\beta_5$	-0.0171	(0.0093)	-0.0151	(0.0087)	-0.0154	(0.0085)
$\beta_6$	0.7648	(0.5303)	0.9042	(0.5358)	0.9204	(0.5511)
$\beta_7$	0.2450	(0.1047)	0.2431	(0.1039)	0.2033	(0.0985)
$\beta_8$	-1.3561	(0.6597)	-1.4976	(0.6585)	-1.4254	(0.6367)
<b>Specification Tests:</b>						
J-Statistic: $\chi^2$ (df)	21.38 (70)		22.59 (74)		23.75 (78)	
Newey Test: $\chi^2$ (df)	2.027 (5)		1.084 (4)		1.326 (8)	
Serial Correlation	-1.557 (P=0.115)		-1.580 (0.114)		-1.611 (P=0.107)	
Functional Form: $\chi^2$ (2)	3.656 (P=0.161)		3.520 (P=0.172)		3.527 (P=0.171)	
$\hat{\rho}$	0.347		0.374		0.356	
Sample Period	1973-89		1973-89		1973-89	
No. of Observations	1513		1513		1513	

*Notes: See notes to Table IV.2*

Table IV.8 reports the Wald statistics associated with tests of restrictions on the Euler equation parameters. These results reinforce the earlier findings obtained with the unconstrained sub-sample. A zero restriction on all of the Euler equation parameters is rejected at p-value = 0.000, whilst the sub-set of parameters which correspond to

the interaction terms with the interest rate are highly significant. The two set of restrictions on the reduced form parameters, as with the sub-samples, are supported, though once again the individual restriction  $\beta_1 = -\beta_7$  can be rejected. The time period and mineral group dummies are again observed to be insignificant.

**Table IV.8**  
*Tests of Parameter Restrictions with GMM Estimates: Full Sample*

Parameter Restriction:	(i) GMM - A	(ii) GMM - B	(iii) GMM - C	(iv) GMM - D
$\beta = 0$	154.57 (9) (P=0.000)	182.12 (9) (P=0.000)	192.31 (9) (P=0.000)	188.96 (9) (P=0.000)
$\beta_4 = \beta_5 = \beta_6 = \beta_7 = \beta_8 = 0$	12.35 (5) (P=0.030)	13.80 (5) (P=0.017)	13.61 (5) (P=0.018)	12.35 (5) (P=0.030)
$\beta_5 = \beta_6 = \beta_7 = \beta_8 = 0$	10.57 (4) (P=0.032)	13.13 (4) (P=0.011)	13.22 (4) (P=0.010)	12.21 (4) (P=0.016)
$\beta_2 = -\beta_3 = -\beta_5$	1.43 (2) (P=0.490)	0.76 (2) (P=0.685)	0.57 (2) (P=0.751)	0.62 (2) (P=0.733)
$\beta_1 = -\beta_7, \beta_2 = -\beta_3 = -\beta_5$	3.40 (3) (P=0.334)	6.03 (3) (P=0.110)	6.71 (3) (P=0.082)	6.35 (3) (P=0.096)
Time Dummies	17.02 (17) (P=0.453)	16.36 (17) (P=0.499)	16.22 (17) (P=0.508)	16.63 (17) (P=0.480)
Time Dummies: 82 - 89	11.55 (8) (P=0.173)	11.11 (8) (P=0.196)	10.99 (8) (P=0.202)	11.58 (8) (P=0.172)
Mineral Dummies	1.46 (5) (P=0.918)	1.61 (5) (P=0.901)	1.33 (5) (P=0.932)	1.31 (5) (P=0.934)

*Notes: All reported statistics are computed as GMM wald tests distributed  $\chi^2$  with degrees of freedom in parentheses. See Newey and West (1987b) for details.*

One negative feature of the estimates detailed in Tables IV.6 to IV.7 is that the dynamics implied by the parameter estimates for  $Q_{it-1}$  and  $Q_{it-2}$  are not consistent with the theoretical model. In particular the positive sign on  $\beta_2$  should imply that  $\beta_0$  is positive and greater than 1. Whilst the former expectation holds, the latter is clearly rejected. Note further the expectation that  $\beta_0$  be greater than 1 reflects the introduction of adjustment costs. If the incorrectly signed (and insignificant, see Table IV.7) estimate of  $\beta_1$  can be interpreted as a rejection of adjustment costs then

the Euler equation model would predict that  $\beta_0$  equals unity zero. A test of  $\beta_0 = 1$  is overwhelmingly rejected for all GMM estimates.

One further gauge of the Euler equation model is to consider the implied estimates of the structural cost parameters. Some computations of these estimates and their associated standard errors are presented in Table IV.9. Whilst the structural parameter estimates have the anticipated sign, they are in general poorly determined.

**Table IV.9**  
*Structural cost parameter estimates: Full Sample*

	GMM-A	GMM-B	GMM-C	GMM-D
$\delta_0$	672.6 (651.1)	267.8 (802.6)	442.7 (810.3)	705.9 (643.2)
$\delta_1$	-31.62 (23.67)	-57.78 (36.32)	-62.98 (39.26)	-52.71 (34.28)
$\delta_2$	21.11 (11.14)	23.94 (13.46)	25.79 (14.51)	21.21 (12.77)
$\delta_3$	45.35 (51.49)	132.5 (80.84)	158.9 (89.90)	148.8 (82.36)
$\chi^2(3)$	3.60 (P=0.308)	3.65 (P=0.301)	3.92 (P=0.070)	3.98 (P=0.263)

*Notes: Standard errors in parentheses. Variance covariance matrix of the structural cost parameters computed as  $v(\hat{\delta}) = (\partial\delta(\beta)/\partial\beta)_{\beta=\hat{\beta}} \cdot v(\hat{\beta}) \cdot (\partial\delta(\beta)/\partial\beta)_{\beta=\hat{\beta}}'$ . See Pesaran and Pesaran (1991).  $\chi^2(3)$  is a test of  $\delta_1 = \delta_2 = \delta_3 = 0$ . Structural parameter estimates obtained by assuming  $\theta^{-1} = \beta_2$ , and estimate of  $\delta_3$  based on  $\beta_8$ .*

The estimates presented in Table IV.9 are based on the reduced form estimates reported in Tables IV.6 and IV.7. Throughout  $\beta_2$  is used to identify  $\theta^{-1}$  and  $\delta_3$  is identified using the reduced form parameter  $\beta_8$  which is motivated by the observation that this reduced form parameter was correctly signed in Tables IV.6 and IV.7. Given the restrictive nature of these computations the figures are only to be regarded as

illustrative. Although there is some variation in the estimates reported in Table IV.9 the general pattern is consistent. The parameter  $\delta_1$  is negative, with the others positive. This negative sign for  $\delta_1$  as noted earlier in Section 4.2 can be interpreted as an indicator of increasing returns in extraction. Note throughout however that  $\delta_1 + \delta_3$  has the opposite sign since  $\delta_3 > |\delta_1|$  which give the choice of functional forms would imply increasing marginal costs in extraction. Less ambiguous is the depletion effect on extraction costs. In line with expectation  $\delta_2$  is positive implying that costs increase with cumulative extraction and therefore depletion (i.e. falling reserves). Moreover the estimates of  $\delta_2$  can be considered the best determined of the structural parameters since it is only this parameter which approaches statistical significance at the 5% level, see GMM-A column. Considered jointly however, the Wald tests reported in Table IV.9 would not reject a zero restriction on the structural cost parameters at the conventional 5 % level.

#### **4.5 Conclusions.**

This chapter has outlined and implemented the GMM approach to the estimation and testing of a theoretical Euler equation for exhaustible resource extraction. This econometric analysis has focused on the testing of the predictions derived from the theoretical model of chapter 3. The central hypothesis under investigation stated that the Euler equation derived under the assumption of unconstrained foreign borrowing should be rejected for constrained borrowers. For the purposes of the analysis a sample of constrained observations was defined in terms of information on the accumulation of debt arrears.

The main findings from this chapter were that an empirical specification of the unconstrained Euler equation could not be rejected by using a number of GMM

specification tests for either unconstrained or constrained observations. The latter finding provides evidence to reject the hypothesis that problem indebtedness has been a factor influencing developing country mineral production. In general the evidence provided in this chapter indicates mixed results for the Euler equation approach to resource use. Though there was no strong evidence that interest rates have a direct influence on extraction, a consistent finding was the statistical significance of variables interacting with the rate of interest which may suggest some empirical merit of the Euler equation model. Against this, the estimated dynamics were not supportive of the Euler equation specification and estimates of the underlying structural cost function parameters were poorly determined. Further reflections on these findings are reserved for chapter 7 which concludes the thesis.

## Appendix

### Asymptotic properties of the GMM specification tests.

Pagan and Vella (1989) note that many of the diagnostic test statistics commonly employed in econometrics can be expressed as tests of suitably defined moments restrictions. The GMM specification tests reported in chapter 4 exploit this basic principle. For the purposes of this appendix it will suffice to outline a generic expression for the test statistic, its asymptotic variance and then indicate how the statistic is applied to specification testing in practice.

Let the moment restrictions of interest be defined by  $E(m(w_i, \theta_0)) = 0$  where  $m(w_i, \theta_0)$  has dimension  $p \times 1$  and  $\theta_0$  is a  $k \times 1$  parameter vector. It is then natural to test these restrictions by determining whether the sample analogue  $\hat{\tau} = N^{-1} \sum_i m(w_i, \hat{\theta})$  is statistically different from zero. This necessitates knowledge of the sample variance.

*The Asymptotic Variance of  $\sqrt{N}\hat{\tau}$ .*

The derivation of the asymptotic distribution of  $\hat{\tau}$  employs the standard assumption that the GMM estimator  $\hat{\theta}$  is  $\sqrt{N}$  consistent. Hence, the asymptotic variance of  $\sqrt{N}\hat{\tau}$  can be obtained from a Taylor series expansion of  $m(w_i, \hat{\theta})$  around  $\theta_0$ . This gives:

$$(A4.1) \quad \sqrt{N}\hat{\tau} = \sqrt{N}\left(N^{-1} \sum_i m(w_i, \theta_0)\right) + \sqrt{N}\left(\underset{N \rightarrow \infty}{p \lim} N^{-1} \frac{\partial m_i}{\partial \theta}\right)(\hat{\theta} - \theta_0) + o_p(1),$$

where  $o_p(1)$  indicates that higher order terms are assumed to converge to zero as  $N \rightarrow \infty$ . Theorem 3.1 in Hansen (1982) establishes the asymptotic distribution of  $\sqrt{N}(\hat{\theta} - \theta_0)$  to be:

$$(A4.2) \quad \sqrt{N}(\hat{\theta} - \theta_0) \xrightarrow{d} N\left(0, (GWG')^{-1}GWVWG'(GWG')^{-1}\right),$$

where  $G$  denotes the  $k \times r$  matrix of derivatives  $\text{plim}_{N \rightarrow \infty} N^{-1} \sum_i \partial g_i / \partial \theta$ ,  $g_i$  is a  $r \times 1$  vector of moments used in GMM estimation,  $V$  is the variance-covariance matrix of  $g_i$ , i.e.  $E(g_i g_i')$  and  $W$  is a suitable GMM weighting matrix. Hansen (1982) also shows the optimal  $W$  is in fact  $E(g_i g_i')^{-1}$ . (A4.2) implies:

$$(A4.3) \quad \sqrt{N}(\hat{\theta} - \theta_0) = (GWG')^{-1} GW(N^{-1/2} \sum_i g_i) + o_p(1).$$

Substituting (A4.3) into (A4.1) gives:

$$(A4.5) \quad \sqrt{N}\hat{\tau} = \sqrt{N}(N^{-1} \sum_i m(w_i, \theta_0)) + \left( \text{plim}_{N \rightarrow \infty} N^{-1} \sum_i \frac{\partial m_i}{\partial \theta} \right) (GWG')^{-1} GW(N^{-1/2} \sum_i g_i),$$

or equivalently:

$$(A4.6) \quad \sqrt{N}\hat{\tau} = \left[ I \quad ; \quad \left( \text{plim}_{N \rightarrow \infty} N^{-1} \sum_i \frac{\partial m_i}{\partial \theta} \right) (GWG')^{-1} GW \right] \begin{bmatrix} N^{-1/2} \sum_i m_i \\ N^{-1/2} \sum_i g_i \end{bmatrix},$$

where  $I$  is  $p \times p$  identity matrix and  $:$  indicates concatenation. Now assume by a Central Limit Theorem:

$$(A4.7) \quad \begin{bmatrix} N^{-1/2} \sum_i m_i \\ N^{-1/2} \sum_i g_i \end{bmatrix} \xrightarrow{d} \mathcal{N}(0, V), \quad V = \begin{bmatrix} V_{mm} & V_{mg} \\ V_{gm} & V_{gg} \end{bmatrix}.$$

where  $V_{mm} = \lim_{N \rightarrow \infty} E \left[ \left( N^{-1/2} \sum_i m_i \right) \left( N^{-1/2} \sum_i m_i \right)' \right]$  and likewise for  $V_{mg}$ ,  $V_{gg}$ . Using

(A4.7) it is then possible to assert:

$$(A4.8) \quad \sqrt{N}\hat{\tau} \xrightarrow{d} \mathcal{N}(0, AVA'),$$

where  $A = \left[ I \quad ; \quad \left( \text{plim}_{N \rightarrow \infty} N^{-1} \sum_i \frac{\partial m_i}{\partial \theta} \right) (GWG')^{-1} GW \right]$ . Note also that for

computational purposes  $AVA'$  can be written as:

(A4.9)

$$AVA' = V_{mm} + 2\left(\underset{N \rightarrow \infty}{p}\lim N^{-1} \sum_i \partial m_i / \partial \theta\right) (GWG')^{-1} GWV_{gm} \\ + \left(\underset{N \rightarrow \infty}{p}\lim N^{-1} \sum_i \partial m_i / \partial \theta\right) \left[ (GWG')^{-1} GWV_{gg} W'G' (GWG')^{-1} \right] \left(\underset{N \rightarrow \infty}{p}\lim N^{-1} \sum_i \partial m_i / \partial \theta\right)'$$

*Computing the Specification Tests.*

From this generic framework for the GMM specification testing, the tests for functional form and serial correlation are computed as follows. The test for functional form is based on the moment restrictions  $E(\tilde{Z}_i' V_i) = 0$  where  $\tilde{Z}_i$  has dimensions  $t \times 2$  with the columns corresponding to squares and cubes of the fitted values of the dependent variable. The reported statistic is then computed as a chi-square test. The test for serial correlation follows Arellano and Bond (1991) with the sample restrictions  $\hat{m}_i$  defined as  $\hat{V}_i' \hat{V}_{i-2}$  where  $\hat{V}_i$  is a  $t \times 1$  vector of GMM residuals.

The test for parameter constancy proceeds along similar lines. Specifically,  $\hat{m}_i = \hat{g}_i$  where  $\hat{g}_i$  is the prediction analogue of  $Z_i' \hat{V}_i$ . The residuals in this case refer to the constrained group prediction errors computed using parameter estimates obtained with the unconstrained sub-sample. The test statistic is then based on the sample moments  $\hat{\tau} = N_2^{-1} \sum_i^{N_2} \hat{g}_i$  where  $N_2$  denotes the constrained group sample size. The reported test statistic is chi-square with the degrees of freedom equal to the number of moment restrictions employed in estimation. This statistic uses the expression for the asymptotic variance of  $\sqrt{N_2} \hat{\tau}$  given in Ghysels and Hall (1990). That is:

$$(A4.10) \quad AVA' = V_{22} + k \left(\underset{N_2 \rightarrow \infty}{p}\lim N_2^{-1} \sum_i \partial \hat{g}_i / \partial \theta\right) (GWG')^{-1} \left(\underset{N_2 \rightarrow \infty}{p}\lim N_2^{-1} \sum_i \partial \hat{g}_i / \partial \theta\right)'$$

where  $k = N_2/N_1$  and is assumed to be a constant which requires the assumption that the sub-sample sizes increase equi-proportionally.

## Data Appendix: Sample, Variable Definitions and Sources.

### a) Sample

**Table IV.10**  
*Structure and characteristics of the country-minerals panel*

Country	Debt	Export Group	Bx	Cp	Ir	Ld	Tn	Zc	
1. Algeria	SDT	XF	0	0	1	1	0	1	3
2. Argentina	SDT	XP	0	0	1	1	1	1	4
3. Bolivia	SDT	XP	0	1	0	1	1	1	4
4. Brazil	SDT	XD	1	1	1	1	1	1	6
5. Chile	MDT	XP	0	1	1	1	0	1	4
6. Columbia	MDT	XD	0	0	1	0	0	0	1
7. Egypt	SDT	XS	0	0	1	0	0	0	1
8. Ghana	SDT	XP	1	0	0	0	0	0	1
9. Guyana	SDT	XP	1	0	0	0	0	0	1
10. Honduras	SDT	XP	0	0	0	1	0	1	2
11. India	MDT	XD	1	1	1	1	0	1	5
12. Indonesia	MDT	XD	1	1	0	0	1	0	3
13. Jamaica	SDT	XS	1	0	0	0	0	0	1
14. Korea (South)	LDT	XM	0	0	1	1	0	1	3
15. Malaysia	LDT	XD	1	1	1	0	1	0	4
16. Mauritania	SDT	XP	0	0	1	0	0	0	1
17. Mexico	SDT	XD	0	1	1	1	1	1	5
18. Morocco	SDT	XD	0	1	1	1	0	1	4
19. Myanmar	SDT	XP	0	0	0	1	1	1	3
20. Niger	SDT	XP	0	0	0	0	1	0	1
21. Nigeria	SDT	XF	0	0	0	0	1	0	1
22. Papua New Guinea	MDT	XP	0	1	0	0	0	0	1
23. Peru	SDT	XP	0	1	1	1	1	1	5
24. Philippines	MDT	XD	0	1	0	0	0	1	2
25. Rwanda	SDT	XP	0	0	0	0	1	0	1
26. Sierra Leone	SDT	XD	1	0	0	0	0	0	1
27. Thailand	LDT	XD	0	0	1	1	1	0	3
28. Tunisia	MDT	XD	0	0	1	1	0	1	3
29. Turkey	MDT	XD	1	1	1	1	0	1	5
30. Venezuela	MDT	XF	0	0	1	0	0	0	1
31. Zaire	SDT	XP	0	1	0	0	1	1	3
32. Zambia	SDT	XP	0	1	0	1	0	1	3
33. Zimbabwe	SDT	XP	0	1	1	0	1	0	3
Totals			10	15	19	16	14	17	91

*Key to World Bank Debtor and Exporter Classifications.*

SDT - Severely Indebted; MDT - Moderately Indebted; LDT - Less Indebted.

XD - Diversified Exporter; XF - Exporter of Fuels (mainly oil); XP - Exporter of Non-Fuel Primary Products; XM - Exporter of Manufactures; XS - Exporter of Services.

*Key to Mineral Codes:*

Bx - Bauxite; Cp - Copper Ore; Ir - Iron Ore; Ld - Lead Ore; Tn - Tin; Zc - Zinc Ore.

*Notes: Source for classifications is the World Debt Tables 1993-1994*

## b) Variable Definitions and Sources

### i. Euler Equation variables

$Q_{it}$  : Defined as an index of mineral production with 1968=100. The use of an index measure was to avoid scaling problems across different types of mineral. Data was obtained from *World Mineral Statistics* which is published annually by the British Geological Survey.

$X_{it}$ : Defined as cumulative mineral production and computed as  $X_{it} = \sum_{s=0}^t Q_{is}$  with  $X_0 = 0$ . Annual production data from World Mineral Statistics for the period 1952-1989 was used to construct the time series for cumulative production with observations for 1968-1989 used in the empirical analysis. Again this variable is expressed as an index with 1968 = 100 to standardise the scale for this variable.

$NP_{mt}$  : Nominal mineral prices obtained from commodity price data tables in *International Financial Statistics Yearbook* (Various Issues). Where it was relevant these nominal prices were converted to US Dollars per metric tonne. The price data used was : Copper (112), Iron Ore (223), Lead (112), Tin (112), Zinc (112). In the case of Bauxite (336) the time series was only available to 1987. To keep the mineral samples comparable, the series for Aluminium (156) was used as proxy for Bauxite prices on the grounds that Aluminium represents Bauxite in its produced form. Converted to index with 1980=100.

$XP_t$  : Defined as the annual index of export prices of industrial countries (1980=1.00) which was used as the deflator for nominal variables in the econometric model. Data was obtained from *International Financial Statistics Yearbook* (Various Issues).

$P_t$  : Defined as the real price per metric tonne of a mineral and computed from  $P_t = NP_t / XP_t$ . For empirical analysis expressed as an index (1968=100).

$i_{jt}$  : Average nominal rate of interest on external debt commitments. This is a weighted average nominal rate as used in World Bank's *World Debt Tables 1993-94* (WDT). The rate of interest is averaged over all types of external debt by source (i.e. Private or Official debt) with the weights determined by the proportion of private or official debt out of total commitments.

$r_{jt}$  : Real rate of interest on debt computed as :

$$r_{jt} = i_{jt} - \pi_t, \text{ where } \pi_t = (XP_t - XP_{t-1}) / XP_{t-1}.$$

$D_{t-1}^{\mu}$  : Dummy variable indicating when borrowing constraints are binding and used to split sample. Arrears information used in construction of indicator was sum of total interest and principal arrears. If the annual change in this figure is positive the dummy variable takes the value 1. WDT provided source for arrears data.

## *ii. Debt Instruments*

CGDP: Consumption share of GDP % (1985 international prices). Source is Penn World Tables Mark 5.2 (PWT). See Summers and Heston (1991) for discussion and details.

DTX: Total external debt to exports % (US dollars). Source is WDT.

DIX: Total debt interest payments to exports % (US dollars). Source is WDT.

RGDPC: Real GDP per capita in constant dollars using Chain Index (1985 international prices). Source is PWT.

RGDPG: Annual rate of growth in real GDP (1985 international prices). Computed using RGDPG and Population data in PWT.

IGDP: Investment share of GDP % (1985 international prices). Source is PWT.

DTY: Total external debt to Gross National Product (U.S. dollars) %. Source is WDT.

DSX: Total debt service to exports (U.S. dollars) %. Source is WDT

RESM: Gross foreign currency reserves relative to imports (U.S. dollars). Expressed in terms of monthly equivalent, i.e. how many months of imports can be financed from reserves. Source is WDT.

IMF: Cumulative dummy indicator of IMF history. Based on annual observations which take value 1 if the country draws upon IMF funds. Source is WDT.

RESCH: Cumulative dummy indicator of rescheduling history. Based on annual observations which take value 1 if the country is observed to reschedule principal and / or interest payments. Source is WDT.

## Chapter 5

### **External indebtedness and the causes of deforestation: a theoretical model.**

#### **5.1 Introduction**

Recent estimates suggest that deforestation in tropical countries has increased markedly during the 1980s (Food and Agriculture Organisation of the United Nations (FAO), 1993). During this same period many developing countries experienced to a greater or lesser extent macroeconomic problems associated with the burden of external indebtedness. The contemporaneous nature of these two observations has led some authors to conclude that these debt problems provide an explanation for the observed increase in deforestation. In support of these conclusions there is empirical evidence pointing to statistically significant (cross-sectional) covariance between measures of deforestation and indicators of external indebtedness. This evidence has not, however, been particularly strong or robust. A more detailed overview of some of this conflicting empirical evidence is reserved for the next chapter which provides an econometric analysis of the debt-deforestation relationship. In this chapter the focus is on this relationship from the perspective of economic theory. A simple theoretical model of forest use by an indebted economy is presented with the aim of analysing the relationship between external indebtedness and deforestation. This analysis whilst of interest in itself, also provides the conceptual framework and testable hypotheses which are considered in chapter 6.

A link between the issues of deforestation and external debt has been popularised with the advent of "Debt-for-Nature" swaps conducted between

conservation groups and developing country governments (see Hansen, 1989; Deacon and Murphy, 1995 for detailed discussion of these debt swaps). Such swaps have enabled some developing countries to reduce a (typically small) part of their outstanding debt in exchange for a commitment to forest conservation.<sup>1</sup> Whilst "Debt-for-Nature" swaps may represent a novel instrument for achieving a measure of debt relief and environmental conservation, there has been no universal presumption that external debt burdens may be a contributory factor to the depletion of tropical forests.<sup>2</sup> Hansen (1989) and Shilling (1992), for example, present arguments which are sceptical about a debt-deforestation link, whilst proponents of the argument (e.g. George, 1989, 1992) appear convinced that debt and deforestation are casually related. One aim of the model presented in this chapter is to clarify some of the issues in the debate about the debt-deforestation relationship which

---

<sup>1</sup>In practice the contractual agreement between the parties to a swap will involve the purchase of some of the outstanding external debt (typically at a discounted price on the secondary debt market) by an external agency (to date mostly conservation groups, e.g. World Wildlife Fund). The developing country is then required to convert the sums received into domestic currency bonds which are, by the contract, allocated to conservation programs. To give some examples: the first ever debt-for-nature swap was negotiated between Conservation International and Bolivia in 1987. This involved the purchase of \$650,000 of Bolivian debt (x% of total outstanding) in exchange for resource (forest) conservation measures. These included re-defining the legal status of the land in the Beni Biosphere Reserve and the designation of three buffer zones around the reserve. The Bolivian government subsequently reneged on its commitments by granting timber concessions in the buffer zones. As noted by Deacon and Murphy (1995) this first swap foundered on its failure to create enforcement incentives and its focus on the output of the swap. i.e. the ambiguous objective of a "sustainable development" in the reserve. More recent swaps have been of a larger magnitude and clearer with regard to enforcement. Costa Rica has been the most prolific swapper conducting 4 deals between 1988-1992 with the debt swapped totalling \$54.6 million. Poland reached agreement with the Paris Club of creditor nations in 1992 which involved the swap of \$3 billion of Polish debt in return for environmental concessions. Deacon and Murphy (1995) have documented that between 1987 and 1992, 34 swaps have been agreed by 19 debtors and worth (in terms of debt) \$1,460 million.

<sup>2</sup>It is now U.S. policy to promote such swaps (Public Law 101-240; U.S. Congress, December 19, 1989), though industrial country governments and institutions such as The World Bank and The International Monetary Fund have refrained from accepting the idea of a debt-deforestation link. Of additional note is empirical evidence presented in Deacon and Murphy (1995) indicating that debt for nature swaps are more prevalent in countries with severe debt servicing problems.

has in the main been conducted in terms of a "widespread sensibilization (of the existence, direction and magnitude of the relationship) without corresponding amounts of analysis." (von Moltke, 1990, quoted in Kahn and McDonald, 1990, p.1)

The rapid removal of forest cover which has been observed and widely reported in recent years, particularly in tropical regions, represents a major example of environmental degradation in developing countries. Concern over deforestation has been evident at a number of levels : in the terms of Repetto (1988) from local villagers to national governments. This diversity of interest points to the multi-faceted nature of the deforestation issue, which itself stems from the myriad of functions forests, and especially tropical forests, can serve. An illustration is given by Pearce,

"...tropical forests are the homeland of many indigenous peoples,...;they provide the habitat for extensive fauna and flora (biodiversity),...; they supply hardwood timber, and other forest products such as fruit, nuts, latex, rattans, meat, honey, resins, oils, etc. ; they provide a recreational facility (e.g. "ecotourism") ; they protect watersheds in terms of water retention, flow regulation [of] water pollution, and organic nutrient cleansing ; they act as a store of carbon dioxide so that,....., carbon dioxide is released, and a cost ensues, if deforestation occurs,...; and finally they also provide a possible regional micro climatic function." (Pearce, 1991, p. 241)

Associated with these functions are a range of economic values or benefits generated by forest resources. The environmental economics literature concerned with the valuation of environmental goods and services has highlighted that these benefits often go beyond those reflected in market

prices.<sup>3</sup> In the case of tropical forests total economic value would include the following:

- Direct Use values : timber production, forest products, recreation.
- Indirect Use values : watershed protection, nutrient cycling, micro climatic functions, carbon storage, ecosystem resilience from biodiversity.
- Non-Use values : existence values arising from bequest motives (Krutilla, 1967); notions of stewardship; intrinsic value of forests.
- Option value<sup>4</sup> : the "risk premium" associated with preservation of future but uncertain benefits.

Taken together these values would also constitute, as a corollary, the total economic cost of deforestation.

This range of values and functions associated with tropical forests heightens the concern that current levels and rates of deforestation may entail very high economic costs in the present and future. In recognition of this, the

---

<sup>3</sup>This is not to say market prices should not reflect this range of benefits, but merely to note that frequently in the case of environmental resources market prices rarely reflect the full marginal social benefit of a resource. The consequence, of course, tends to be under-provision of the resource or service. Also, in the case of forestry resources the range of functions they serve means a number of competing uses for the resource. However, rarely do market prices for direct uses such as logging incorporate the full social opportunity cost of logging activity as the benefits of conserving the resource, e.g. ecological functions such as carbon storage, are non-monetary. Moreover, these public good benefits have national and global dimensions. An individual country benefits from the watershed protection functions of forest resources, whilst the carbon sink function has global benefits in the form of absorbing carbon dioxide (a major greenhouse gas).

<sup>4</sup>There is an extensive literature on option value, see for example Bishop (1982). Option value is defined as the difference between option price (i.e. the state independent payment which leaves an individual indifferent between having and not having an uncertain benefit with certainty. When supply of a resource is uncertain, but future demand is certain (e.g. tropical forests as argued by Pearce, 1989) then OV will be positive assuming risk aversion. However the sign is generally indeterminate with the introduction of different attitudes to risk and demand uncertainties.

deforestation issue and the appropriate policy response has been at the forefront of recent attempts at global environmental management.<sup>5</sup> This concern has also been matched by an growing economics literature on deforestation. Repetto and Gillis (1988) provide a comprehensive survey of the impact of public policies on the forest resource with ten case-studies.<sup>6</sup> Mahar (1989) and Binswanger (1991) have provided further analysis of deforestation in the Brazilian Amazon (see also Barbier, 1989 and Pearce, Barbier and Markandya, 1990). More recently Brown and Pearce (1994) have presented an overview of the issues with a range of studies which provide econometric and case-study evidence on the causes of deforestation.<sup>7</sup>

The economic literature on the causes of recent deforestation has emphasised that many of the benefits (costs) of forest resources (deforestation) are not reflected in existing market prices for land and timber. Hence, over-use of the forest resource results from a range of market failures. In addition many of these market failures have government policy as their origin (see Repetto and Gillis, 1988; Panayotou, 1992). Market failure and policy failure constitute the

---

<sup>5</sup>For example, the Tropical Forestry Action Plan was launched in 1985 under the auspices of FAO, the United Nations agency with responsibility for monitoring global forest resources. More recently, the United Nations Conference on Environment and Development held in 1992 at Rio de Janeiro has emphasised again the need for international co-ordination to combat deforestation. This was evident in a Statement of Forest Principles and provisions in Agenda 21, the Climate Change convention and the Biodiversity Convention aimed at forest preservation. A consequence of the Rio conference was a review on forestry issues under the auspices of the UN Commission on Sustainable Development which is expected to conclude in 1997. In 1993 the International Tropical Timber agreement (which established the International Tropical Timber Organisation to protect the future of the tropical timber trade and conserve forest ecosystem) was the subject of re-negotiation. Developing country producers (e.g. Brazil, Malaysia) wanted all tropical timbers to be covered by the agreement. This met with resistance from consumer countries.

<sup>6</sup>The countries included are Brazil, China, the Philippines, Indonesia, Malaysia, Liberia, Ghana, Gabon, Ivory Coast and the United States.

<sup>7</sup>A variety of approaches are evident in this volume. For example, cross-sectional regressions, empirical studies of single countries or regions and analysis of related issues, e.g. the tropical timber trade.

underlying causes of the deforestation problem. They manifest themselves in a range of outcomes which have to date been viewed as the proximate causes of deforestation, i.e. excessive logging, slash and burn agriculture, shifting cultivation, population pressures (see for example Allen and Barnes, 1985).

The idea that external debt burdens may contribute to deforestation also reflects market and policy failures. The policy failure view of the debt-deforestation linkage has a number of possible interpretations. Firstly, a high level of external indebtedness may be an indicator of macroeconomic mismanagement by the debtor. For example trade and fiscal policies which resulted in over-valued exchange rates and fiscal deficits were associated with the increased levels of indebtedness in many of the already highly indebted Latin America countries (Sachs, 1989). Consequently the need to meet higher debt-servicing through increased export of natural resources may be rooted in underlying macroeconomic imbalances created by inappropriate government economic policies. A second line of argument is that government policies which encourage deforestation may themselves originate from the financial pressures generated by high debt burdens, e.g. Burgess (1992), Capistrano and Kiker (1990, 1995). For example, credit subsidies to agriculturalists encourage the conversion of forested land to pasture. The rationale for this type of policy it is argued is the desire to increase the production of tradable commodities which through export generate valuable foreign exchange for debt servicing. Equally, domestic production may supplant imports with the same effect. The results presented in this chapter provide an analytical basis for why these incentives to encourage forest conversion might exist for a "problem debtor".

At the level of market failures the analysis presented in chapters 2 and 3 highlighted that imperfections in international capital markets may create incentives for a resource-exporting economy to increase the extraction or depletion of natural resources. Recall for example the models presented by Rauscher (1989, 1990) which address the optimal use of an environmental resource by an indebted economy (see chapter 2). By assuming interest payments to be a convex function of the level of outstanding debt to reflect risk premia, Rauscher demonstrates that the incentive to increase depletion arises because higher extraction reduces the cost of indebtedness by reducing the stock of debt.<sup>8</sup> An alternative interpretation of imperfect international capital markets was provided in chapter 3. In this model imperfections arise from credit ceilings, i.e. upper limits on the supply of new debt. An incentive to increase resource depletion arises since the generated liquidity provides the constrained debtor with a means of alleviating the costs associated with capital market imperfections. The model presented in this chapter emphasises the market failure interpretation of the debt-deforestation link and follows the approach already adopted in chapter 3. The model considers a small open economy which produces and trades a commodity which uses forest inputs.<sup>9</sup> The role of indebtedness in the model emerges with constraints on the economy's ability to borrow foreign capital. In other words the economy is

---

<sup>8</sup> Consider for example the facts of the 1980s debt crisis. In the 1970s relatively lax lending policies allowed the accumulation of high levels of debt. In the early 1980s debtors faced rises in real interest rates driven by economic conditions in lender economies. The real cost of their outstanding debt correspondingly rose and thus the cost of being highly indebted. Rauscher's model suggests the optimal response is increased resource depletion.

<sup>9</sup> Examples, using FAO categories, would be Sawlogs & Veneer Logs, Sawnwood, Wood-based panels and Plywood. The percentages of total world exports for these commodity categories attributable to developing countries in 1990 (1980) were: 41.9% (57.3%), 62.6% (65.9%), 42.8% (29.1%) and 72.9% (58.2%) which is suggestive of a move to value-added wood exports over the last decade. In terms of Total Forest products (which includes wood pulp, newsprint, paper) the percentage of world exports accounted for by developing countries was 13.4% (16.6%).

faced with a liquidity "squeeze". Even in the case where interest payments are increasing in outstanding debt (i.e. the Rauscher assumption) deforestation is shown to vary with debt only when the economy faces binding constraints on its foreign borrowing.

The rest of the chapter is structured as follows. Section 5.2 presents an overview of recent data on forest resources and their rate of change, i.e. deforestation, to provide some background and context to the model and analysis outlined in sections 5.3 and 5.4. In section 5.3 equilibrium solutions with unconstrained and constrained borrowing are derived, whilst section 5.4 presents a comparative statics analysis for both cases. The key findings are that deforestation is positively related to debt and negatively related to credit ceilings *only in the constrained case*. A mathematical appendix provides details of these and other results. The chapter concludes with a summary of the main findings and highlights the relevance of the model to previous empirical investigations of the debt-deforestation link.

## **5.2 The global forest resource and its rates of change: an overview.**

Since the early 1970s data on land-use patterns, including the extent of forested land, has benefited immeasurably from satellite imagery and remote sensing technology. Landsat 1,2,3,4 and 5 have been providing satellite images since 1972. The NOAA AVHRR satellites have been operational since 1979. Importantly, as the technology has progressed so the precision of the forested land data has also improved. For example, Landsat 3 did not have enough resolution to discriminate between forest vegetation and the vegetation of cropland. Its successor Landsat 4 however was 2.5 times more powerful.

Nevertheless despite the improving technology, over the last few decades estimates of the global forested area have shown considerable variation. Table V.1 gives an illustration of this variation with recent estimates varying between 3,700 and 6100 million hectares.

**Table V.1**

*Estimates of the Global Forest Resource.*

Source:	Forest Category	Area (Million Ha)
Zon & Sparhawk (1923)	Forest Area	3031
FAO (1946/1937)	Forest	3650
Haden-Guest et al. (1956)	Forest	3914
FAO (1963)	Forest Land	4126
Persson (1974)	Forest Land	4030
	Closed Forest	2800
Eyre (1978)	Total Forest	6050
Global 2000 (1975)	Closed Forest	2563
Barney (1980)	Open Woodlands	1200
Matthews (1983)	Forest	3927
	Woodland	1200
	Total	5237
WRI (1986)	Total Wooded Area	5228
FAO (1987)	Forest & Woodland	4087

*Source : Mathers (1990)*

One source of the variation lies with the definitions employed by each estimate (as reflected by the non-uniformity of the categories adopted).<sup>10</sup> This problem remains evident with current data sources. For example the most recent estimate for total global forest resources is 3400 million hectares in 1990 (World Resources Institute (WRI), 1994). This figure is based on FAO data for 76 tropical countries which cover 98 % of tropical land area (FAO, 1993) and UNECE / FAO data for forests in temperate zones (UNECE/FAO, 1993).<sup>11</sup>

<sup>10</sup>The classification used by FAO is the most widely adopted. This defines the following : Forest and Woodland is land under natural or planned stands of trees and may include land earmarked for future reforestation; Closed Forest is land with a forest cover, with tree crowns covering more than 20 per cent of the land area; Open woodland comprises land with tree crown cover of 5-20 per cent of the surface area.

<sup>11</sup>UNECE is the United Nations Economic Commission for Europe.

Each data-source adopts different definitions of forests reflecting respective differences between forest eco-systems in tropical and temperate zones. Another difficulty arises with changes in measurement methodologies over time. This is evident with the 1990 Forest Resources Assessment undertaken by FAO in tropical countries (see FAO, 1988 for detail on the methodology of the 1990 Assessment. A summary is also provided in WRI, 1994). These definitional and measurement issues become even more important when referring to the extent and rate of deforestation.

### *5.2.1 Estimates of the Rate of Deforestation.*

Despite the recent concern over deforestation and controversial claims that present trends will lead to outright elimination of tropical forests, forests and woodlands continue to cover around 40 % of the earth's land surface.<sup>12</sup> This area is approximately 3.5 times greater than the area devoted to crop production (Repetto, 1988). In addition to this Mathers (1990) states that around 80 % of the pre-agriculturalist forest area remains intact. This observation however says little about the distribution of forest decline. Whereas the vast tracts of boreal forest in the former Soviet Union remain largely intact, in other regions, particularly tropical, the forest resource is undergoing unprecedented change.<sup>13</sup> Repetto (1988) notes that in the post-1945 period there has been a discernible shift in deforestation activity from industrialised countries to the developing world.<sup>14</sup> Between 1950 and 1983, for

---

<sup>12</sup>Examples of these projections are: Guppy (1984), using figures from Lanly (1982), who suggested 2057 as the date for the demise of the tropical rainforest. Myers (1983) was only willing to give tropical forests 38 years before elimination.

<sup>13</sup> WRI (1994) provides a 1990 figure for forest cover in the former Soviet Union 1990 of 755 million hectares or 22.2 % of the estimated global total. Average annual deforestation between 1981-90 is only 0.2 % compared to 0.8 % for tropical forests.

<sup>14</sup> Around half of remaining closed and open forests are to be found in developing countries.

example, Forest and Woodland in Central America fell by 38 % and in Africa by 24%.

Documentation of deforestation in tropical countries gathered apace in the late 1970s and 1980s as the benefits of satellite imagery and remote sensing technology were utilised. Three of the early contributions are worthy of note as they reveal the role of different definitions in producing conflicting estimates. They are respectively the FAO Production Yearbooks, a study conducted by Lanly (1982) on behalf of FAO / United Nations Environment Programme (UNEP) and an American National Academy of Science contribution carried out by Myers (1980).<sup>15</sup> It can be noted that though differences arise as to magnitudes of deforestation, in all three sources there is agreement on the general trend towards contraction of the tropical forest resource. Table V.2 gives some illustrative figures from each of the sources. The FAO Production Yearbook figures are based on the average annual percentage change in Forest & Woodland (see footnote 7) over the period 1968-78 with 1968 as the base. Lanly is calculated as the average annual percent change of closed broad-leaved, coniferous or bamboo forest between 1976-80. Myers adopts the average annual percentage change in tropical moist forest and includes all forms of forest conversion including logging.<sup>16</sup>

---

<sup>15</sup>Note that the FAO Production Yearbook data differs from the data obtained from the Forest Resources Assessments undertaken by the same organisation. The Production Yearbooks give annual figures for Total Forest and Woodland. The FAO assessments have recently been in collaboration with the United Nations Environment Programme and produce estimates of the forest resource at five yearly intervals, e.g. 1980, 1985, 1990. Deforestation can then be estimated by the change in the forest resource in the interval between two assessment observations. It is this latter FAO data source which is employed to construct the measure of deforestation used in the econometric analysis presented in chapter 6.

<sup>16</sup>Tropical moist forest includes evergreen or partly evergreen forests, wetland and mangrove forest but excludes deciduous dry forest.

**Table V.2***Three Estimates of Tropical Deforestation in the 1970s*

Region:	FAO Production	Lanly(1982)	Myers(1980)
All Countries	- 0.53	- 1.52	- 2.0
Africa	- 0.77	- 1.52	- 2.5
Latin America	- 0.62	- 1.46	- 0.3
Asia	- 0.21	- 1.59	- 1.8

*Source : Allen & Barnes (1985)*

The figures in Table V.2 provide an indication of the discrepancy between estimates of rates of deforestation based on different definitions of the forest resource. The difference is starker when expressed in terms of hectares deforested. Lanly (1982) estimated 7.5 million hectares of tropical forest were disturbed annually, whereas Myers suggested a figure of 22 million hectares. Much of the discrepancy is accounted for by the definitions adopted. The FAO Production Yearbook figures strictly do not compare since both closed and open forests are included in the definition.<sup>17</sup> The difference between Lanly and Myers is accounted for in the main by the respective interpretations of deforestation. Lanly (1982) is based on what can be termed the "quantitative" view. That is deforestation is recorded as the complete and permanent removal of forest cover, in this case of closed tropical forests. Myers by contrast adopts the "qualitative" definition of deforestation activity which incorporates all types of forest resource depletion, including marked modification, fundamental transformation or outright removal of the resource. The motivation for attempting to measure in this qualitative manner lies with the impoverishment of forest ecosystems which can arise with major disturbance rather than removal. Hence the inclusion of forest affected by logging in the Myers study.

<sup>17</sup>In Allen and Barnes (1985) Spearman rank correlations are used to confirm a closer association between the figures based on closed forest (Lanly and Myers) and to also confirm the weaker association between the FAO Production Yearbook data and the closed forest data.

Repetto (1988) identifies the qualitative depletion of the tropical resource which can arise from logging. Between 30-50 per cent of an area of forest can be destroyed or damaged during selective logging for commercially valuable species.<sup>18</sup> This can often be sufficient to impoverish soils and impede forest regeneration.

The most recent estimates of deforestation in tropical countries are provided by FAO (1993). These estimates are based on the 1990 Forest Resource Assessment already mentioned and compared with estimates of forest cover from FAO's 1980 assessment. The estimates are based on a "quantitative" view of deforestation:

*"Annual deforestation refers to clearing of forest lands for all forms of agricultural uses.....and for other land uses such as settlements, other infrastructures and mining. In tropical countries this entails clearing that reduces tree crown cover to less than 10 %. As defined....deforestation does not include other alterations such as selective logging (unless the forest cover is permanently reduced to less than 10 %), that can substantially affect forest soil, wildlife and its habitat, and the global carbon cycle." (World Resources Institute, 1994, p. 312)*

Table V.3 summarises some of this data by region.

---

<sup>18</sup>The phenomenon of selective cutting is known as "high-grading". Gillis (1988a) provides a detailed discussion in relation to Indonesia.

**Table V.3***Tropical Deforestation 1981-90<sup>19</sup>*

Geographical Region	Average Annual Deforestation	
	Extent ( 000's ha)	% Change
World		-0.8
Africa		-0.7
West Sahelian Africa	295	-0.7
East Sahelian Africa	595	-0.8
West Africa	591	-1.0
Central Africa	1140	-0.5
Tropical Southern Africa	1345	-0.8
Asia		-1.2
South Asia	551	-0.8
Continental South East Asia	1314	-1.5
Insular South East Asia	1926	-1.2
The Americas		-0.7
Central America & Mexico	1112	-1.4
Caribbean Sub-Region	122	-0.3
Tropical South America	6174	-0.7

Source: *World Resources Institute (1994)*

These estimates of deforestation during the 1980s suggest an increase in the rate of forest resource depletion. The 1980 FAO assessment estimated tropical forests were decreasing at an average annual rate of 0.58 % or 11.3 million hectares per year. This compares with an average annual rate of 0.8 % in Table V.3. In terms of the extent of forest loss this rate is equivalent to 15.4 million hectares which represents an approximate increase in the average annual reduction in tropical forests of 37 %. Such comparisons are problematic given the different methodology of the 1990 assessment. However, even with comparisons using revised 1980 data the conclusion remains that the rate of deforestation increased in the 1980s (see FAO, 1990).

<sup>19</sup>The data refers to change in total forest. Detail on the regional classifications can be found in World Resources Institute (1994).

### 5.3 A model of deforestation in an indebted economy.

Despite the measurement and definitional difficulties associated with monitoring trends in deforestation, awareness of deforestation, particularly tropical deforestation, undoubtedly increased during the 1980s. This prompted a considerable economic literature addressing the causes of deforestation. One feature of this extensive and wide-ranging literature, as briefly noted in the Introduction to this chapter, has been the general absence of analytical modelling of the deforestation problem.<sup>20</sup> Deacon (1995) considers the role of public policies in deforestation from the analytical perspective, but lacks any econometric estimation or testing.<sup>21</sup> He presents a simple general equilibrium model of an economy producing and trading two goods; one is produced with forest inputs, whilst the other is produced only with non-forest inputs. The focus in Deacon's paper is on the impact of government policy (analysed through different types of taxes) on deforestation. In this chapter Deacon's general framework is extended to incorporate the indebtedness situation of the economy. This is achieved by relaxing his assumption that trade must balance. Since the focus in this chapter is on the relationship between deforestation and indebtedness, this extension to Deacon's model does not incorporate the policy / tax variables which provide the basis for his analysis of the impact of government policies on deforestation.

---

<sup>20</sup>This is particularly true of some of the empirical work which has lacked a foundation in explicit economic theory. There are some examples where an attempt has been made to remedy this. See for example Kahn and McDonald (1990, 1995) in the context of debt and deforestation and Panayotou and Sungsuwan (1994) in the context of Thailand.

<sup>21</sup>Of note however is the comment by Deacon that "A second intent (of his paper) was to propose a general framework that may prove useful in organising future empirical work on deforestation" (Deacon, 1995, p. 17)

The model is static in nature. Thus the focus is necessarily on long run relationships which is consistent with the available data on deforestation. In addition, most empirical deforestation studies have utilised cross-sectional data.<sup>22</sup> A further institutional justification for a static model is that prevailing systems of land tenure and timber concessions may mean that the objectives of agents are defined over a very limited number of time periods. This is particularly relevant in situations where the nature of property rights for land are such that land titles are conferred only for agricultural use (see for example discussions in Southgate and Pearce, 1988 and Southgate, 1991).<sup>23</sup> As a consequence the user cost of forest resource use can be treated as external to the decisions of private agents. Given this institutional constraint the future flow of forest services that is foregone as a result of deforestation is not seen as a cost by private agents. Similarly in the context of logging, Repetto and Gillis (1988) document at length examples of inefficient timber policies where royalties and fees levied on logging companies have fallen short of true stumpage values which, it is argued, encourages loggers to maximise short run rents. A more general institutional reason for treating the user cost as external is that, especially in the developing country context, forests can be regarded as a free access resource.<sup>24</sup> In an environment where the forest and its services are

---

<sup>22</sup>Kahn and McDonald (1990, 1995) present a dynamic theoretical model linking debt and deforestation, but estimate their empirical model with cross-sectional data when time series data would seem appropriate. Annual time-series data on Forest and Woodlands from the FAO Production Yearbooks is available and could be used to construct time-series for deforestation. However the reliability of this data has been seriously questioned. See Mathers (1990) for a discussion.

<sup>23</sup>There is a sizeable literature addressing the specific issue of land tenure regimes and their impact on deforestation. For a formal exposition see Mendelsohn (1994); empirical evidence is presented in Southgate et. al. (1991) and Deacon (1994) and Hecht and Cockburn (1990) provide a discussion in the context of the Brazilian Amazon.

<sup>24</sup>Capistrano and Kiker (1995) note that about 90 % of closed broadleaved tropical forests are state-owned.

public goods and the appropriate regulatory framework is absent, private agents have no incentive to internalise the cost that their use of the forest resource (e.g. to collect fuelwood) imposes on current or future generations.<sup>25</sup> It follows therefore that the model is not concerned with the *socially optimal* use of a forest resource since domestic imperfections (market and policy) which give rise to external costs are embedded in its structure.<sup>26</sup> With these considerations in mind, the model is focused on what Deacon (1995) terms the "unregulated (private) equilibrium" level of forest resource use.

### 5.3.1 Domestic production possibilities and the balance of payments

Consider an economy which produces and consumes two goods denoted by X and Y. The good X is produced with forest inputs, whilst Y is not. Thus very loosely X can be thought of as a primary commodity and Y as a manufactured good. Whilst for present purposes it is convenient to think of X as a single good it could equally define a vector of commodities produced with forest inputs. The production of X is described by the function:

$$(5.1) \quad X = X(L^X, P),$$

where  $X(\cdot)$  is a strictly concave production function,  $L^X$  is the labour input and  $P$  denotes the forest input. The interpretation of this latter input depends on the

---

<sup>25</sup>Southgate et. al. (1991) cite Ecuador to illustrate the absence of effective regulation of forest use in the developing country context. As of 1987 a staff of only 119 permanent and seasonal forest rangers were available to patrol over 4 million hectares of Ecuadorian national parks.

<sup>26</sup> In this case society's objective function would preferably be defined in terms of social welfare over time to allow investigation of the intertemporal trade-offs in forest use. An example where preferences are specified in this manner is Barrett (1992) which considers the issue of environmental preservation within an optimal growth framework. The issue addressed by Barrett concerns the conditions under which an environmental resource (e.g. rainforest) is preserved or developed / depleted (i.e. deforestation). The intertemporal framework is also adopted by Ehui, Hertel and Preckel (1990) in an analysis of forest resource depletion.

nature of X. In the context of an agricultural commodity P would define the land input to production obtained by forest clearance. If X represents wood production then P would represent the input of timber harvests.

It is assumed that there is a strict trade-off between direct use of the forest resource (i.e. as an input in the production of X) and alternative uses.<sup>27</sup> If F denotes the stock of standing forests then P and F are constrained by  $P+F=1$ , which captures the idea of the trade-off.<sup>28</sup> This constraint is obvious when P would denote forest clearance intended for agricultural purposes. It is less clear when P would denote the fraction of forested land which is harvested for timber. However, it can be noted that increasing the volume of timber harvested will increase the length of time a given area of land is not forested and therefore reduce the flow of forest services.<sup>29</sup> Assuming the flow of forest services to be proportional to the stock of standing forest, then F can also be viewed as the fraction of forested land providing forest services (other than direct inputs for the production of X). The constraint on the use of the forest will remain  $F=1-P$ , implying a strict trade-off between forest services and logging. This relates to the discussion in Section 5.2 where it was noted that

---

<sup>27</sup>As noted in the Introduction to this chapter examples of alternative uses would be recreation (e.g. eco-tourism), watershed protection, carbon storage and nutrient cycling. These uses can be viewed as examples of the flow of services obtained from the stock of forests.

<sup>28</sup>Thus F is the fraction of forested land maintained as standing forests and P is the fraction which is cleared.

<sup>29</sup>The volume of timber (V) at a given time t will be a function of the time interval since the previous harvest. If the previous harvest was at time s, then V is a function of t-s. Deacon (1995) notes that if this growth relationship is concave then increasing  $\dot{P}$  (which requires increasing  $V/(t-s)$ , i.e. the harvest per period) is obtained by decreasing the interval t-s. The fraction of time forest services are provided and the average volume of timber on the land are both reduced. This latter point is particularly relevant to tropical forests which provide a wide range of eco-system and climatic functions. Moreover, Panayotou and Sungsuwan (1994) note that minimum felling and rotation cycles (i.e. t-s) for tropical forests are around 35-50 years. Logging practice in tropical forests has rarely been consistent with this kind of cycle. Deforestation in Cote D'Ivoire is a good example of significant forest clearance and therefore decline in the flow of forest services attributable to excessive harvests (see Gillis, 1988b).

once an area of forest is logged and the land is no longer capable of regenerating natural forest cover depletion of the forest is qualitative (i.e. the extent of forest services) and eventually quantitative (i.e. the extent of forest cover).

The conversion of forested land incurs two types of cost. The first, user cost, as already mentioned is not considered since the model is static. The second type of cost is the opportunity cost of physically clearing forest areas. The "production" of P requires inputs which are assumed to be only labour and is described by:

$$(5.2) \quad P = P(L^P)$$

The good Y is also produced using labour and the production function is similarly:

$$(5.3) \quad Y = Y(L^Y),$$

with total available labour constrained by:

$$(5.4) \quad L^X + L^Y + L^P = 1.$$

This restriction on available labour defines the economy's production possibilities. Assuming the production functions in (5.2) and (5.3) to be linearly homogenous then the constraint on labour is equivalently:

$$(5.5) \quad (Y_L L^X + Y_L P_L^{-1} P) + Y = Y_L,$$

where  $Y_L, P_L$  are the respective marginal products of labour in the production of Y and P. Deacon (1995) terms  $(Y_L L^X + Y_L P_L^{-1} P)$  the private costs to the

economy of producing  $X$  with  $Y_L$  and  $Y_L P_L^{-1}$  defining the effective prices for inputs used to produce  $X$ .

The economy can choose to consume  $X$  and  $Y$  or engage in trade with the outside world. Assuming a small open economy implies relative prices of the commodities are treated as given. Unlike Deacon's model it is not assumed that trade in  $X$  and  $Y$  must balance. Specifically, the economy is assumed to be a net debtor with interest payments determined by the convex function  $h(D)$ , with  $D$  denoting the inherited stock of debt which for the purposes of analysis is assumed to be exogenously given.<sup>30</sup> Flows of capital are for simplicity the supply of new debt  $B$  and the repayment of principal  $R$ . The balance of payments can then be defined as:

$$(5.6) \quad B - R - h(D) = y^m - \gamma x^e,$$

where  $\gamma$  is the real world price of  $X$ ,  $x^e = X - x^c$ ,  $y^m = y^c - Y$  and  $x^c$  ( $y^c$ ) denotes domestic consumption of good  $X$  ( $Y$ ). Where  $x^e > 0$  and  $y^m > 0$  the economy is a net exporter of good  $X$  and net importer of  $Y$ . Conversely,  $x^e < 0$  and  $y^m < 0$  characterises a net importer of  $X$  and net exporter of  $Y$ . The case of primary interest is where the economy is a net exporter of  $X$  which is the good produced with forest inputs. Moreover  $x^e > 0$  and  $y^m > 0$  broadly describe economies with comparative advantages in forest and agricultural products, a characteristic which is, in the main, observed in developing economies. Eq. (5.6) simply states that the current account determines the demand for new debt. This demand is satisfied if the borrower faces unconstrained lending. If

---

<sup>30</sup>The convexity assumption reflects factors such as default risk which are a particular feature of sovereign borrowing. Thus the marginal cost of external debt is increasing in the level of debt reflecting a higher probability of default.

the borrower is viewed as a "problem" debtor by international lenders then there may in fact exist limits to this ability to borrow. In other words there is an upper limit or ceiling on  $B$ .<sup>31</sup> This constraint takes the form:

$$(5.7) \quad B^* - B \geq 0,$$

or using (5.6),

$$(5.8) \quad B^* - R - h(D) - y^m + \gamma x^e \geq 0.$$

The inequality in Eq. (5.8) will hold with equality when the credit ceiling binds.

### 5.3.2 Unconstrained and constrained equilibria

The economy must choose the domestic consumption levels of  $X$  and  $Y$  which maximise utility. This objective is represented by a strictly concave utility function denoted by:

$$(5.9) \quad U = U(x^c, y^c, \bar{F}),$$

and the properties  $U_x > 0$ ,  $U_y > 0$ ,  $U_F > 0$ ,  $U_{xx} < 0$ ,  $U_{yy} < 0$ ,  $U_{FF} < 0$  and  $U_{xy} = U_{yx} \geq 0$ .<sup>32</sup> The inclusion of  $F$ , the forest resource, as an argument in the objective function (5.9) arises from utility which is derived from the flow of services provided by standing forest, e.g. forest products, watershed protection, biodiversity. The social optimum for this problem would involve maximising (5.9) with respect to the choice variables  $x^c$ ,  $y^c$  and  $F$  subject to the constraints

---

<sup>31</sup>This is analogous to the constraints considered in chapters 2 and 3. For justification of the existence of these constraints see the discussion in chapter 2.

<sup>32</sup>Subscripts denote partial derivatives.

describing the economy's production possibilities (5.4) and the balance of payments, i.e. (5.6) and (5.8). From the perspective of social costs and benefits this would ensure that the social marginal benefit of forest clearance is equated with the social marginal cost. However, as already noted, there are good reasons for treating the cost of foregone forest services arising from forest clearance (i.e. the user costs) as external to individual private agents. In an unregulated equilibrium arising from open access use of the forest resource,  $F$  is regarded as fixed in the choice problem faced by private agents. The bar above  $F$  in the objective function denotes the fact that utility is maximised with the flow of forest services taken as given by private agents.

The choice problem facing private agents can be considered in two steps (see Deacon, 1995). Firstly, the efficient mix of inputs used in the production of  $X$  is determined and then second, the levels of consumption which maximise (5.9). In the first element of the choice problem the economy seeks to minimise the private cost of producing  $X$ . More formally the problem can be stated as:

$$(5.10) \quad \text{Min}_{L^X, P} \quad \alpha L^X + \pi P \quad \text{s.t.} \quad X = X(L^X, P),$$

where it has been assumed that  $Y_L = \alpha$  and  $Y_L P_L^{-1} = \pi$ . Let  $\lambda$  denote the Lagrange multiplier on the production function constraint. Given the assumption of a strictly concave production function the first order conditions are sufficient to minimise (5.10). With respect to labour and forest inputs these conditions are:

$$(5.11) \quad \alpha - \lambda X_L = 0,$$

$$(5.12) \quad \pi - \lambda X_p = 0.$$

From these first order conditions the cost-minimising factor demands can be derived as:

$$(5.13) \quad L^X = L^X(\alpha, \pi, X),$$

$$(5.14) \quad P = P(\alpha, \pi, X).$$

Using (5.13) and (5.14) the private costs of producing  $X$  can be re-expressed in terms of the cost function:

$$(5.15) \quad C = C(\alpha, \pi, X),$$

where the derivatives of  $C(\cdot)$  with respect to  $\alpha$  and  $\pi$  give (5.13) and (5.14) and costs are positive and increasing in  $X$ .

The second component of the choice problem can now be considered. The problem is to maximise (5.9) subject to (5.8) and the (private) cost-minimising solution for producing a given quantity of  $X$ . Inserting (5.15) into (5.5) and noting  $Y \equiv y^c - y^m$  domestic expenditure on  $Y$  can be written as:

$$(5.16) \quad y^c = \alpha - C(\alpha, \pi, X) + [B - R - h(D) + \gamma x^e],$$

where (5.6) has been used to substitute for imports of  $Y$ . Substituting (5.16) into (5.9) and noting  $x^c \equiv X - x^e$  the problem is to choose the levels of  $X$  and  $x^e$  which maximise (5.9) subject to (5.8). The Lagrangian for this problem is given by:

$$(5.17) \quad \begin{aligned} \ell = & U(X - x^e, \alpha - C(\alpha, \pi, X) + [B - R - h(D) + \gamma x^e], \bar{F}) \\ & + \mu(B - R - h(D) - y^m + \gamma x^e), \end{aligned}$$

and for the primary case of interest where the economy has its comparative advantage in X, the associated first order conditions are (subscripts denote partial derivatives):<sup>33</sup>

$$(5.18) \quad \partial \ell / \partial X = U_x - U_y C_x = 0,$$

$$(5.19) \quad \partial \ell / \partial x^e = -U_x + U_y \gamma + \mu \gamma \leq 0; \quad x^e \geq 0; \quad x^e (\partial \ell / \partial x^e) = 0,$$

$$(5.20) \quad \partial \ell / \partial \mu = B^* - R - h(D) - y^m + x^e \geq 0; \quad \mu \geq 0; \quad (\partial \ell / \partial \mu) = 0.$$

Eq. (5.18) implies that:

$$(5.21) \quad U_x / U_y = C_x(\alpha, \pi, X),$$

i.e. in equilibrium the marginal rate of substitution in consumption is equated with the marginal cost of producing X. Assuming trade in X is non-zero then (5.19) must hold with equality. Eq. (5.20) then identifies two possible situations which are dependent on the foreign borrowing regime faced by the economy. Firstly if the credit ceiling is slack then (5.20) would imply  $\mu = 0$ . The first order condition (5.19) is then  $U_x / U_y = \gamma$  for  $x^e > 0$  (or  $x^e < 0$ , see footnote 30) which in combination with (5.21) gives:

$$(5.22) \quad C_x = \gamma,$$

which simply states that with unconstrained foreign borrowing in equilibrium the marginal cost of X is set equal to its (real) world price. The second case

<sup>33</sup>The converse case of holding comparative advantage in Y whilst being a net importer of X can be considered in (5.17) with the modification that the choice variables are now X and  $-x^e$ . (5.18) remains unchanged, whilst (5.19) becomes:

$$\partial \ell / \partial (-x^e) = U_x - U_y \gamma - \mu \gamma \leq 0; \quad -x^e \geq 0; \quad -x^e (\partial \ell / \partial (-x^e)) = 0.$$

(5.20) is modified to the extent that  $y^m < 0$  and  $x^e < 0$ . Of note is the fact that the equilibrium (i.e. first order) conditions are invariant to the signs on net trade in Y and X. It is with the comparative statics that the assumptions about the signs of  $y^m$  and  $x^e$  make a difference to the results. This is highlighted in Section 5.4 below.

arises when the credit ceiling binds and therefore  $\mu > 0$ . (5.19) and (5.21) now imply:

$$(5.23) \quad C_x = \gamma(1 + \hat{\mu}),$$

where  $\hat{\mu} = \mu/U_y$ . The interpretation of (5.23) remains that in equilibrium the marginal cost of X is set equal to the marginal benefit of X, but unlike (5.22) the marginal benefit is no longer simply the given world price of X when foreign borrowing is constrained. The additional component to the marginal benefit given by  $\gamma\hat{\mu}$  indicates that the production of X brings an extra gain when the economy faces a binding credit ceiling. This is simply the additional liquidity benefit of X which arises because the economy is unable to use net borrowing to finance the current account. The multiplier  $\mu$  measures the marginal increment in the objective function obtained if the binding borrowing constraint were to be relaxed by one unit. Thus  $\mu$  can be interpreted as the shadow price of scarce foreign exchange and  $\gamma\hat{\mu}$  can be viewed as a measure of the extra shadow value of producing X in a constrained borrowing regime. Where  $x^e > 0$  this extra benefit arises from export, whilst for the case of  $x^e < 0$ , the extra liquidity benefit of producing X is obtained by the substitution of domestic production for imported X.

Comparing (5.22) and (5.23) it is evident that the equilibrium level of X will be higher when the credit ceiling is binding. Since  $\gamma(1 + \hat{\mu}) > \gamma$ , marginal costs must be greater in a constrained borrowing regime, implying equilibrium production of good X is higher given costs are convex in X.<sup>34</sup>

---

<sup>34</sup>The reasoning here is analogous to that presented in Section 3.4 of chapter 3.

## 5.4 External indebtedness as a cause of deforestation: comparative static analysis.

### 5.4.1 The case of unconstrained foreign borrowing

In an unconstrained foreign borrowing regime, the first order conditions (5.18)-(5.20) implicitly define equilibrium solutions for  $X$  and  $x^e$  as functions of the exogenous variables  $\alpha$ ,  $\pi$ ,  $\gamma$  and the inherited stock of debt,  $D$ . That is:

$$(5.24) \quad \begin{aligned} \bar{X} &= X(\alpha, \pi, \gamma, D) \\ \bar{x}^e &= x^e(\alpha, \pi, \gamma, D). \end{aligned}$$

In combination with the (constant output) factor demand for forest inputs (5.14) the equilibrium solutions (5.24) can be used to analyse the effect of marginal changes in the exogenous variables on deforestation as represented by converted forested land  $P$ .

The focus of the analysis in this chapter is on the relationship between deforestation and debt which is reflected in the results presented below. An appendix to this chapter outlines these results in detail and provides analysis of the effect of marginal changes in the real price of  $X$ ,  $\gamma$ , and the input prices  $\alpha$  and  $\pi$ .<sup>35</sup>

By the definition of an unconstrained borrowing regime, deforestation must be independent of any credit ceiling  $B^*$ . Thus any relationship between debt and

---

<sup>35</sup>These results for the unconstrained and constrained cases, though not of primary interest for the moment prove useful for the empirical analysis considered in chapter 6

deforestation in an unconstrained economy will depend on any effect that a change in the stock of debt has on forest clearance. To assess this relationship it is essential to consider the effect that changes in  $D$  have on equilibrium production and trade in  $X$ .<sup>36</sup> These effects are summarised by Lemma 1.

**Lemma 1.** *In an unconstrained borrowing regime: i) net exports (imports) of  $X$  are increasing (decreasing) in  $D$  and ii) production of  $X$  is independent of  $D$ .*

**Proof.** See Appendix.

The first part of Lemma 1 presents an intuitive result. Where an economy holds a comparative advantage in  $X$  (i.e. net exports are positive) a higher stock of debt implies higher export. This must follow from the balance of payments expression (5.6) since, *ceteris paribus* (i.e. given levels of  $B$ ,  $R$  and  $y^m$ ), a higher stock of debt increases interest repayments which are met by increased export of  $X$ . The converse applies for the case where comparative advantage lies in  $Y$ . Net exports of  $X$  are thus negative (net imports positive) and again, *ceteris paribus*, (i.e. given levels of  $B$ ,  $R$  and  $y^m$ ), higher interest repayments are met by reducing imports of  $X$ . The second part of Lemma 1 is perhaps the most interesting result. It suggests that even if interest payments are increasing in the stock of debt, in an unconstrained borrowing regime production of  $X$  does not change with changes in the stock of debt. This finding can be related to the equilibrium condition for unconstrained borrowing (5.23). In (5.23) the marginal benefit of producing  $X$  is given by  $\gamma$ , its exogenously determined

---

<sup>36</sup>This becomes evident below.

world price. Since this exogenous price is unaffected by  $D$ , production decisions at the margin are likewise unaffected by  $D$ .

With production of  $X$  independent of  $D$  the following proposition about the relationship between debt and deforestation can now be stated.

**Proposition 1.** *When a debtor faces unconstrained foreign borrowing, the equilibrium level of forest conversion is independent of the stock of debt.*

Differentiating (5.14) with respect to  $D$  gives:

$$(5.25) \quad \partial \bar{P} / \partial D = (\partial \bar{P} / \partial \bar{X}) \partial \bar{X} / \partial D.$$

Lemma 1 established  $\partial \bar{X} / \partial D = 0$  and it follows in (5.25) that  $\partial \bar{P} / \partial D = 0$ .

This result has a simple intuition. For a given change in the level of inherited debt, the debtor will have to meet increased interest charges or equivalently, *ceteris paribus*, face a deterioration in the current account. From eq. (5.6) it can be seen that the current account balance can be thought of as the demand for new (net) borrowing ( $B - R$ ). In an unconstrained borrowing regime the observed level of new borrowing is demand determined (see McFadden et al., 1985; Hajivassiliou, 1987). Thus in this framework the unconstrained debtor is able to meet the increased interest payments with an offsetting inflow to the capital account which avoids the need to, say, increase export of  $X$  and therefore inputs of  $P$ . At first sight (5.25) would appear to be at odds with the findings in Rauscher (1989, 1990) which show that when interest payments are a convex function of debt, the optimal time paths for debt and resource use are

not independent. This result holds however in an intertemporal context where the shadow value of resource stock is incorporated into the equilibrium conditions and intertemporal efficiency requires the rate of increase in the marginal productivity of the natural resource to equal the rate of interest on debt less the marginal rate of regeneration (for renewable resources).<sup>37</sup> The assumption that the marginal cost of debt is increasing in the stock of debt ensures that the time paths of resource use which satisfies this efficiency condition cannot be independent of the level of debt. Proposition 1 differs from Rauscher's finding precisely because intertemporal efficiency is not considered by decision-makers and in the context of forest use in developing countries (as already noted earlier in this chapter) the assumption of short time horizons would appear reasonable.

#### 5.4.2 *The case of constrained foreign borrowing*

When foreign borrowing is constrained to the credit ceiling  $B^*$  the optimal solution to (5.18), (5.19) and (5.20) is given by the implicit functions :<sup>38</sup>

$$(5.26) \quad \begin{aligned} \bar{X} &= X(\alpha, \pi, \gamma, D, B^*) \\ \bar{x}^e &= x^e(\alpha, \pi, \gamma, D, B^*) \\ \bar{\mu} &= \mu(\alpha, \pi, \gamma, D, B^*) \end{aligned}$$

(5.26) suggests that the indebtedness situation of a debtor economy in a constrained borrowing regime may be related to equilibrium forest clearance

---

<sup>37</sup>In the present model the marginal productivity of the natural resource would correspond to the term  $\partial X/\partial P$ .

<sup>38</sup>Note that the implicit functions applicable in the constrained regime are assumed to be continuously differentiable in the credit ceiling  $B^*$ .

through two channels. The first is the stock of debt which has been shown not to influence forest clearance when borrowing is unconstrained. The second is the level of the credit ceiling itself. Changes in this credit ceiling can be interpreted as making the liquidity "squeeze" for constrained debtors tighter or slacker. The former is obviously of most interest since it would capture the type of liquidity crisis which has recently faced many problem debtors. As in the case of unconstrained borrowing the analysis for the constrained borrowing case focuses on the relationship between deforestation and the economy's indebtedness as measured by  $D$  and  $B^*$ . Analysis of the effects of marginal changes in  $\gamma$ ,  $\alpha$  and  $\pi$  with constrained borrowing is detailed in the Appendix to this chapter.

*a) The effect of debt on deforestation.*

As with the case of unconstrained borrowing the first step in determining the relationship between the stock of debt and deforestation in a constrained borrowing regime is to consider the effect a marginal change in  $D$  has on equilibrium production of  $X$ . This is summarised by Lemma 2.

**Lemma 2.** *In a constrained borrowing regime equilibrium production of  $X$  is increasing in  $D$ .*

**Proof.** The details are reserved for the Appendix to this chapter. In the appendix it is shown that:

$$(5.27) \quad \frac{\partial \bar{X}}{\partial D} = -\gamma (U_{xx} - C_{\bar{X}} U_{xy}) (\partial h / \partial D) / |\bar{H}| > 0,$$

where  $\bar{X}$  denotes equilibrium production of X and subscripts denote partial derivatives (which are evaluated at the optimal values determined by the first order conditions). The determinant of the bordered Hessian,  $|\bar{H}|$ , is positive which follows if the bordered Hessian is negative definite at the optimum and therefore sufficient for a maximum (see chapter appendix for details). Given  $\gamma > 0$ ,  $U_{xx} < 0$ ,  $C_{\bar{X}} > 0$  and  $U_{xy} \geq 0$  and  $\partial h / \partial D > 0$  the numerator in (5.27) is unambiguously positive and therefore  $\partial \bar{X} / \partial D$  is unambiguously positive.

Thus in contrast to the unconstrained case, when an economy is faced with binding constraints on foreign borrowing an increase in the level of inherited debt will imply a rise in equilibrium production of X. This difference can be related to the equilibrium conditions given in (5.23) and (5.24). It has already been noted above that (5.23) implies production decisions at the margin depend on the exogenously determined price  $\gamma$ . The condition (5.24) shows that with constrained borrowing the marginal benefits of production depend additionally on  $\mu$  and  $U_y$ , neither of which are independent of the stock of debt given the solutions in (5.26). Thus with constrained borrowing, production decisions at the margin *are* influenced by D. In addition this result holds irrespective of whether the economy is a net exporter or net importer of X. This arises because the additional liquidity benefit of producing X in a constrained borrowing regime is evident in both trade situations. In the case of the net exporter the incremental increase in production benefits the economy with the earning of scarce foreign exchange, whilst for the net importer domestic production substitutes for imported X (details are provided in the Appendix).

Given Lemma 2, the effect of a marginal change in debt on equilibrium forest clearance is summarised by Proposition 2

**Proposition 2.** *If  $P$  is a normal input in the production of  $X$  equilibrium forest conversion is increasing in the inherited stock of debt when a debtor country faces a binding credit ceiling.*

Defining  $P$  to be a normal input implies  $\partial\bar{P}/\partial X > 0$  and therefore the sign of  $\partial\bar{P}/\partial D$  in a constrained borrowing regime is determined by  $\text{sign}\{\partial\bar{X}/\partial D\}$ . Lemma 2 established this positive in a constrained borrowing regime and it follows  $\partial\bar{P}/\partial D > 0$ .

This relationship between deforestation and levels of debt in constrained borrowing regimes is entirely an output effect. A marginal increase in the inherited stock of debt increases production of  $X$  and so long as  $P$  is a normal input the derived demand for deforestation increases. Combining Propositions 1 and 2 it can be concluded that the hypothesis of a positive association between deforestation and debt should only be anticipated in "problem" debtor economies, i.e. economies which face binding credit ceilings.

*b) The effect of credit ceilings on deforestation*

The level of the credit ceiling provides another source for the relationship between deforestation and indebtedness in a constrained borrowing regime. A fall in the credit ceiling will effectively increase the burden of a given level of

indebtedness in the sense that the domestic resource cost of servicing outstanding foreign liabilities increases. This is established more formally with Lemma 3.

**Lemma 3.** *In a constrained borrowing regime equilibrium production of X is decreasing in the credit ceiling B\*.*

**Proof:** Details are provided in the appendix. Here it is sufficient to note that:

$$(5.28) \quad \frac{\partial \bar{X}}{\partial B^*} = \gamma (U_{xx} - C_{\bar{X}} U_{xy}) / |\bar{H}| < 0,$$

The determinant of the bordered Hessian,  $|\bar{H}|$ , as noted above is positive since the second order conditions for a maximum are satisfied. The numerator in (5.28) is unambiguously negative since  $\gamma > 0$  and therefore the derivative  $\partial \bar{X} / \partial B^*$  is unambiguously negative.

With respect to trade in X, the marginal effect of a change in the credit ceiling in a net exporter is given by (again see appendix for details):

$$(5.29) \quad \frac{\partial \bar{x}^e}{\partial B^*} = -1/\gamma < 0.$$

In the case of a net importer the sign in (5.29) is reversed.

(5.28) and (5.29) show that if the liquidity "squeeze" tightens through a fall in the credit ceiling, then equilibrium levels of X and its export (import) must increase (decrease). The interpretation of these results would be that for constrained debtor countries the more severe is the liquidity crisis or the lower is their creditworthiness (measured by the level of the credit ceiling) then the

greater is the reliance on domestic sources of international liquidity to finance the balance of payments. Moreover it can be shown that the relative magnitudes of the production and trade effects imply that domestic consumption of  $X$  must fall as a result of a fall in the credit ceiling (see Appendix).<sup>39</sup>

The consequences that this effect of a change in the credit ceiling has for deforestation are summarised by the following proposition.

**Proposition 3.** *If  $P$  is a normal input in the production of  $X$  then for constrained debtors a fall in the credit ceiling will imply an increase in the equilibrium level of forest conversion.*

For a marginal change in a binding credit ceiling, the effect on forest conversion is given by:

$$(5.30) \quad \frac{\partial \bar{P}}{\partial B^*} = \left( \frac{\partial \bar{P}}{\partial \bar{X}} \right) \frac{\partial \bar{X}}{\partial B^*} < 0.$$

As in the case of a change in debt, the sign of  $\frac{\partial \bar{P}}{\partial B^*}$  is determined by  $\text{sign} \left\{ \frac{\partial \bar{X}}{\partial B^*} \right\}$ . Lemma 3 has shown  $\frac{\partial \bar{X}}{\partial B^*} < 0$  and it follows  $\frac{\partial \bar{P}}{\partial B^*} < 0$ . Thus the liquidity "squeeze" which increases domestic production of  $X$  leads to an increase in the derived demand for forest inputs so long as  $P$  is a normal input. Also, as with the effect of changes in debt, this result holds for net exporters and importers of  $X$ .

## 5.5 Conclusions

---

<sup>39</sup>The same is true for the effects on production and trade arising from a marginal change in  $D$ . See details in Appendix to this chapter.

This chapter has considered the relationship between external indebtedness and deforestation from an analytical perspective. A static model of deforestation in an indebted economy was outlined based on a general model of deforestation presented in Deacon (1995). This model presented a stylised representation of an economy which trades a commodity produced using forest inputs and produces and trades another commodity which uses only non-forest inputs. The economy is assumed to be a net debtor with interest payments increasing in the stock of debt. In addition, net foreign borrowings may be used to offset any current account deficit. The economy is considered to be a "problem" debtor when its ability to borrow on international capital markets is constrained. That is, it faces a binding credit ceiling. It was shown that compared to a "no debt problem" situation defined by the absence of binding lender constraints on the ability to borrow foreign capital, the equilibrium production of goods which require forest inputs would need to be higher when such constraints bind. The effect of reductions in this credit ceiling and the economy's inherited stock of debt were analysed and it was shown that the equilibrium level of forest conversion varies inversely with the credit ceiling for a problem debtor and is positively related to the inherited stock of debt. Of further note is the finding that when the credit ceiling does not bind equilibrium forest conversion is independent of the economy's stock of debt.

To conclude, this chapter has provided some analytical insight concerning the idea that the problems of external indebtedness and deforestation are related. A second aim of the model as mentioned above was to provide a framework which would permit econometric analysis of the link. In some ways this is

perhaps the crucial element of the discussion about the debt deforestation link. Whilst the analytical model confirms some of the simple intuition which underlies the debt-deforestation hypothesis it cannot address the magnitude or significance of the relationship. The analytical model emphasises the importance of what might be called "debt regimes". That is, a regime characterised by unconstrained lending and another regime defined by binding credit ceilings. The analytical results suggest the testable empirical hypotheses that deforestation is orthogonal to debt and credit ceilings for unconstrained countries, but not for constrained countries. Almost all of the existing empirical investigations of the debt-deforestation hypothesis have ignored this distinction by assuming that under the alternative debt and deforestation are correlated for all (sample) countries.

A more general econometric issue concerns the appropriate specification of regressors in a reduced form expression for deforestation. Some studies of the debt link specify models where debt measures are included along side variables such as timber production and agricultural output as independent variables, e.g. Burgess (1992).<sup>40</sup> The theoretical model presented in this chapter emphasises that such variables are choice variables (i.e. both could be considered proxies for X) which are functions of prices (input and output) and under certain circumstances, the indebtedness situation of the economy. Thus the theoretical model provides a rationale for questioning on econometric grounds empirical specifications which include endogenous choice variables (e.g. timber production, agricultural production) alongside debt variables as independent regressors.

---

<sup>40</sup>These variables have also used as regressors in more general empirical analyses of the causes of deforestation, e.g. Allen and Barnes (1985), Southgate (1991).

Finally, given the emphasis placed on unconstrained and constrained debt regimes in this chapter an approach to the estimation and testing of the debt-deforestation hypothesis which differs from existing empirical studies would appear appropriate. Instead of hypothesising that the conditioning set of regressors in a model of deforestation should, under the alternative, include debt variables for all sample observations, the alternative approach to the econometric analysis of the debt-deforestation would focus on testing for differences between constrained and non-unconstrained sub-samples. Equivalently, the alternative hypothesis would be that it is appropriate to include debt variables as conditioning regressors only for the sub-sample of constrained observations. These econometric issues are pursued further in the next chapter which present an empirical analysis of the debt-deforestation hypothesis.

## Appendix

### Comparative Static Results.

This appendix sets out the workings for the conditions used to prove Lemmas 1,2 and 3 in the main text. Comparative static results for variables not discussed in the main text, i.e.  $\alpha$ ,  $\pi$  and  $\gamma$ , are also presented for both borrowing regimes in this Appendix.

#### I. Comparative statics with unconstrained borrowing.

With unconstrained borrowing the first order conditions (5.18) and (5.19) define the equilibrium conditions:

$$\begin{aligned}
 (A5.1) \quad & U_x(\bar{x}^c, \bar{y}^c) - U_y(\bar{x}^c, \bar{y}^c) C_x(\alpha, \pi, \bar{X}) = 0, \\
 & -U_x(\bar{x}^c, \bar{y}^c) + \gamma U_y(\bar{x}^c, \bar{y}^c) = 0, \text{ for } x^e > 0, \\
 & U_x(\bar{x}^c, \bar{y}^c) - \gamma U_y(\bar{x}^c, \bar{y}^c) = 0, \text{ for } -x^e > 0,
 \end{aligned}$$

where a bar over a variable denotes an optimal value and  $x^e > 0$  denotes a net exporter of  $X$  and  $-x^e > 0$  denotes a net importer. Analysis of the comparative static properties of the system of equations in (A5.1) is possible if the second order conditions for a maximum are satisfied. These conditions are satisfied given the concavity of the utility function and the convexity of the cost function. More precisely the second order conditions are satisfied if the Hessian matrix of second order partial derivatives is negative definite at the optimum defined by the first order conditions. Differentiating (A5.1) with respect to  $X$  and  $x^e$  the Hessian matrix in the net exporter case is given by:

$$(A5.2) \quad \mathbf{H} = \begin{bmatrix} \partial^2 \ell / \partial X^2 & \partial^2 \ell / \partial X \partial x^e \\ \partial^2 \ell / \partial x^e \partial X & \partial^2 \ell / \partial (x^e)^2 \end{bmatrix} = \begin{bmatrix} H_{11} & H_{12} \\ H_{21} & H_{22} \end{bmatrix}$$

$$H_{11} = (U_{xx} - U_y C_{xx} - 2U_{xy} C_x + U_{yy} C_x^2)$$

where<sup>41</sup>:

$$H_{12} = H_{21} = (-U_{xx} + (\gamma + C_x)U_{xy} - \gamma C_x U_{yy})$$

$$H_{22} = (U_{xx} - 2U_{xy}\gamma + U_{yy}\gamma^2)$$

The determinant of the Hessian is given by  $|\mathbf{H}| = H_{11}H_{22} - H_{12}^2$  which is positive if the second order conditions are met. Since (A5.1) implies  $C_x = \gamma$ , it is useful to note that it follows  $H_{11} = H_{22} - U_y C_{xx}$  and  $H_{12} = -H_{22}$ . The Hessian determinant can thus be expressed as:

$$(A5.3) \quad |\mathbf{H}| = -U_y C_{xx} H_{22},$$

which is positive as required given  $H_{22} < 0$ . Since the Hessian determinant is non-zero the implicit-function theorem can be applied to obtain the implicit functions:

$$(A5.4) \quad \bar{X} = X(\alpha, \pi, \gamma, D)$$

$$\bar{x}^e = x^e(\alpha, \pi, \gamma, D).$$

It is easy to show that the case of the net importer of X similarly satisfies the implicit function theorem. In this case  $H_{12} = H_{21} = (U_{xx} - (\gamma + C_x)U_{xy} + \gamma C_x U_{yy})$  and  $H_{12} = H_{22}$ . Note however that this still implies  $|\mathbf{H}| = -U_y C_{xx} H_{22} > 0$ .

### *ii. Proof of Lemma 1.*

Totally differentiating (A5.1) with respect to D whilst bearing in mind the implicit solutions (A5.4), noting the definitions of  $\bar{x}^e$  and  $\bar{y}^e$  imply

---

<sup>41</sup>Symmetry of the cross-partial derivatives is used in all derivations.

$\partial \bar{x}^e / \partial D = \partial \bar{X} / \partial D - \partial \bar{x}^e / \partial D$  and  $\partial \bar{y}^e / \partial D = -\partial h / \partial D + \gamma \partial \bar{x}^e / \partial D - C_X \partial \bar{X} / \partial D$  and then dividing the result by  $dD$  gives in matrix form:

$$(A5.5) \quad H_X = \begin{bmatrix} H_{11} & H_{12} \\ H_{21} & H_{22} \end{bmatrix} \begin{bmatrix} \partial \bar{X} / \partial D \\ \partial \bar{x}^e / \partial D \end{bmatrix} = \begin{bmatrix} h_D (U_{xy} - U_{yy} C_X) \\ -h_D (U_{xy} - U_{yy} \gamma) \end{bmatrix}$$

where  $h_D$  denotes  $\partial h / \partial D$ .

The effect of a marginal change in inherited debt on equilibrium export is, using Cramer's Rule, given by:

$$(A5.6) \quad \frac{\partial x^e}{\partial D} = \frac{1}{|H|} \begin{vmatrix} H_{11} & h_D (U_{xy} - U_{yy} C_X) \\ H_{21} & -h_D (U_{xy} - U_{yy} \gamma) \end{vmatrix} = \frac{h_D (U_{xy} - U_{yy} \gamma)}{-H_{22}} > 0,$$

where the unconstrained equilibrium condition  $C_X = \gamma$  has been used in the derivation of (A5.6). Thus in an unconstrained borrowing regime net exports of X are increasing in D. Since the case of a net importer can be defined as  $x^e < 0$ , (A5.6) also implies that net imports are decreasing in D.

Applying Cramer's Rule to solve for  $\partial \bar{X} / \partial D$  in (A5.5) gives:

$$(A5.7) \quad \frac{\partial \bar{X}}{\partial D} = \frac{1}{|H|} \begin{vmatrix} h_D (U_{xy} - U_{yy} C_X) & H_{11} \\ -h_D (U_{xy} - U_{yy} \gamma) & H_{22} \end{vmatrix} \\ = \frac{h_D (H_{22} (U_{xy} - U_{yy} C_X) + H_{21} (U_{xy} - U_{yy} \gamma))}{-U_y C_{XX} H_{22}}$$

Using  $C_X = \gamma$  and  $H_{21} = -H_{22}$  which holds with unconstrained borrowing (A5.7) implies  $\partial \bar{X} / \partial D = 0$ . Thus in an unconstrained regime equilibrium production of X is independent of D.  $\square$

*lii. The effect of a change in the output price  $\gamma$  on equilibrium forest conversion.*

Differentiating (5.14) with respect to  $\gamma$  gives:

$$(A5.8) \quad dP/d\gamma = (\partial P/\partial X)\partial X/\partial\gamma,$$

where the sign of this derivative is determined by the sign of  $\partial X/\partial\gamma$  since  $P$  is a normal input. Analogous to the case of the input prices, the marginal effect of a change in  $\gamma$  on equilibrium production of  $X$  can be found by differentiating the unconstrained equilibrium condition. The resulting expression is:

$$(A5.9) \quad \partial\bar{X}/\partial\gamma = 1/C_{xx} > 0,$$

which implies equilibrium forest conversion is increasing in the output price of  $X$ . Moreover this relationship holds irrespective of the trade situation. Thus for net exporters and importers of  $X$  an increase in the world price for this good will lead to increased deforestation. Intuitively, the same marginal change in  $\gamma$  would be expected to increase equilibrium exports in the net exporter case and decrease equilibrium imports in the net importer case. Of interest is the finding that in each of the cases the magnitudes involved with these trade effects imply that domestic consumption of  $X$  falls. Again this is intuitive since the increase in the price of  $X$  should see substitution in consumption towards good  $Y$ . To be more precise about these trade effects, after totally differentiating the system (A5.1) for the net exporter and importer cases with respect to  $\hat{\gamma}$  and using the implicit solutions (A5.4) it can be shown that:

$$(A5.10) \quad \frac{\partial \bar{X}^e}{\partial \gamma} = \frac{1}{C_{xx}} + \left( \frac{U_y + x^e (U_{xy} - \gamma U_{yy})}{(-U_{xx} + 2\gamma U_{xy} - \gamma^2 U_{yy})} \right) > 0,$$

and in the net importer case:

$$(A5.11) \quad \frac{\partial \bar{X}^m}{\partial \gamma} = -\frac{1}{C_{xx}} + \left( \frac{U_y + x^m (U_{xy} - \gamma U_{yy})}{(U_{xx} - 2\gamma U_{xy} + \gamma^2 U_{yy})} \right) < 0.$$

Comparing (A5.10) with (A5.9), the increase in net exports is greater than the increase in production implying a marginal increase in  $\gamma$  leads to a fall in domestic consumption equal to:

$$(A5.12) \quad \frac{\partial \bar{X}^e}{\partial \gamma} = - \left( \frac{U_y + x^e (U_{xy} - \gamma U_{yy})}{(-U_{xx} + 2\gamma U_{xy} - \gamma^2 U_{yy})} \right) < 0.$$

A similar comparison between (A5.11) and (A5.9) reveals that the fall in imports is greater than the additional domestic production which again implies a fall in domestic consumption of X with magnitude:

$$(A5.13) \quad \frac{\partial \bar{X}^m}{\partial \gamma} = \left( \frac{U_y + x^m (U_{xy} - \gamma U_{yy})}{(U_{xx} - 2\gamma U_{xy} + \gamma^2 U_{yy})} \right) < 0.$$

*liii. The effect of change in the input prices  $\alpha$  and  $\pi$  on equilibrium forest conversion.*

The effects of marginal changes in  $\alpha$  and  $\pi$  on equilibrium forest conversion can be found by substituting (A5.4) into (5.14) and differentiating with respect to the input prices. This gives the expressions:

$$(A5.14) \quad d\bar{P}/d\alpha = \partial\bar{P}/\partial\alpha + (\partial\bar{P}/\partial\bar{X})\partial\bar{X}/\partial\alpha,$$

$$(A5.15) \quad d\bar{P}/d\pi = \partial\bar{P}/\partial\pi + (\partial\bar{P}/\partial\bar{X})\partial\bar{X}/\partial\pi.$$

(A5.14) gives the effect that a marginal change in the price of the other input, labour, has for forest conversion. The effect has two components. The term  $\partial P/\partial\alpha$  captures the substitution effect of a change in relative input prices and is necessarily positive. The second term is an output effect which given the normality of P depends on the sign of  $\partial X/\partial\alpha$ . This is easily shown to be negative if labour is also a normal input in the production of X. Differentiating the unconstrained equilibrium condition  $\gamma - C_X = 0$  with respect to  $\alpha$  gives:

$$(A5.16) \quad \partial\bar{X}/\partial\alpha = -C_{X\alpha}/C_{XX} < 0,$$

since by duality  $C_{X\alpha} = \partial L^X/\partial\alpha$  which is positive if  $L^X$  is a normal input. Thus the input and output effects work in opposite directions. An increase in the price of labour inputs leads to substitution towards input P thereby increasing forest conversion for each unit of X which is produced. The output effect arises since a higher price for labour inputs increases the overall marginal cost of producing X which will imply a shift in demand away from X to Y. Reduced demand for X will correspondingly lead to lower demand for forest inputs and therefore reduced deforestation. Consequently, the overall effect of a change in  $\alpha$  is ambiguous.

A change in the price of forest inputs,  $\pi$ , is not however ambiguous. In (A5.15) the own input price effect  $\partial P/\partial\pi$  is necessarily negative, whilst the sign of  $\partial X/\partial\pi$  can be obtained in an analogous manner to (A5.16) giving:

$$(A5.17) \quad \partial\bar{X}/\partial\pi = -C_{X\pi}/C_{XX} = (\partial\bar{P}/\partial\bar{X})/C_{XX} < 0.$$

Assuming  $P$  is a normal input ensures the output effect is, like the substitution effect, negative implying that an increase in the price of forest inputs unambiguously reduces deforestation.

## II. Comparative statics with constrained borrowing.

For  $x^e > 0$  and  $B = B^*$  the first order conditions (5.18), (5.19) and (5.20) define the equilibrium conditions:

$$(A5.19) \quad \begin{aligned} U_x(\bar{x}^c, \bar{y}^c) - U_y(\bar{x}^c, \bar{y}^c) C_x(\alpha, \pi, \bar{X}) &= 0, \\ -U_x(\bar{x}^c, \bar{y}^c) + \gamma U_y(\bar{x}^c, \bar{y}^c) &= 0, \\ B^* - R - h(D) - y^m + \gamma x^e &= 0. \end{aligned}$$

As with unconstrained borrowing the assumptions of a concave utility function and convex cost function ensure satisfaction of the second order conditions for, in the case of a binding credit ceiling, a constrained maximum. This is easily checked by considering the Bordered Hessian matrix which is negative definite if the second order conditions are satisfied. Differentiating (A5.19) with respect to the  $X$ ,  $x^e$  and  $\mu$  gives in matrix form:

$$(A5.20) \quad \bar{H} = \begin{bmatrix} \partial^2 \ell / \partial X^2 & \partial^2 \ell / \partial X \partial x^e & \partial^2 \ell / \partial X \partial \mu \\ \partial^2 \ell / \partial x^e \partial X & \partial^2 \ell / \partial (x^e)^2 & \partial^2 \ell / \partial x^e \partial \mu \\ \partial^2 \ell / \partial \mu \partial X & \partial^2 \ell / \partial \mu \partial x^e & \partial^2 \ell / \partial \mu^2 \end{bmatrix} = \begin{bmatrix} H_{11} & H_{12} & 0 \\ H_{21} & H_{22} & \gamma \\ 0 & \gamma & 0 \end{bmatrix}$$

where the elements  $H_{ij}$  have already been defined by (A5.2). The determinant of the Bordered Hessian is thus:

$$(A5.21) \quad |\bar{H}| = -\gamma^2 H_{11},$$

which is positive as required since  $H_{11} < 0$ . Applying the implicit-function theorem the optimal values of  $X$ ,  $x^e$  and  $\mu$  can be defined by the implicit functions:

$$(A5.22) \quad \begin{aligned} \bar{X} &= X(\alpha, \pi, \gamma, D, B^*) \\ \bar{x}^e &= x^e(\alpha, \pi, \gamma, D, B^*) \\ \bar{\mu} &= \mu(\alpha, \pi, \gamma, D, B^*) \end{aligned}$$

For a net importer it is easy to show that the Bordered Hessian is given by:

$$(A5.23) \quad \bar{H} = \begin{bmatrix} H_{11} & -H_{12} & 0 \\ -H_{21} & H_{22} & -\gamma \\ 0 & -\gamma & 0 \end{bmatrix}$$

with  $|\bar{H}| = -\gamma^2 H_{11} > 0$ .

### *Ili Proof of Lemma 2*

Totally differentiating (A5.19) with respect to  $D$ , using the implicit solutions (A5.22) and then dividing the result by  $dD$  gives in matrix form:

$$(A5.24) \quad \begin{bmatrix} H_{11} & H_{12} & 0 \\ H_{21} & H_{22} & \gamma \\ 0 & \gamma & 0 \end{bmatrix} \begin{bmatrix} \partial \bar{X} / \partial D \\ \partial \bar{x}^e / \partial D \\ \partial \bar{\mu} / \partial D \end{bmatrix} = \begin{bmatrix} h_D (U_{xy} - U_{yy} C_x) \\ -h_D (U_{xy} - U_{yy} \gamma) \\ h_D \end{bmatrix}$$

Cramer's Rule can be used to show:

$$(A5.25) \quad \frac{\partial \bar{X}}{\partial D} = \frac{1}{|\bar{H}|} \begin{vmatrix} h_D(U_{xy} - U_{yy}C_X) & H_{12} & 0 \\ -h_D(U_{xy} - U_{yy}\gamma) & H_{22} & \gamma \\ h_D & \gamma & 0 \end{vmatrix} \\ = \frac{-\gamma(U_{xx} - C_X U_{xy})h_D}{|\bar{H}|} = \frac{+ve}{+ve} > 0.$$

In the net importer case the change in equilibrium production is identical to (A5.25). Repeating the above steps with the assumption  $x^m = -x^e > 0$  gives:

$$(A5.26) \quad \frac{\partial \bar{X}}{\partial D} = \frac{1}{|\bar{H}|} \begin{vmatrix} h_D(U_{xy} - U_{yy}C_X) & -H_{12} & 0 \\ +h_D(U_{xy} - U_{yy}\gamma) & H_{22} & -\gamma \\ h_D & -\gamma & 0 \end{vmatrix} \\ = \frac{-\gamma(U_{xx} - C_X U_{xy})h_D}{|\bar{H}|} = \frac{+ve}{+ve} > 0.$$

Hence in a constrained borrowing regime equilibrium production of X is increasing in D. ■

The trade effects of a marginal change in D for the net exporter and net importer are given respectively by:

$$(A5.27) \quad \frac{\partial \bar{x}^e}{\partial D} = \frac{1}{|\bar{H}|} \begin{vmatrix} H_{11} & h_D(U_{xy} - U_{yy}C_X) & 0 \\ H_{21} & -h_D(U_{xy} - U_{yy}\gamma) & \gamma \\ 0 & h_D & 0 \end{vmatrix} = \frac{h_D}{\gamma} > 0,$$

$$(A5.28) \quad \frac{\partial \bar{x}^m}{\partial D} = \frac{1}{|\bar{H}|} \begin{vmatrix} H_{11} & h_D(U_{xy} - U_{yy}C_X) & 0 \\ -H_{21} & +h_D(U_{xy} - U_{yy}\gamma) & -\gamma \\ 0 & h_D & 0 \end{vmatrix} = -\frac{h_D}{\gamma} < 0.$$

Two points can be made with respect to these trade effects. Firstly, in both cases they are larger in absolute terms than the magnitude of the marginal change in

production. It is sufficient for the argument to illustrate this with the net exporter case. (5.25) can be equivalently written as:

$$(A5.29) \quad \frac{\partial \bar{X}}{\partial D} = \frac{h_D \phi_1}{\gamma(\phi_1 - \phi_2)} = \frac{\partial \bar{X}^e}{\partial D} \left( \frac{\phi_1}{\phi_1 - \phi_2} \right),$$

where  $\phi_1 = U_{xx} - C_x U_{xy} < 0$  and  $\phi_2 = (C_x U_{xy} - U_{yy} C_x^2 + U_y C_{xx}) > 0$ . Given the signs on  $\phi_1$  and  $\phi_2$  the term  $\phi_1/(\phi_1 - \phi_2)$  must be less than 1 which implies the equilibrium change in production is less than the equilibrium change in the level of X traded. In other words, a marginal increase in the stock of inherited debt also leads to a decrease in the domestic consumption of X. The second point concerns the relative size of the trade effects in constrained and unconstrained borrowing regimes. Again using the net exporter case to illustrate, the marginal effect on trade of a change in D for the unconstrained case (see A5.6) can equivalently be written as:

$$(A5.30) \quad \left( \frac{\partial \bar{X}^e}{\partial D} \right)_u = \frac{h_D}{\gamma} \left( \frac{\theta_1}{\theta_1 + \theta_2} \right) = \left( \frac{\partial \bar{X}^e}{\partial D} \right)_c \left( \frac{\theta_1}{\theta_1 + \theta_2} \right),$$

where  $\theta_1$  defines  $U_{xy} - U_{yy}\gamma > 0$  and  $\theta_2$  defines  $U_{xy} - U_{xx}/\gamma > 0$ . The signs on  $\theta_1$  and  $\theta_2$  indicate the term  $\theta_1/(\theta_1 + \theta_2)$  is positive and less than 1. Thus (A5.30) supports the intuitive idea that the trade effect of a change in D is larger in a constrained borrowing regime.

### *Ilii. Proof of Lemma 3*

Totally differentiating (A5.19) with respect to  $B^*$  and dividing through by  $dB^*$  gives in matrix form:

$$(A5.31) \quad \begin{bmatrix} H_{11} & H_{12} & 0 \\ H_{21} & H_{22} & \gamma \\ 0 & \gamma & 0 \end{bmatrix} \begin{bmatrix} \partial \bar{X} / \partial B^* \\ \partial \bar{X}^e / \partial B^* \\ \partial \bar{\mu} / \partial B^* \end{bmatrix} = \begin{bmatrix} -U_{xy} + U_{yy} C_x \\ U_{xy} - U_{yy} \gamma \\ -1 \end{bmatrix}$$

The expressions given in the main text for  $\partial \bar{X} / \partial B^*$  and  $\partial \bar{X}^e / \partial B^*$  are derived using Cramer's Rule.

$$(A5.32) \quad \frac{\partial \bar{X}}{\partial B^*} = \frac{1}{|\bar{H}|} \begin{vmatrix} -U_{xy} + U_{yy} C_x & H_{12} & 0 \\ U_{xy} - U_{yy} \gamma & H_{22} & \gamma \\ -1 & \gamma & 0 \end{vmatrix}$$

$$= \frac{\gamma(U_{xx} - C_x U_{xy})}{|\bar{H}|} = \frac{-ve}{+ve} < 0.$$

$$(A5.33) \quad \frac{\partial \bar{X}^e}{\partial B^*} = \frac{1}{|\bar{H}|} \begin{vmatrix} H_{11} & -U_{xy} + U_{yy} C_x & 0 \\ H_{21} & U_{xy} - U_{yy} \gamma & \gamma \\ 0 & -1 & 0 \end{vmatrix} = -\frac{1}{\gamma} < 0.$$

(A5.32) and (A5.33) establish that equilibrium production and export of X are both decreasing in the credit ceiling  $B^*$ . ■

For the case of the net importer analogous reasoning to that employed in IIIi for changes in D shows that  $\partial \bar{X} / \partial B^*$  is identical to (A5.32) and  $\partial \bar{X}^m / \partial B^* = 1/\gamma > 0$ . Furthermore the first observation in IIIi about the magnitude of the trade effects are replicated for the case of the credit ceiling. That is:

$$(A5.34) \quad \frac{\partial \bar{X}}{\partial B^*} = -\frac{\phi_1}{\gamma(\phi_1 - \phi_2)} = \frac{\partial \bar{X}^e}{\partial B^*} \left( \frac{\phi_1}{\phi_1 - \phi_2} \right)$$

which implies a fall in the credit ceiling leads to a decrease in domestic consumption of X. Likewise in the net importer case, the fall in imports implied by a decrease in the credit ceiling outweighs the increase in production of X and so domestic consumption of X declines.

IIiii. *The effect of a change in the output price  $\gamma$  on equilibrium forest conversion.*

With unconstrained borrowing it was found that a marginal increase (decrease) in  $\gamma$  would increase (decrease) equilibrium production of X irrespective of the balance of trade in X (i.e. net exporter or importer). In addition the intuition that an increase (decrease) in this price would increase (decrease) exports or decrease (increase) imports was confirmed. By contrast, in a constrained borrowing regime the production and trade responses to a marginal change in  $\gamma$  are notably different. Consider first the effect on equilibrium production of X in the net exporter case. Totally differentiating (A5.19) with respect to  $\gamma$  and dividing the resulting expressions by  $d\gamma$  gives in matrix form:

$$(A5.35) \quad \begin{bmatrix} H_{11} & H_{12} & 0 \\ H_{21} & H_{22} & \gamma \\ 0 & \gamma & 0 \end{bmatrix} \begin{bmatrix} \partial \bar{X} / \partial \gamma \\ \partial \bar{x}^e / \partial \gamma \\ \partial \bar{\mu} / \partial \gamma \end{bmatrix} = \begin{bmatrix} -x^e (U_{xy} - U_{yy} C_x) \\ x^e (U_{xy} - U_{yy} \gamma) - U_y - \mu \\ -x^e \end{bmatrix}$$

Solving for  $\partial \bar{X} / \partial \gamma$  and  $\partial \bar{x}^e / \partial \gamma$  gives:

$$(A5.36) \quad \frac{\partial \bar{X}}{\partial \gamma} = \frac{\gamma x^e (U_{xx} - C_x U_{xy})}{|\bar{H}|} = \frac{-ve}{+ve} < 0,$$

$$(A5.37) \quad \frac{\partial \bar{x}^e}{\partial \gamma} = -\frac{x^e}{\gamma} = \frac{-ve}{+ve} < 0.$$

Equivalent expressions to (A5.36) and (A5.37) for the net importer case are given by:

$$(A5.38) \quad \frac{\partial \bar{X}}{\partial \gamma} = -\frac{\gamma x^m (U_{xx} - C_x U_{xy})}{|\bar{H}|} = \frac{+ve}{+ve} > 0,$$

$$(A5.39) \quad \frac{\partial \bar{x}^m}{\partial \gamma} = -\frac{x^m}{\gamma} = \frac{-ve}{+ve} < 0.$$

Thus in a constrained borrowing regime it is the trade effects which now have the same sign and the production effects which differ for the net exporter and net importer cases. So for a marginal fall in  $\gamma$  production and export increase in a net exporter, whereas the same change faced by a net importer implies increased import and decreased production of X. These latter effects for the case of the net importer are less counter-intuitive than those for the net exporter. A fall in the price of X makes it more attractive to consume, but less so to produce. and since the production effect is a proportion of the trade effect (i.e. (A5.38) and (A5.39) imply  $\partial \bar{X} / \partial \gamma = -(\partial \bar{x}^m / \partial \gamma)(\phi_1 / \phi_1 - \phi_2)$ ) there must be a net increase in domestic consumption. (Conversely, an increase in  $\gamma$  implies a net decrease in domestic consumption). In other words, the demand effect outweighs the supply effect.

The effects for the net exporter are perhaps less obvious. Two factors in combination help explain these results. These are the nature of the balance of payments constraint when credit ceilings bind and the structure of the choice problem. The binding ceiling on B in effect imposes a "target" for the current account since net foreign borrowing is no longer free to balance any level of current account deficit. Moreover, the choice variables available to decision-makers are by construction X and  $x^e$  which become the instruments for achieving this target and crucially, when the ceiling binds the choices over X

and  $x^e$  become constrained choices. This idea is interestingly exactly the "target revenue" explanation suggested by Gilbert (1986, 1989) for the *negative* correlation he found between aggregate developing country debt-servicing levels and primary commodity prices. (See earlier discussion in chapter 4). This negative correlation arose, he suggested, because debt-servicing constraints forced debtors to raise foreign exchange revenue regardless of prevailing relative prices. Thus a fall in primary commodity prices would lead to *increased* export in the attempt to achieve revenue targets. So if a constrained debtor must finance through export the target  $\gamma x^e = T = y^m + R + h(D) - B^*$ , a  $\zeta$  % fall in  $\gamma$  requires a  $\zeta$  % increase in  $x^e$  to ensure foreign exchange revenues are maintained. Note therefore that (A5.37) implies an own price elasticity for exports of - 1. One final point is that as found with previous results the increased export which comes from a fall in  $\gamma$  is divided between changes in production and consumption. Since (A5.36) and (A5.37) combine to give  $\partial \bar{X} / \partial \gamma = -(\partial \bar{x}^m / \partial \gamma)(\phi_1 / \phi_1 - \phi_2)$  domestic consumption of X can be shown to fall as a result of a decrease in  $\gamma$ .

IIiv. *The effect of changes in the input prices  $\alpha$  and  $\pi$  on equilibrium forest conversion.*

With unconstrained borrowing it was noted that the effect of marginal changes in  $\alpha$  and  $\pi$  on equilibrium forest conversion were respectively ambiguous and negative. In the case of constrained borrowing these same findings emerge only if the effect of an input price change on marginal cost is assumed to be large. By duality this equivalently requires the output responsiveness of the input demands to be high. Since the partial effect of changes in the input prices on

equilibrium forest conversion are easily established (see discussion in Iiii. of this Appendix), the overall change in forest conversion from a change in input prices depends on the output effects  $\partial X/\partial\alpha$  and  $\partial X/\partial\pi$ . In the constrained borrowing case these effects can be evaluated from the matrix system of equations:

$$(A5.40) \quad \begin{bmatrix} H_{11} & H_{12} & 0 \\ H_{21} & H_{22} & \gamma \\ 0 & \gamma & 0 \end{bmatrix} \begin{bmatrix} \partial\bar{X}/\partial\psi \\ \partial\bar{x}^e/\partial\psi \\ \partial\bar{\mu}/\partial\psi \end{bmatrix} = \begin{bmatrix} (1-C_\psi)(-U_{xy} + U_{yy}C_X) + U_y C_{X\psi} \\ (1-C_\psi)(U_{xy} - U_{yy}\gamma) \\ 0 \end{bmatrix}$$

where  $\psi$  denotes  $\alpha$  or  $\pi$ .

Solving for  $\partial X/\partial\psi$  ( $\psi = \alpha, \pi$ ) gives:

$$(A5.41) \quad \frac{\partial\bar{X}}{\partial\psi} = \frac{-\gamma^2 c_1}{|\mathbf{H}|} = \frac{c_1}{H_{11}},$$

where  $c_1 = (1-C_\psi)(-U_{xy} + U_{yy}C_X) + U_y C_{X\psi}$ . The expression  $\partial X/\partial\psi$  is negative (as with unconstrained borrowing) if  $c_1$  is shown to be positive. The first part of  $c_1$  will be negative since  $-U_{xy} + U_{yy}C_X < 0$  and  $(1 - C_\psi) > 0$ . Note in particular with the latter that  $C_\psi$  denotes in fact the cost-minimising factor demands (5.13) and (5.14) in section 5.3.2. ;(i.e.  $C_\alpha = L^X$  and  $C_\pi = P$ ). The identities  $P+F=1$  and  $L^X + L^Y + L^P = 1$ , see section 5.3.1, ensure  $(1 - C_\alpha) > 0$  and  $(1 - C_\pi) > 0$ . The second part of  $c_1$  is positive assuming normal inputs since by duality  $C_{X\alpha} = \partial L^X/\partial X$  and  $C_{X\pi} = \partial P/\partial X$ . Assuming these terms to be relatively large  $c_1$  can then be assumed to positive. Additionally these conjectures could reflect decreasing returns to each factor input if a given change in  $X$  is associated with a proportionately greater change in factor inputs. This is worth noting since the first part of  $c_1$  tends to zero as  $L^X$  or  $P$  tends to

one. That is when the greater proportion of the labour force is involved in the production of X and when the majority of forested land has been converted. In both cases it would be reasonable to assume the existence of decreasing returns. For example, where P was a relatively high proportion of total land, any further forest conversion would be of marginally productive land. This has been one of the characteristics of forest clearance in Latin America (Southgate, 1991).

## Chapter 6

### **External indebtedness and the causes of deforestation: an econometric analysis**

#### **6.1 Introduction and Related Literature.**

This chapter presents an econometric analysis of the relationship between external indebtedness and the deforestation of tropical forests in a sample of developing countries. The empirical model and the approach to estimation and testing is guided by the analytical model of deforestation in indebted economies presented in chapter 5.

The hypothesised link between indebtedness and deforestation is the most commonly cited example of a debt-resources link and has been the focus of a small but growing body of empirical research. Perhaps the least rigorous analysis of the hypothesised association between debt and deforestation is presented in George (1992). With a descriptive analysis of the respective rankings of developing country debtors and deforesters she concludes:

- "- Third world countries where significant stands of tropical forests remain also have significant debt burdens, either in absolute terms or relative to size of their economies and to their capacity to pay.
- Third world countries that deforested the most or the fastest in the 1980s were also, on the whole, the largest debtors.
- In a number of smaller countries with less significant forest reserves deforesters were also the most heavily indebted.
- Countries with the highest "debt service ratios" or subject to the highest levels of IMF "conditionality" also tend to be the largest and fastest deforesters." (George, 1992, p 8-9)

Given the nature of the analysis it would be dubious, to say the least, to infer anything conclusive about a debt-deforestation link.<sup>1</sup> The issue has however been subjected to somewhat more rigorous statistical analysis in a number of recent econometric studies which have attempted to establish whether there is in fact the statistical association George seems to have assumed. In general these studies have reached conflicting conclusions.

Evidence rejecting the debt-deforestation link can be found in Capistrano and Kiker (1990, 1995), and Shafik (1994).<sup>2</sup> Capistrano and Kiker, (hereafter C&K), (1990, 1995) present results from an analysis of the influence of international economic conditions on forest depletion over the period 1967-85. The basis for their thesis is that international macroeconomic conditions have been influential in shaping domestic policies towards forest use: "Government policies...are not created in a vacuum" (C&K, 1990, p.4). A cross-section of 45 developing countries was examined over four distinct time periods; 1967-71, 1972-75, 1976-80, 1981-85.<sup>3</sup> Each period was characterised by a set of stylised international economic conditions: 1967-71 as the end years of the Bretton-Woods fixed exchange rate regime; 1972-75 as a period of grain shortages, the oil price hike and increasing external borrowing; 1976-80 as a period of high

---

<sup>1</sup>George clearly believes deforestation and debt to be correlated on the basis of these observations, but no statistical tests of correlation are actually presented. Calculation of Spearman rank correlations using the two sets of data cited by George revealed correlations of 0.53 and 0.486 between the debt and deforestation rankings. The former is significant at the 5% level for a two-tailed test and the latter significant at the 10% level.

<sup>2</sup>A study by Gullison and Losos (1993) is also of note in this context. Their statistical analysis looks at the explanatory power of debt variables in explaining the time-series variance in timber and beef exports for nine different Latin American countries. In this region timber production and cattle-ranching have been commonly cited as factors behind deforestation. They conclude that debt does not influence these export variables, but these conclusions are hampered by sample sizes of only 10 observations

<sup>3</sup>Pooling over the four time periods was also considered by Capistrano and Kiker, but this was deemed inappropriate given evidence of structural change in the estimated parameters.

commodity prices and more oil price increases with the beginnings of world recession in its latter years; 1981-85 a period in which world economic activity was in general depressed with many developing countries experiencing real increases in their debt burdens. The measure of tropical forest depletion adopted by C&K is based on the area of closed broad-leaved forest disturbed by industrial logging.<sup>4</sup> This they argue correlates strongly with the areas of deforestation. However, whilst they correctly argue that logging can be an indicator of the first stages of deforestation, in many countries industrial logging does not significantly contribute to the deforestation process (Burgess, 1992). For example, Brazil is by far the largest deforester in terms of area but industrial logging is generally considered to be relatively unimportant compared to the demand for agricultural land.

In the empirical model estimated by C&K the ratio of external debt servicing to total exports provides the primary measure for the debt burden hypothesised to be positively correlated with forest depletion. This variable is found to be significant only in the 1972-75 period and is *negatively* correlated with forest depletion. The time period may provide an explanation for this finding. International credit particularly towards the mid 1970s was becoming more readily available to developing country borrowers at very low (even negative) real rates of interest. This readily available and cheap source of capital could thus substitute for liquidated forest capital. Intuitively, to the extent that the debt service to export ratio reflects an increased reliance on foreign capital, a negative correlation between debt and forest depletion could be anticipated. More formally, the theoretical model presented in chapter 5 would also predict

---

<sup>4</sup>Closed broad-leaved forests comprise approximately 97 per cent of closed tropical forests.

this effect since it was established that  $\partial \bar{P} / \partial B^* < 0$ , i.e. a relaxation of credit ceilings would imply a fall in equilibrium levels of forest conversion. Moreover, the late 1960s and early 1970s have been identified as a period of constrained international lending (see Eaton and Gersovitz, 1981 and Kharas, 1984) which means the subsequent international lending in the mid 1970s could be interpreted as an increase in credit ceilings. However, of note is the consistently negative coefficient C&K find for the debt-service ratio in all periods, including 1981-85 when debt service burdens were rising sharply.

In addition to the debt-service ratio, C&K also consider a version of their model where international competitiveness (measured by real exchange rate devaluations) is allowed to interact with a dummy variable indicator of the international credit status of countries. This dummy is defined using World Bank debtor classifications taking the value one for highly indebted countries and zero for all others. The hypothesis here is that the effect of real devaluations on forest depletion should be greater for the highly indebted group of debtors where (presumably) the need for scarce foreign exchange is greatest. C&K do not reject the null of no difference in the effect of real devaluations on forest depletion for the highly indebted countries and the rest of the sample.

The main focus in Shafik (1994) is on the relationship between rates of deforestation and per capita income levels. This relationship is often interpreted in terms of a more general question about the link between environmental quality and the level of economic development, the maintained hypothesis being that there exists a Kuznets type (i.e. inverted U) relationship between

environmental quality and levels of economic development.<sup>5</sup> In addition the relationship between deforestation rates and a vector of macroeconomic policy variables, including proxies for indebtedness, is investigated with a fixed effects regression model over the period 1962-86. Overall, Shafik concludes that there is no evidence to suggest that macroeconomic variables, including debt per capita, are significant correlates of deforestation rates based on the failure to reject zero restrictions on these policy variables.<sup>6</sup>

Contrary to the C&K and Shafik studies, evidence of a significant and positive statistical association between deforestation and debt variables can be found in Burgess (1992) and Kahn and McDonald (1990, 1995). In Burgess a linear regression model is used to examine the impact of timber production, agricultural demand, population and government policies on deforestation. In a tacit acceptance of the C&K view that government policies were shaped by international economic conditions, the debt-service ratio is taken to represent the impact of public policy failures on deforestation.<sup>7</sup> For a sample of 54 developing countries Burgess finds the debt-service ratio to be positively signed and statistically significant.<sup>8</sup> The model specification and choice of

---

<sup>5</sup>Kuznets curves are usually associated with the literature on development and income inequality. Another example of the environmental interpretation of Kuznets type curves is Selden and Song (1994) who present an empirical analysis using a quadratic specification of the relationship between environmental quality (in terms of air pollution) and per capita income levels. The model and estimation results outlined below are used to discuss similar propositions in the context of deforestation.

<sup>6</sup>The use of annual deforestation data makes these results suspect since annual series for deforestation are extremely unreliable (see discussion in section 5.2 of the previous chapter).

<sup>7</sup> Repetto and Gillis (1988), Southgate, Sierra and Brown (1991) and Deacon (1994) provide evidence and discussion indicating that some policy failures can be attributed to solely domestic factors, e.g. property right regimes, population pressures. Therefore the use of the debt-service ratio is probably insufficient for capturing the impact of government policies on deforestation.

<sup>8</sup>Burgess runs two regressions, one with African and Asian dummies to account for regional variation and one without. In the former the debt-service ratio is significant at the 10 % level and at the 5% level in the latter.

estimation method in this paper are however questionable, casting doubt therefore on the results. The model includes measures of timber production and agricultural demand (food production per capita) as independent regressors. The theoretical model from chapter 5 would indicate however that these variables should be viewed as endogenous choice variables, which for "problem" debtors are themselves a function of indebtedness. Given this endogeneity, ordinary least squares techniques (as used by Burgess) are inappropriate.<sup>9</sup>

The empirical investigations reported by Kahn and McDonald (1990, 1995) (hereafter K&McD) are, unlike the studies mentioned so far, based on an explicit theoretical model. The economic model linking debt and deforestation outlined by K&McD uses the optimal growth framework applied to an open economy context. An important feature of this model is the assumption of a limit to the extent to which the economy can substitute between current and future consumption. This gives rise to a set of unconstrained and constrained optimality conditions (analogous to those presented in chapters 3 and 5). Solving these conditions for the optimal level of deforestation, they show that only in the constrained case is optimal deforestation a function of the economy's indebtedness with this optimal level increasing in the minimum consumption level and competing uses for output (i.e. investment, government spending and interest payment on debt).<sup>10</sup> A difficulty presented by the K&McD model is the manner in which the constrained and unconstrained

---

<sup>9</sup>Furthermore, no diagnostics tests are reported in the paper. Empirical investigations of the debt-deforestation link undertaken by Economics undergraduates at the University of Edinburgh which have attempted to replicate the Burgess findings tend to reject linear functional forms and homoscedastic errors.

<sup>10</sup>Explicit solutions are made possible by assuming functional forms for an aggregate production function, e.g. one functional form considered is the Cobb-Douglas.

solutions are defined. The distinction depends on a binding lower bound on consumption levels, but as they themselves recognise this bound is not observable. Consequently their empirical model is conditioned on a set of socio-economic indicators (e.g. income level dummies, index of development, population) to control for these lower bounds. Deforestation between 1981-85 is examined in a sample of 55 tropical countries and in just over half of the reported estimations, the debt variable (debt-servicing) is positively signed and statistically significant.<sup>11</sup> K&McD conclude on the basis of these results that the null of no relationship between indebtedness and deforestation can be rejected in favour of the alternative that they are positively correlated.<sup>12</sup>

The inability to identify the consumption lower bound precludes K&McD from testing for differences between constrained and unconstrained countries. The alternative hypothesis therefore states that for *all* (sample) countries debt servicing and deforestation are positively correlated, contrary to the theoretical prediction that the correlation is observed only with constrained countries under the alternative. In the econometric analysis outlined later in this chapter these hypothesised differences are the focus of the estimation and testing. The advantage of the analytical model presented in chapter 5 relative to the K&McD model is that the constrained and unconstrained equilibrium solutions are defined in a way which permits the construction of a qualitative dummy indicator of constrained and unconstrained regimes using approaches which are well established in the international debt literature.<sup>13</sup> These indicators as

---

<sup>11</sup>That is countries lying between the tropics of Cancer and Capricorn.

<sup>12</sup>Their conclusions attach greatest weight to the estimations which exclude choice variables as regressors (i.e. investment and net change in debt) and instrument (with lagged values) a government expenditure variable. In these regressions all debt service variables are positively signed and 3 of 4 are statistically significant at the 5 % for a one-tailed test.

<sup>13</sup>The approaches are similar but not identical to those discussed in Chapter 4.

detailed in Section 6.3.1 utilise information on debt arrears. More generally, the econometric analysis presented in this chapter parallels that of chapter 4 which employed GMM methods. To date, these econometric methods have not been considered in the debt-deforestation literature.<sup>14</sup>

The rest of the chapter is outlined as follows. The next section outlines the empirical model of deforestation. Section 6.3 discusses some issues concerning econometric estimation and testing of the debt-deforestation link. A particular focus is on the appropriate way to test for the hypothesised debt effect. This relies on identifying "problem" (constrained) debtors and "non-problem" (unconstrained) debtors and testing for differences between the two subsamples. The methods used to classify debtor countries are outlined at the end of this section. Section 6.4 discusses the data used in the analysis and presents the empirical results. Section 6.5 concludes.

## **6.2 The Empirical Model.**

The starting point for the empirical model is the expression for equilibrium deforestation derived in chapter 5.

---

<sup>14</sup>One other paper in this literature which only recently came to my attention is an unpublished working paper by Murphy (1994). In this paper a simple two period model of deforestation and external borrowing is outlined to demonstrate the (by now familiar) idea that consumption and resource use (i.e. deforestation) decisions cannot be separated when borrowers face imperfect capital markets. In the empirical investigation Murphy seeks to test the hypothesis that debt and deforestation are correlated for only credit-constrained countries in a sample of 87 developing countries. The findings are supportive of this theoretical proposition with the 1981 debt to export ratio found to be a positive and statistically significant correlate of deforestation in the 1981-85 period for rescheduling debtors. This approach to the debt-deforestation hypothesis echoes the approach taken in this chapter. I am grateful to Prof. Robert Deacon for bringing this paper to my attention.

$$(6.1) \quad \bar{P} = \begin{cases} P(\alpha, \beta, X(\alpha, \beta, \gamma)) & (\text{for } B^* > B) \\ P(\alpha, \beta, X(\alpha, \beta, \gamma, D, B^*)) & (\text{for } B^* = B) \end{cases}$$

In (6.1) deforestation is a function of the endogenously determined vector  $X$ .<sup>15</sup> For the purposes of the econometric analysis (6.1) can be expressed solely in terms of exogenous variables using the solutions for equilibrium  $X$  given in chapter 5. That is:

$$(6.2) \quad \bar{P} = \begin{cases} P(\alpha, \beta, \gamma) & (\text{for } B^* > B) \\ P(\alpha, \beta, \gamma, D, B^*) & (\text{for } B^* = B) \end{cases}$$

(6.2) summarises in general terms the competing model specifications considered in this chapter. In most of the existing empirical literature on the debt-deforestation hypothesis the null specification would be defined by the function  $P(\alpha, \pi, \gamma)$  which competes with the alternative  $P(\alpha, \pi, \gamma, D, B^*)$ . However, as already noted above this "alternative" is hypothesised to hold only for constrained countries. Equivalently, theory suggests the model specification  $P(\alpha, \pi, \gamma)$  holds for unconstrained countries under the null *and* alternative hypotheses, but is rejected under the alternative for those classed as constrained. The econometric tests outlined below are constructed in a way which permits testing of this interpretation of the debt-deforestation hypothesis.

For the purposes of defining the parameterised model it will prove useful to re-define (6.2) in terms of the stock of forests. Recall that land use is constrained by the condition  $P = 1 - F$ , where  $F$  defines land maintained as forest. It is then straightforward to define the equilibrium stock of forests by the function:

---

<sup>15</sup>Note that the unconstrained expression excludes the variable  $D$  (i.e. inherited debt) given the finding in chapter 5 that for the unconstrained case  $X$  (and therefore  $P$ ) is independent of the inherited level of debt.

$$(6.3) \quad \bar{F} = \begin{cases} F(\alpha, \pi, \gamma) & (\text{for } B^* > B) \\ F(\alpha, \pi, \gamma, D, B^*) & (\text{for } B^* = B), \end{cases}$$

where previous signs on partial derivatives are now reversed. Specifically,  $\partial \bar{F} / \partial D < 0$  and  $\partial \bar{F} / \partial B^* > 0$ , i.e. for constrained countries the equilibrium level of forested land is decreasing in inherited stocks of debt and increasing in credit ceiling levels.

Eq. (6.3) defines the level of forest cover entirely in terms of economic variables. A more general model would incorporate environmental factors such as climate, soil conditions and geographical terrain. More precisely, let  $M_{it}$  denote the level of forest *biomass* in country  $i$  at time  $t$ . Following Deacon (1994)  $M_{it}$  can be described by the separable function:

$$(6.4) \quad M_{it} = G(E_i)H(W_{it}),$$

where  $E_i$  is a vector of environmental factors which are assumed constant over time and  $W_{it}$  is a vector of socio-economic variables in levels to be defined below. Defining a model of deforestation in terms of forest biomass presents however an empirical difficulty since available forest resource data typically measures land area which is forested rather than the volume of biomass. Moreover, the unit of measurement which is implicit in the theoretical model summarised by (6.3) is similarly in terms of land area. A simple approach which overcomes this empirical difficulty with (6.4) and ensures consistency with the theoretical model is to assume:

$$(6.5) \quad M_{it} = c_i F_{it},$$

where  $F_{it}$  is forested land area and  $c_i$  is a time invariant measure of biomass per unit of forest area.<sup>16</sup> Using (6.5) the area of forested land can then be defined by:

$$(6.6) \quad F_{it} = [G(E_i)/c_i]H(W_{it}).$$

The model of forest cover (6.6) provides a framework for testing the theoretical propositions of chapter 5 by now assuming that the variables in the vector  $W_{it}$  include empirical measures of  $\alpha$ ,  $\pi$ ,  $\gamma$  and, of primary interest, inherited debt and the credit ceiling  $B^*$ . The assumptions made so far imply that  $c_i$  and  $E_i$  can be treated as country-specific effects which are unchanging over time. Taking the natural logarithm of (6.6) and first differencing then defines:

$$(6.7) \quad D_{it} = \ln(F_{it}) - \ln(F_{it-1}) = \ln[H(W_{it})] - \ln[H(W_{it-1})]$$

$D_{it}$  represents the change in the natural logarithm of forest area between the periods  $t$  and  $t-1$  and therefore defines the rate of change in forest cover. In the empirical models considered below the dependent variable is specified as the *absolute* rate of change in forest cover, i.e. the rate of deforestation. Note therefore that the expected signs on the relationships between  $D_{it}$  and the variables of interest are restored to the sign of the comparative static results from chapter 5. In addition, given that these theoretical propositions have been derived within a static model the empirical model is assumed to hold over the longer run and the empirical investigation focuses on the cross-sectional dimension of (6.7). The econometric analysis reflects this feature of the theoretical model with the use of a quinquennial rather than annual model.

---

<sup>16</sup>This assumption will imply a quantitative definition of deforestation. Recall the discussion in section 2 of chapter 5.

Thus for example the rate of deforestation over the period 1981-85 is defined by the absolute value of  $\ln(F_{i85}) - \ln(F_{i80})$ .<sup>17</sup>

An econometric model can be obtained from (6.7) by choosing a functional form for the function  $\ln H(W_{it})$ . A general functional form can be obtained with a second order Taylor series expansion of  $\ln H(W_{it})$  about the point  $\ln W = 0$ . This gives the approximation:<sup>18</sup>

$$(6.8) \ln H_{it} \approx \theta_0 + \sum_k \left( \frac{\partial \ln H}{\partial \ln w_k} \right)_t \ln w_{kt} + 0.5 \sum_k \sum_m \left( \frac{\partial^2 \ln H}{\partial \ln w_k \partial \ln w_m} \right) \ln w_{kt} \ln w_{mt},$$

with all derivatives evaluated at  $\ln W_{it} = 0$ . Imposing symmetry on the cross-partial derivatives and defining the derivatives in (6.8) as parameters, the model of deforestation (6.7) can now be specified as the econometric model:

$$(6.9) \quad D_{it} = \left[ \theta_{0t} + \sum_k \theta_{kt} \ln w_{k,it} + 0.5 \sum_k \sum_m \delta_{kmt} \ln w_{k,it} \ln w_{m,it} \right] - \left[ \theta_{0,t-1} + \sum_k \theta_{k,t-1} \ln w_{k,i,t-1} + 0.5 \sum_k \sum_m \delta_{km,t-1} \ln w_{k,i,t-1} \ln w_{m,i,t-1} \right] + \varepsilon_{it},$$

where  $\varepsilon_{it}$  accounts for random influences on deforestation satisfying  $E(\varepsilon) = 0$  and a variance-covariance matrix defined by  $E(\varepsilon\varepsilon') = \Omega$ . If the slope parameters

<sup>17</sup>The use of this approach also reflects the available data on deforestation. Note that dividing by five would provide the average annual rate of deforestation. However since the number of periods in the model would simply re-scale the dependent and explanatory variables by the same constant, no gain is achieved by expressing the model in terms of average annual values. Additionally, as noted in chapter 5, measurement methodologies have changed over time. The econometric analysis presented below is based on data from the 1990 FAO Assessment which has where possible also revised data from earlier assessments (e.g. 1980) in line with new methods of measurement, see FAO (1990), FAO (1993).

<sup>18</sup>This is of course the transcendental logarithmic, i.e. translog, functional form which has the properties of nesting other functional forms, e.g. Cobb-Douglas, and providing a second order approximation to any arbitrary function. This functional form has been employed extensively in econometric analysis.

in (6.9) satisfy the restriction of constancy over time then the econometric model is equivalently:

$$(6.10) \quad D_{it} = \phi + \sum_k \theta_k (\ln w_{k,it} - \ln w_{k,it-1}) + 0.5 \sum_k \delta_k \left( (\ln w_{k,it})^2 - (\ln w_{k,it-1})^2 \right) + 0.5 \sum_k \sum_m \delta_{km} (\ln w_{k,it} \ln w_{m,it} - \ln w_{k,it-1} \ln w_{m,it-1}) + \varepsilon_{it},$$

where  $\phi = \theta_{0t} - \theta_{0t-1}$  defines an intercept term. (6.10) expresses the rate of deforestation as a linear function of the rates of change in the explanatory variables, for  $k = m$  the rate of change in quadratic terms and for  $k \neq m$  the rate of change in their interactions. In the empirical analysis these parameter restrictions are tested and cannot be rejected (see empirical results reported in 6.4.2). The presence of interactions between the variables in the vector  $W_{it}$  moreover allows for potential non-linearities (in variables) which have not been investigated to any real extent in previous debt-deforestation literature.<sup>19</sup> In particular the inclusion of quadratic terms allows for tests of Kuznets type relationships between deforestation and the explanatory variables in  $W$ .

### 6.3 Econometric Estimation and Testing.

The idea that financial pressures or borrowing constraints may influence the behaviour of economic agents has been investigated in other contexts. A notable example of this has been the empirical literature on optimal investment decisions made by firms where there is the possibility of financial / borrowing

---

<sup>19</sup>Panayotou and Sungsuwan (1994) do however estimate a translog model with provincial level data in an econometric analysis of deforestation in Thailand but can not reject the nested Cobb Douglas specification. Murphy (1994) also investigates and rejects a quadratic debt term in his debt-deforestation analysis.

constraints (see for example Whited, 1992; Bond and Meghir, 1994). The distinction made in this literature is that for firms who do not face financial constraints optimal investment behaviour should satisfy the appropriate investment Euler equation. This can be defined as the null specification for the firm investment model. For firms who *are* faced with financial constraints then the null Euler equation should be violated as optimal investment behaviour is now also a function of these constraints. Thus recalling the earlier discussion in chapter 4, if  $\Lambda$  defines a vector of instruments which correlate with the financial constraints, then it is expected that for financially constrained firms:

$$(6.11) \quad E(\Lambda'\varepsilon) \neq 0,$$

where  $\varepsilon$  defines the error term in the null specification of the econometric model. In other words the null error term is not orthogonal to  $\Lambda$  indicating that the null model is mis-specified. This focus on the orthogonality between the error in the econometric model and the sets of instruments used in estimation is central to the Generalised Method of Moments (GMM) approach to estimation and testing which has been widely employed in the Euler equation literature.<sup>20</sup>

The key point from this brief résumé of ideas already presented in chapters 3 and 4 is that testing for the presence of financially constrained choices using GMM techniques relies on testing for differences in behaviour between unconstrained and constrained agents. The theoretical model of deforestation presented in chapter 5 suggests that the role of indebtedness can also be investigated by testing for differences between constrained and unconstrained

---

<sup>20</sup>The error in the econometric model is usually assumed to arise from rational expectations forecast error in these models. Thus by the assumption of rational expectations it is expected that any forecast error is orthogonal to the information set used by agents.

countries. For example, the hypotheses of primary interest state that for unconstrained countries deforestation is independent of debt and credit ceilings, whereas this orthogonality is violated for constrained countries. Testing these propositions is thus equivalent to testing a null specification in which zero restrictions on debt related variables are valid for unconstrained countries *and* no differences are observed between unconstrained and constrained countries.<sup>21</sup> In the context of GMM estimation this can be interpreted as testing the validity of extra over identifying restrictions which arise from a specification where it is assumed that deforestation is orthogonal to variables correlated with constrained borrowing regimes or "problem" indebtedness. That is, the null specification is defined by the condition that deforestation is orthogonal to debt and credit ceilings.

Suppose initially therefore that in (6.10) the vector of explanatory variables excludes variables correlated with constrained borrowing regimes. That is the vector  $W_{it}$  is restricted to empirical proxies for  $\alpha$ ,  $\pi$  and  $\gamma$ . For notational ease, hereafter  $f(W_{it}, W_{it-1})$  denotes the translog specification of the explanatory variables and  $\beta$  defines the vector of slope parameters. In addition, the vector of debt related variables (i.e. empirical measures of inherited debt and credit ceilings) is denoted by  $\Lambda$ . A more succinct way of writing the null specification of (6.10) for time period  $t$  is thus:<sup>22</sup>

$$(6.12) \quad D_i = \phi + f(W_{it}, W_{it-1})\beta + \varepsilon_i \quad i = 1, \dots, N$$

<sup>21</sup>The latter of course implies that the same zero restrictions are valid for constrained countries.

<sup>22</sup>It is worth emphasising at this point that the econometric analysis considers only cross-sectional relationships. Accordingly, any reference to time periods or time-subscripts is used to discriminate between different cross-sections.

Identification of the parameter vector  $\beta$  in the GMM methodology relies on the conditional moment restrictions  $E(\varepsilon_i | I_i) = 0$ , where  $I_i$  defines in this context the information set for observation  $i$ . For any row vector of observations  $z_i \in I_i$ , with dimension  $q$  these conditional moments can be re-written as the  $q$  unconditional moments:

$$(6.13) \quad E\left(z_i' \left\{ D_i - \phi - f(W_{it}, W_{it-1})' \beta \right\}\right) = 0.$$

A GMM estimator of the parameters in (6.12) is then obtained from the sample counterparts to (6.13). That is:

$$(6.14) \quad \frac{1}{N} \sum_{i=1}^n z_i' (D_i - \phi - f(W_{it}, W_{it-1})' \beta) = \frac{1}{N} Z' \varepsilon = 0$$

where  $Z = (z_1', \dots, z_n')$  is a  $n \times q$  matrix of instruments and  $\varepsilon$  is a  $n$ -vector with typical element  $\varepsilon_i = D_i - \phi - f(W_{it}, W_{it-1})' \beta$ .

If the parameter vector  $\beta$  is allowed to vary between the cross-sections  $t$  and  $t-1$  then there are  $2p$  parameters to be estimated where  $p$  refers to the dimension of the vector  $W_i$ .<sup>23</sup> Accordingly, if the instrument vector  $z_i$  is defined by  $(f(W_{it}), f(W_{it-1}))$  then there are  $q = 2p$  sample moments available to identify the  $2p$  parameters in the null specification (6.12). In other words the null model is exactly identified. If the restrictions  $\beta_t = \beta_{t-1}$  are imposed then only  $p$  parameters need to be estimated, in which case the model is over identified with the number of over identifying restrictions also equal to  $p$ . With  $2p$  moment conditions to solve for only  $p$  parameters, the sample moments in (6.14) can be used to define a criterion function which is minimised to obtain

<sup>23</sup>There are of course in total  $2p+1$  parameters if the intercept is included. The discussion focuses on the slope coefficients since it is with these parameters that the over identifying restriction used in the GMM estimation arise.

GMM estimates. Hansen (1982) has shown efficient GMM estimates are obtained by minimising the quadratic form:

$$(6.15) \quad \varepsilon'Z(Z'\Omega Z)^{-1}Z'\varepsilon,$$

where  $Z'\Omega Z$  is the asymptotic variance-covariance matrix of the empirical moments.<sup>24</sup> Recall that  $\Omega$  is defined as  $E(\varepsilon\varepsilon')$ . If it is assumed that the variance-covariance matrix of the errors satisfies  $\Omega = \sigma^2 I_n$  where  $I_n$  is a  $n \times n$  identity matrix then the minimisation of (6.15) uses  $Z'\Omega Z = Z'Z$ . If this is relaxed to allow for, say, conditional heteroskedasticity of an unknown form then a consistent estimator for  $Z'\Omega Z$  following White (1980) is used in the minimisation of (6.15).<sup>25</sup>

Two approaches can be used to test the debt-deforestation hypothesis within the GMM framework outlined above. The first approach involves testing for mis-specifications in the null model (6.12). More specifically, this approach tests the validity of extra over-identifying restrictions which arise from excluding debt related variables as explanatory variables, but including them as instruments. In terms of sample moments this implies the extra restrictions:

$$(6.16) \quad \frac{1}{N} \sum_{i=1}^N \Lambda_i' \varepsilon_i = \frac{1}{N} \Lambda' \varepsilon = 0,$$

where  $\Lambda_i = (\Lambda_{it} \ \Lambda_{it-1})$  is a  $1 \times r$  vector containing observations on variables correlated with inherited debt and credit ceilings.<sup>26</sup> A total of  $p + r$  over

<sup>24</sup>The scaling factors  $1/n$  for the empirical moments and  $1/n^2$  for the variance-covariance matrix of the moments cancel out to give (6.15).

<sup>25</sup>White's estimator of  $Z'\Omega Z$  in this context would be given by  $\sum_{i=1}^n \hat{\varepsilon}_i^2 z_i' z_i$  where  $\hat{\varepsilon}_i$  is an initial consistent estimate of  $\varepsilon_i$ . These initial estimates are usually obtained by setting  $\Omega = I_n$ .

<sup>26</sup>Note that in  $\Lambda$  the debt instruments may be, but not necessarily, specified in the same way as  $f(W)$ . It is easier to think them as being specified in a similar manner to  $W$ , particularly when the exclusion of debt related variables from the set of explanatory variables is relaxed.

identifying restrictions are then implied when the instruments  $z_i = (W_i \Lambda_i)$  are employed in the estimation of  $\beta$  in (6.12). The validity of these restrictions can then be tested with Hansen's test of over-identifying restrictions (see Hansen, 1982). This  $\chi^2$  test statistic is simply the minimised value of the GMM criterion (6.15) with  $p + r$  degrees of freedom.<sup>27</sup> However this general test for mis-specification is testing the validity of all  $p + r$  moment restrictions. Testing for mis-specifications in the null model arising from the use of debt related instruments should really focus on the validity of the set of  $r$  moment restrictions defined by (6.16). A further point is that the empirical proposition under investigation states the null that the restrictions in (6.16) are true for both unconstrained and constrained observations, whilst under the alternative they remain valid for unconstrained, but not constrained observations. One way of testing for this type of mis-specification is to partition the vector of moment conditions defined in (6.16) and test for, in the terms of Newey (1985), mis-specification which given a priori information can be restricted to a subset of "contaminated" instruments. In the present context it is maintained a priori that for constrained observations debt related instruments are "contaminated" in the sense of exhibiting covariance with the error term under the alternative. Thus, if  $u$  denotes unconstrained and  $c$  constrained the matrix of debt-related instruments  $\Lambda$  can be partitioned as  $(\Lambda_u \Lambda_c)$ . The instrument matrix  $Z = (W_1 \dots W_t \Lambda)$  can itself then be partitioned as  $(Z_1 \ Z_2)$  where  $Z_2 = \Lambda_c$ . Under the alternative therefore the mis-specification takes the form:<sup>28</sup>

<sup>27</sup>In Hansen (1982) this statistic is actually defined as  $N$  times the minimised criterion. This arises because Hansen defines the GMM criterion as  $(N^{-1}\hat{\varepsilon}'Z)\Phi^{-1}(N^{-1}Z'\hat{\varepsilon})$  where  $\Phi = N^{-1}Z'\hat{\varepsilon}\hat{\varepsilon}'Z$  is a consistent estimate of the asymptotic covariance matrix of the empirical moments. Multiplying the criterion by  $N$  offsets the use of  $N^{-1}$  rather than  $N^{-2}$  with  $\Phi$ . Use of (6.15) is numerically equivalent.

<sup>28</sup>Note here that it is being assumed that the  $p$  over-identifying restrictions which arise from parameter constancy are valid.

$$(6.17) \quad E(Z_1'\varepsilon) = 0 \text{ and } E(Z_2'\varepsilon) = c.$$

Following Newey (1985) a GMM test statistic for mis-specifications of this nature in linear models can be computed as:<sup>29</sup>

$$(6.18) \quad m_T = \hat{\varepsilon}'R \left[ R'\hat{\Omega}R - R'\tilde{Z}(\tilde{Z}'\hat{\Omega}\tilde{Z})^{-1}\tilde{Z}'R \right]^{-1} R'\hat{\varepsilon} \sim \chi^2(r_c),$$

where  $\hat{\varepsilon}$  is a vector of GMM residuals obtained under the null,  $R$  is a  $n \times r_c$  matrix defined by  $(I_n - Z_1(Z_1'Z_1)^{-1}Z_1')Z_2$  and  $\tilde{Z} = Z'(Z'Z)^{-1}Z'X$  with  $X$  containing the set of regressors for the null model.<sup>30</sup>

This first approach to testing the debt-deforestation hypothesis focuses on a null specification which maintains deforestation to be orthogonal to debt related variables for all observations. A rejection of the null specification based on the specification tests noted above would suggest that the conditioning set of regressors for constrained countries should include debt-related variables. A second approach to testing would therefore interpret the moment restrictions in (6.16) as akin to zero restrictions on the parameters which capture the influence of debt related variables on deforestation. GMM versions of the classical Lagrange Multiplier, Wald and Likelihood ratio hypothesis tests of zero restrictions on parameters have been presented in Newey and West (1987b) and are employed in the second approach to econometric testing of the debt-deforestation hypothesis. This can be summarised in terms of the model:

<sup>29</sup>That is, linear in parameters. Note also that this is an alternative to the Hausman type test for the validity of a subset of the vector of moment restrictions which was discussed in Chapter 4.

<sup>30</sup>Note that  $r_c$  is the number of columns in  $Z_2$ .

$$(6.19) \quad D_i = \phi + f(W_{it}, W_{it-1})\beta + g(\Lambda_{it}, \Lambda_{it-1})\psi + \Gamma^c g(\Lambda_{it}, \Lambda_{it-1})\psi^c + \varepsilon_i$$

where  $\Gamma^c$  is a dummy indicator of constrained countries (to be defined explicitly below) and the restriction  $\psi^c = 0$ , if satisfied suggest no differences are observed between constrained and unconstrained countries. In terms of the null hypothesis suggested by the theoretical model from chapter 5 this restriction could be more fully specified as  $\psi^c = \psi = 0$ .

### 6.3.1 Constrained vs unconstrained regimes

The preceding discussion has outlined an approach to the econometric testing of the debt-deforestation hypothesis which tests for the violation of the assumption of orthogonality between debt-related variables and the null model error for constrained (country) observations. A prerequisite for the implementation of this approach to econometric testing is a method for discriminating constrained from unconstrained observations. Until now the distinction between these two country types has depended upon an unobservable binding credit ceiling. The difficulty presented by specifying the hypotheses in these terms, as suggested above, is resolved by defining the dummy variable  $\Gamma^c$  which is an indicator of binding credit constraints. This dummy indicator is defined using established approaches in the international debt literature (see for example McFadden et al., 1985; Hajivassiliou, 1987). The starting point for the approach is to observe that in international lending the actual (i.e. traded) supply of new loans is either the notional demands of borrowers or the constrained supply permitted by lenders.<sup>31</sup> Crucially, the

---

<sup>31</sup>This is based on the idea that international capital markets are non-walrasian, i.e. quantity rather than price is more prevalent in the determination of equilibrium trades because of risks arising from imperfect information about the creditworthiness of borrowers and default risks

observed level will be the minimum of these two possible determinants. If  $B^d$  denotes the notional demand from the borrower then  $B = \min \{B^d, B^*\}$ . Thus if a borrower is constrained then their notional demand (determined by the current account) must be greater than the actual supply of new loans.

This situation, as noted by, Hajivassiliou (1987) corresponds to a regime of "moderate excess demand". The question is how this "moderate excess demand" is manifested in an observable manner. One indicator which has been identified is the accumulation of debt arrears. The intuition for this is straightforward. In any given period a debtor must balance its international payments; any deficit on the current account must be matched by the required capital inflow. If this inflow is constrained by credit ceilings then debtor countries will draw upon "involuntary" loans by allowing debt servicing obligations to fall in arrears. This idea can be related to the balance of payments with the expression:

$$(6.20) \quad B^d = R + h(D) + y^m - \gamma x^e + \Delta A = B + \Delta A,$$

where  $\Delta A$  denotes the change in arrears,  $R+h(D)$  is debt-servicing and  $y^m - \gamma x^e$  is the trade balance.<sup>32</sup> If  $B=B^d$  then clearly  $\Delta A=0$ , but if  $B=B^*$  then  $B<B^d$ . For (6.20) to hold with equality when lending constraints bind it is therefore required that  $\Delta A > 0$ .<sup>33</sup> Thus the dummy indicator of binding constraints can be based on:  $\Gamma^c = 1$  if  $\Delta A > 0$ ;  $\Gamma^c = 0$  if  $\Delta A \leq 0$

---

which are a feature of sovereign lending. For more detailed analysis on these general issues see Eaton (1993) and Eaton and Gersovitz (1981).

<sup>32</sup> This modifies the balance of payments expression used in Chapter 5. See also similar reasoning employed in Chapter 4.

<sup>33</sup>The illustration is obviously simplistic in the sense that currency reserves have been ignored in the expression for the balance of payments. If included it could be argued that the change in reserves would meet any shortfall in international liquidity or indeed the current account would adjust. As noted previously in Chapter 4, Hajivassiliou assumes the (political) cost of

## 6.4 Data and empirical results

### 6.4.1 Data

In the empirical investigation the debt-deforestation hypothesis is examined for the periods 1981-85 and 1986-90. The dependent variable in each model is defined as the change in the natural logarithm of forest cover which is approximate to the rate of deforestation. The data on forest cover used to define the dependent variable was obtained from World Resources Institute (1994) which itself summarises data available from the 1990 Forest Resources Assessment published in FAO (1993) and data for forest cover in temperate zones published in UNECE / FAO (1993). Table VI.1 presents summary statistics for deforestation in the full sample and unconstrained / constrained sub-samples. For the full sample of 55 countries mean deforestation shows a slight increase over 1986-90 compared to 1981-85. More notable is the spread around the 1986-90 mean which is associated with a standard deviation of 0.1358 compared to a figure of 0.0647 in the previous five year period. Comparing the two sub-samples, in the 1981-85 period the difference in means is relatively small. In the 1986-90 period mean deforestation is higher in constrained countries. Moreover there is greater cross-sectional variability in deforestation for this group. One final observation from Table VI.1 is the relative size of the sub-samples. In the 1981-85 period the arrears indicator

---

deviating from targets for current account and foreign currency reserves are such that the regime of moderate excess demand is characterised by arrears accumulation. One further point is that current account adjustments would require changes to production and consumption plans which are likely to involve lags, whereas arrears accumulation is the immediate result of a non-action.

classifies 67 % of the observations as constrained. This figure rises to 73% of sample observations in the period 1986-90.

**Table VI.1**  
*Deforestation in Sample Countries: Summary Statistics*

Period	1981-85			1986-90		
	mean	std. dev	N	mean	std. dev	N
Full Sample	0.0646	0.0647	55	0.0725	0.1358	55
Unconstrained	0.0664	0.0616	18	0.0513	0.0926	15
Constrained	0.0637	0.0671	37	0.0804	0.1491	40

*Notes:*

1. *Deforestation is defined at the rate of change in total forest area between 1981-85 and 1986-90. Data source on forest area is World Resources Institute (1994).*
2. *The Unconstrained and Constrained sub-samples are classified respectively by Debt arrears. Data source for debt arrears is World Debt Tables 1993-94.*

The vector of explanatory variables for the empirical model would ideally include measures for  $\alpha$  and  $\pi$  which recall represent the unit opportunity costs to the economy of labour and forest inputs used in the production of good X. Obvious aggregate measures for these variables are however typically unavailable in the developing country context. In most econometric analyses of the causes of deforestation it has been practice to include income and population variables as regressors, e.g. real per capita income and population growth or density (see Allen and Barnes, 1985; Southgate, 1991, and Deacon, 1994). To the extent that cross-sectional variation in  $\alpha$  and  $\pi$  will reflect differences in technology, the structure of the labour force and more generally levels of economic development, income and population variables may be adequate proxies.

In some deforestation studies measures of infrastructural development have also been considered as explanatory variables. For example the extent of the road network may be positively associated with deforestation since a more extensive transport network may imply easier access to areas of virgin forest and lower costs in bringing commodities to the marketplace (see Southgate, Sierra and Brown 1991 and Panayotou and Sungsuwan, 1994). Again this type of consideration could be broadly viewed as a technological / level of economic development factor which may influence differentially the marginal productivity of inputs across countries. It may be difficult, however, to disentangle the cross-sectional variation in infrastructural development from that of the general level of development as proxied by income levels.

Consequently empirical proxies for what might be termed domestic influences on deforestation are restricted in this analysis to population and income measures. One other domestic factor which it could be argued is a determinant of cross-sectional variation in deforestation is the nature of property right regimes for forested land. The difficulty here is the lack of obvious measures of property right regimes at the aggregate level. Deacon (1994) uses political measures such as military governments, civil unrest and constitutional changes to proxy situations of ownership insecurity, whilst at a more disaggregated level, Southgate, Sierra and Brown (1991) incorporate the effect of insecure land tenure on deforestation within Ecuador. Such considerations are however omitted from the present analysis, though it might be argued that where systems of land tenure are responsible for population movements into areas of virgin forest some measure of population pressure in rural areas may capture some aspect of the institutional reality governing land use decisions. To reflect

this the population measure used in the empirical analysis is defined as rural population in millions (RPOP) which was estimated using information on total population and urban population obtained from the World Bank's *Socio-Economic Indicators 1990-91*. A further motivation for this choice of population variable is that changes in rural population rather than total population would reasonably be expected to be more closely related to land use changes at the agricultural frontier. The income variable (RY) is defined as the level of real gross national product per capita and is denominated in U.S. dollars (1987 prices).

In the case of the unconstrained equilibrium the other predicted explanatory variable was the given world price of good X,  $\gamma$ . Assuming this price to be denominated in U.S. dollars there are two relevant dimensions to the relationship between deforestation and dollar prices. The first is that changes in dollar prices have consequences for deforestation through the output effects derived in chapter 5. The second consideration is that changes in the *value* of the dollar may also have consequences for deforestation, again through the output effect of these changes. Thus for example a real depreciation of local currency relative to the dollar would be anticipated to encourage the allocation of factor inputs to the production of traded commodities implying for countries with comparative advantage in X increased forest clearance. To allow for this distinction between dollar prices and the domestic currency value of goods traded in dollars the empirical model includes a price variable and an exchange rate variable. The price measures used are the dollar unit value indices of agricultural (AP) and timber exports (TP) available in *FAO* data sources. The exchange rate variable is defined as a real exchange rate index with base

1987=100. A common proxy for this real exchange rate is the definition (see Edwards, 1988):

$$(6.21) \quad q = \frac{P^S}{P^{\text{Dom}}} \cdot e,$$

where  $e$  is the nominal bilateral exchange rate with the U.S. dollar,  $P^S$  is the U.S. wholesale price index which is a proxy for the foreign price of traded goods and  $P^{\text{Dom}}$  is a domestic price index which is usually interpreted as a proxy for the domestic price of non-traded goods.<sup>34</sup> Increases (decreases) in  $q$  imply real depreciations (appreciations).

The final set of variables considered in the empirical analysis are the indicators of constrained borrowing regimes and empirical measures for inherited debt and credit ceilings. The arrears approach indicator is based on annual data on the change in principal and / or interest arrears which is grouped into five year periods, e.g. 1981-85, 1986-90. If this change in arrears is observed to be positive then an annual dummy indicator takes the value 1, zero otherwise. Over a five year period if the proportion of non-zero values for the dummy is greater than 50 % then the observation (country) is classed as constrained over that period.<sup>35</sup>

The theoretical results from chapter 5 suggested that the inherited stock of debt and the level of the credit ceiling were determinants of deforestation when credit constraints were binding. These theoretical variables are made

---

<sup>34</sup>The choice of proxy for the domestic price index was constrained by data availability. In most cases the the consumer price index was used, but where not available the domestic GDP deflator index was employed.

<sup>35</sup>In practice if  $0.2 * \sum_{s=1}^5 D_{i,s} > 0.4$  the country is classed as constrained.

operational for the purposes of the empirical analysis by defining the debt variables in terms of the debt to export ratio (DTX) and proxying  $B^*$  with a variable defined in terms of the total level of arrears expressed relative to total debt (ARDT). The first variable DTX, or some variant e.g. debt service to exports, has been the most common proxy for debt burdens in the debt-deforestation literature. In the empirical specifications considered below DTX is "lagged". This reflects the premise of the theoretical model that is the inherited stock of debt which was relevant in the comparative static analysis for constrained regimes. This also ensures that debt can be considered exogenous in the empirical model. It means, for example, that in the model for deforestation between 1986-90, the 1985 and 1980 values for DTX enter as regressors. If the model parameters can be restricted to be equal over time then growth in DTX over the period 1981-85 is hypothesised to be correlated with deforestation over 1986-90. Empirical proxies for credit ceilings have not been considered elsewhere in the debt-deforestation literature. The motivation for defining the empirical measure for credit ceilings in terms of arrears has already been alluded to in the discussion of 6.3.1. Moreover, as noted previously in chapter 4 Hajivassiliou (1987) contends that information on debt arrears provides valuable information about the severity of credit ceilings. Put simply, manipulation of the balance of payments constraint in 6.3.1 showed that arrears accumulation could be anticipated as a consequence of binding borrowing constraints. Intuitively, the lower the level of the ceiling then the greater the anticipated recourse to arrears accumulation.<sup>36</sup> Thus the total level of arrears, appropriately scaled with respect to the level of debt, may reasonably be expected to reflect cross-variation in credit ceilings. Note also

---

<sup>36</sup>There would be a limit here of course, since as Hajivassiliou makes explicit lenders will equally have a limit on permitted arrears accumulation.

that the assumed inverse relationship between credit ceilings and arrears accumulation will imply that the theoretical proposition  $\partial P/\partial B^* < 0$  is replaced by the empirical hypothesis that for constrained countries  $\text{cov}(D, \text{ARDT}) > 0$ . Again to ensure exogeneity the arrears variable is specified in terms of the observation at the beginning of the relevant period. The *World Debt Tables 1993-94* provides the data for the debt variables used in the empirical analysis. DTX is obtained directly from this source whilst ARDT is constructed by defining total arrears as the sum of interest and principal arrears on external liabilities to official and private creditors. This sum is then expressed relative to total external debt. An appendix to this chapter provides summary statistics for the explanatory variables for the full sample and the constrained / unconstrained sub-samples along with more detail on the variable definitions.

#### 6.4.2 Empirical results <sup>37</sup>

The empirical analysis starts with a general translog specification for a basic deforestation model which excludes any debt variables. Two issues are of interest in these initial investigations. The first concerns the validity of the parameter restrictions  $\beta_t = \beta_{t-1}$ , which state the null hypothesis that the parameters of the model are constant over different cross-sections. A convenient test of these restrictions is to employ a GMM version of a Lagrange Multiplier test (see Newey and West, 1987b) based on estimation of the restricted model, i.e. with  $\beta_t = \beta_{t-1}$ . In the case where the instruments used in estimation are defined by  $z_i = \{\ln w_{kit}, \ln w_{kit-1}, \ln w_{kit}^2, \ln w_{kit-1}^2, \ln w_{kit} \ln w_{mit}, \ln w_{kit-1} \ln w_{mit-1}\}$  under the alternative of  $\beta_t \neq \beta_{t-1}$  the model is exactly identified.

---

<sup>37</sup>The estimations and computations were obtained using *SHAZAM* version 7.0.

Newey and West (1987b) have established that where the unrestricted model is exactly identified the Lagrange Multiplier test statistic based on a restricted model is equivalent to Hansen's test of over-identifying restrictions (see also Davidson and MacKinnon, 1993). Thus the J-statistic can be used to test the restrictions  $\beta_t = \beta_{t-1}$ .<sup>38</sup>

With the second question the specific issue of interest is to determine whether zero restrictions on the parameters for non-quadratic interaction terms in the translog specification are valid. GMM equivalents of the LM test statistic were computed to test these restrictions in the basic deforestation model. In the period 1981-85 the value for this statistic was  $\chi^2 = 0.195$  and for the 1986-90 period the value was  $\chi^2 = 0.427$ , both with 10 degrees of freedom. Thus the zero restrictions on these parameters cannot be rejected. Thus in the remainder of the empirical analysis all non-quadratic interaction terms were excluded from the estimating equations and instrument sets.

---

<sup>38</sup>The reasoning for the equivalence of these test statistics in this case is reasonably intuitive. Imposing  $\beta_t = \beta_{t-1}$  creates the over-identifying restrictions of the model when the instrument set is  $z_t$ .

*(a) The basic deforestation model*

Table VI.2 reports the estimates for the basic deforestation model. Two GMM specification tests are reported for each cross-section. First, the J-statistics report the Hansen test of over-identifying restrictions and the associated p-values clearly indicate these restrictions cannot be rejected. Moreover, as outlined above, these statistics can be interpreted as tests of  $\beta_t = \beta_{t-1}$ . The second set of tests are with respect to functional form. Following the testing procedures outlined in Pagan and Vella (1989) the validity of the adopted functional form is examined by testing a set of moment restrictions which take the form  $E(\tilde{Z}_i \varepsilon_i) = 0$ , where  $\tilde{Z}_i$  denotes a  $1 \times p$  row vector. The functional form tests are based on sample equivalents of these restrictions (i.e.  $N^{-1} \sum_{i=1}^N \tilde{Z}_i \varepsilon_i$ ) with the elements in  $\tilde{Z}_i$  defined by powers of the fitted values obtained after estimation. The results report a  $\chi^2$  statistic for  $\tilde{Z}_i = (\hat{D}_i^2 \hat{D}_i^3)$  where  $\hat{D}_i$  denote fitted values of the dependent variable. Individual "t"-statistics are also reported.<sup>39</sup> The set of results in Table VI.2 indicate that the moment restrictions with respect to functional form cannot be rejected: a finding which is replicated in all the reported results, see Tables VI.4 and VI.6.<sup>40</sup> A final general observation from Table VI.2 is the adequacy of the fit of the estimated models. The  $\bar{R}^2$  measure and the estimated standard error of the residuals indicate the explanatory power of the basic model to be low.<sup>41</sup>

<sup>39</sup>These are properly interpreted as pseudo t-statistics as they do not follow the student's t-distribution, but are asymptotically distributed as  $N(0,1)$ .

<sup>40</sup>Column (ii) for 1981-85 provides some weak evidence of a mis-specified functional form, but this can perhaps be taken as further support for the inclusion of the quadratic terms in column (i).

<sup>41</sup>In the context of IV estimation it is well known that  $\bar{R}^2$  is not an appropriate criteria for model selection (Pesaran and Smith, 1990). However it remains common practice, even in IV and GMM estimation, to quote  $\bar{R}^2$  as a measure of model adequacy, e.g. Pesaran (1990), Young (1992).

**Table VI.2**  
*GMM estimation of the basic deforestation model.*

N = 55 Dependent variable: $\ln F_t - \ln F_{t-1}$	1981-85		1986-90	
Constant	0.0147 (0.0315)	-0.0040 (0.0234)	0.1587 (0.0458)	0.1721 (0.0353)
Africa Dummy	0.0050 (0.0253)	0.0336 (0.0142)	-0.0924 (0.0440)	-0.0919 (0.0348)
Latin America Dummy	0.0236 (0.0312)	0.0345 (0.0156)	-0.0198 (0.0495)	-0.0467 (0.0372)
$\ln TP_t - \ln TP_{t-1}$	0.1734 (0.1375)	0.0345 (0.0156)	0.0443 (0.1767)	-0.0031 (0.0119)
$(\ln TP_t^2 - \ln TP_{t-1}^2)$	-0.0153 (0.0145)	---- ----	-0.0035 (0.0183)	---- ----
$\ln AP_t - \ln AP_{t-1}$	-0.0592 (0.1160)	-0.0018 (0.0109)	0.3152 (0.6477)	0.0489 (0.0329)
$(\ln AP_t^2 - \ln AP_{t-1}^2)$	0.0069 (0.0160)	---- ----	-0.0326 (0.0754)	---- ----
$\ln q_t - \ln q_{t-1}$	0.0246 (0.0737)	-0.0102 (0.0171)	0.0984 (0.0410)	0.0209 (0.0066)
$(\ln q_t^2 - \ln q_{t-1}^2)$	-0.0046 (0.0080)	---- ----	-0.0138 (0.0071)	---- ----
$\ln RP_{t-1} - \ln RP_{t-2}$	1.0992 (0.3353)	0.6118 (0.2108)	-0.7290 (0.3737)	-0.5738 (0.2684)
$(\ln RP_{t-1}^2 - \ln RP_{t-2}^2)$	-0.0909 (0.0488)	---- ----	0.0214 (0.0727)	---- ----
$\ln RY_{t-1} - \ln RY_{t-2}$	-0.2016 (0.1111)	0.0329 (0.0180)	0.1078 (0.2130)	-0.0338 (0.0326)
$(\ln RY_{t-1}^2 - \ln RY_{t-2}^2)$	0.0198 (0.0090)	---- ----	-0.0117 (0.0176)	---- ----
J-statistic : $\chi^2$ (df)	2.22(10)	11.59(15)	4.87(10)	9.64(15)
P-value	0.99	0.71	0.90	0.84
Functional Form:				
$\chi^2(2)$ (P-value)	0.894 (0.64)	3.002 (0.22)	0.646 (0.72)	1.401 (0.50)
$\tau_{sq}$ (P-value)	0.747 (0.23)	1.512 (0.14)	0.667 (0.50)	0.585 (0.56)
$\tau_{cb}$ (P-value)	0.554 (0.29)	1.704 (0.09)	0.699 (0.48)	0.684 (0.49)
Wald Test : $\chi^2$ (df)	12.27(5)	----	6.25(5)	----
P-value	0.03		0.28	
$\bar{R}^2$	0.0355	0.0352	0.0660	0.0927
s.e.e	0.0633	0.0634	0.1310	0.1280

Notes to Table VI.2:

1 The weighting matrix  $Z' \tilde{\Omega} Z$  is computed using White's estimator  $\sum_{i=1}^n \tilde{\varepsilon}_i^2 z_i' z_i$  and a degrees of freedom correction factor  $n/n-k$ . Heteroskedasticity consistent standard errors in parentheses. See White (1980).

2. The set of instruments used is  $z_i = \{1, \text{regional dummies, } \ln TP_{it}, \ln TP_{it-p}, \ln AP_{it}, \ln AP_{it-p}, \ln q_{it}, \ln q_{it-p}, \ln RP_{it-p}, \ln RP_{it-2p}, \ln RY_{it-p}, \ln RY_{it-2p}, \ln TP_{it}^2, \ln TP_{it-p}^2, \ln AP_{it}^2, \ln AP_{it-p}^2, \ln q_{it}^2, \ln q_{it-p}^2, \ln RP_{it-p}^2, \ln RP_{it-2p}^2, \ln RY_{it}^2, \ln RY_{it-2}^2\}$

3.  $J$ -statistic denotes Hansen's test of over-identifying restrictions. See Hansen (1982)

4.  $\tau_{sq}$  denotes the pseudo  $t$ -statistic associated with squared fitted values in functional form test.  $\tau_{cb}$  denotes cubed fitted values. See Pagan and Vella (1989) for details on the test statistic and the computation of its variance.

5. Wald tests the hypothesis of a zero restriction on quadratic terms see Newey and West (1987b).

6.  $\bar{R}^2$  computed as  $1 - (s.e.e / sd)^2$ , where  $s.e.e$  is the standard error of the residuals and  $sd$  is the standard deviation of the dependent variable. Residuals are computed from  $\varepsilon_i = y_i - x_i' \beta_{GMM}$

Columns (i) and (ii) in Table VI.2 report the parameter estimates for the 1981-85 cross-section. The significant explanatory variables are rural population growth (RPG) and growth in real per capita income, where growth refers to the rate of change between 1976-80. This follows other cross-sectional studies (e.g. Deacon 1994) which have found that the anticipated relationship between population and income variables are observed when these explanatory variables are "lagged" which in this context refers to the previous five year period. The  $t$ -values for the coefficients on the log linear terms are respectively 3.75 ( $p < 0.01$ ) and -2.07 ( $p < 0.05$ ). Table VI.2 also reports a test of a zero restriction on quadratic terms included in the basic specification. For 1981-85 a Wald test of these restrictions gives  $\chi^2 = 12.27$  ( $p = 0.03$ ) which indicates that the restrictions implied by the null hypothesis can be rejected. On close inspection of the  $t$ -values however, only the quadratic terms for  $RP$  and  $RY$  are individually significant. The coefficients on the quadratic terms provide useful information about the nature of the non-linear relationship between deforestation and the explanatory variables. In the literature on the relationship between income levels and environmental quality interest has centred on the

estimated turning points of the quadratic relationship. Similar observations can be offered in this analysis about the relationship between the explanatory variables considered here and the rate of change in forest cover, based on an estimate of the implied turning point which is computed for variable  $w_k$  using  $\hat{\beta}_{w_k}$ , the estimated coefficient on the log linear term and the parameter estimate for the quadratic term  $\hat{\beta}_{w_k^2}$  using the expression  $\hat{\beta}_{w_k}^{TP} = -\hat{\beta}_{w_k} / 2\hat{\beta}_{w_k^2}$ . Thus to illustrate, the estimates of 1.0992 for  $\hat{\beta}_{w_k}$ , and -0.0909 for  $\hat{\beta}_{w_k^2}$  imply a concave relationship between deforestation and rural population. The estimated turning point implied is 6.04 which recall refers to the turning point when the variables are defined in natural logarithms. Taking the antilog, therefore, gives a rural population turning point of 422 (millions). A similar computation for the income turning point gives a figure of 162.54 (real U.S. dollars) for a convex relationship, i.e. deforestation is increasing in real per capita incomes for levels above \$162.54. In the rest of the analysis the discussion about turning points in quadratic functions is confined to the relationship between deforestation and the debt variables since this is the main relationship of interest. Moreover in these cases standard errors are computed for these turning points which allow hypotheses about the turning points to be tested.

The only other variable in col (i) which approaches statistical significance is timber prices ( $t = 1.44$ ). If quadratic terms are dropped then the  $t$  value for timber price growth is 2.52 and therefore the timber price parameter is statistically significant at  $p < 0.05$ . However it has already been noted that the parameter restrictions implied by dropping these terms are rejected. A final point about the estimates for the 1981-85 period is that the estimated model includes dummy variables to allow for unobserved heterogeneity between

groups of countries. The estimates on the African and Asian country dummies are small in magnitude and not statistically different from zero. Thus the null of a common intercept for all countries cannot be rejected for the 1981-85 model.

Cols. (iii) and (iv) in Table VI.2 provide the equivalent estimates for the period 1986-90. Interestingly these results suggest some very different features to the causal explanation for deforestation over 1986-90. For example the restriction on the quadratic terms cannot now be rejected (Wald = 6.25,  $p=0.28$ ) and the estimates of the log-linear model in col (iv) indicate that movements in real exchange rates over 1986-90 ( $t = 3.2$ ) and to a lesser extent agricultural prices for the same period ( $t=1.49$ ) are determinants of deforestation over 1986-90. Also of note is the statistically significant and negative estimate for the RP coefficient in both cols. (iii) and (iv). This combined with the results already highlighted would appear to suggest an element of structural change in the casual explanations for deforestation in the early 1980's and late 1980's. A further pointer to this is the significance of the African country dummy in 1986-90. This apparent structural change was investigated with a test of parameter stability.<sup>42</sup> The test statistic is distributed under the null as  $\chi^2(13)$

---

<sup>42</sup>The test for parameter stability between the cross-sections 1981-85 and 1986-90 is constructed using a D-statistic (GMM equivalent of the Likelihood ratio test, see Newey and West, 1987b) which is distributed under the null  $\chi^2(p)$ , where  $p$  is the number of parameter restrictions. In essence this tests whether it is appropriate to pool over cross-sections. Let  $X_s$  denote the  $n \times p$  regressor matrix for the  $s$ th cross-section and similarly  $\beta_s$  is the  $p \times 1$  parameter vector for the  $s$ th cross-section. The vector of errors in the unrestricted model can be written as:

$$E^u = \begin{bmatrix} \varepsilon_{81-85} \\ \varepsilon_{86-90} \end{bmatrix} = \begin{bmatrix} D_{81-85} \\ D_{86-90} \end{bmatrix} - \begin{bmatrix} X_{81-85} & 0 \\ 0 & X_{86-90} \end{bmatrix} \begin{bmatrix} \beta_{81-85} \\ \beta_{86-90} \end{bmatrix},$$

The instrument matrix  $Z$  is defined to be block diagonal, i.e.  $Z = \text{diag}(Z_{81-85} \ Z_{86-90})$  and likewise  $\Sigma$  is the block diagonal weighting matrix defined by:

with a computed value of 46.807 ( $p=0.0004$ ). Stability in the parameters between the cross-sections is therefore rejected.

*(b) Testing for debt effects*

The empirical literature on debt and deforestation has almost universally investigated the relationship with the alternative hypothesis that debt variables and deforestation are correlated for all sample countries. The empirical propositions which arise from the theoretical model of chapter 5 and the discussion in 6.3 of this chapter suggest that the alternative hypothesis should be constructed in a way that discriminates between constrained and unconstrained countries. However, to provide a ready comparison with existing literature the effect of debt variables was investigated initially without distinguishing between constrained and unconstrained observations. The results of the estimation and testing of the deforestation model which includes debt variables but does not discriminate between type of borrower are presented in Tables VI.3 and VI.4 below.

---


$$\begin{bmatrix} (Z' \tilde{\Omega} Z)_{81-85} & 0 \\ 0 & (Z' \tilde{\Omega} Z)_{86-90} \end{bmatrix}$$

The GMM estimator in the unrestricted case is obtained by minimising:

$$[Z' E^u]' \Sigma^{-1} [Z' E^u]$$

and then for the restricted estimation minimisation is subject to the constraint that the parameter vectors for each cross-section are equal. The test statistic is then computed as the difference between the restricted and unrestricted Hansen tests of over-identifying restrictions.

**Table VI.3**  
*Testing for the absence of debt effects in the basic model*

	1981-1985	1986-1990
J-Statistic: $\chi^2(\text{df})$	21.62 (18)	14.33
P-value	0.250	0.71
Test of debt moment restrictions: $\chi^2(\text{df})$	18.02 (8)	10.64(8)
P-value	0.026	0.22
Test of zero restriction on debt coefficients: $\chi^2(\text{df})$	7.86(4)	1.11(4)
P-value	0.097	0.89

*Notes: The instrument set is extended to include  $\ln ARDT_{t-1}$ ,  $\ln ARDT_{t-2}$ ,  $\ln DTX_{t-1}$ ,  $\ln DTX_{t-2}$ ,  $\ln ARDT_{t-1}^2$ ,  $\ln ARDT_{t-2}^2$ ,  $\ln DTX_{t-1}^2$ ,  $\ln DTX_{t-2}^2$ .*

In Table VI.3 tests for misspecification in a model which imposes moment restrictions on debt instruments are reported. In both periods the J-statistic suggests that the complete set of over identifying restrictions cannot be rejected. Focusing on the debt moment restriction alone the evidence suggests that these restrictions are rejected for the 1981-85 period. This finding is supported by a test of a zero restriction on the debt variable coefficients estimates which is reported in Table VI.3.<sup>43</sup>

<sup>43</sup>Note the numerical equivalence of the difference between the restricted model J-statistics in Table IV.3 and the unrestricted value in Table IV.4, which defines the GMM equivalent of the likelihood ratio test and the Wald tests reported in Table IV.3. This equivalence for the type of restrictions considered here has been established formally by Newey and West (1987b). See their Proposition 4.

**Table VI.4**  
*Parameter Estimates for debt variables in basic deforestation model*

n=55: Dependent variable: $\ln F_t - \ln F_{t-1}$	1981-85		1986-90	
	ARDT	DTX	ARDT	DTX
$\ln X_{t-1} - \ln X_{t-2}$	0.0251 (0.0263)	0.1571 (0.078)	0.0107 (0.0352)	-0.1310 (0.1333)
$\ln X^2_{t-1} - \ln X^2_{t-2}$	-0.0093 (0.0087)	-0.0151 (0.0084)	-0.0034 (0.0098)	0.0116 (0.0115)
J-statistic : $\chi^2$ (df) P-value	13.76(14) 0.47		13.23(14) 0.51	
Functional Form: $\chi^2(2)$ (P-value)	1.818 (0.40)		0.719 (0.70)	
$\tau_{sq}$ (P-value)	1.156 (0.26)		0.503 (0.61)	
$\tau_{cb}$ (P-value)	1.003 (0.32)		0.571 (0.57)	
Wald Test : $\chi^2$ (df): P-value	9.32(5) 0.097		6.73(5) 0.24	
$\bar{R}^2$ s.e.e	0.0676 0.0625		-0.0628 <sup>44</sup> 0.1389	

Notes:

1. J-statistic is test of over-identifying restrictions in the unrestricted model with debt variables.
2. See also notes to Tables VI.2 and VI.3.

For the 1981-85 period the coefficients associated with the linear terms for the debt variables are both positive, with DTX statistically significant (t-value = 2.01). Together with the estimates on the quadratic terms, there is evidence of a concave relationship between debt variables and levels of deforestation. For DTX, since only this variable is statistically significant the estimated turning point is 181.8 %. This compares with, for example, a full sample mean of 171.5 % which suggests, ceteris paribus, the mean DTX observation is on the

<sup>44</sup>The negative figure for the adjusted  $R^2$  is an artifact of the inclusion of insignificant explanatory variables and the model's low explanatory power. The unadjusted  $R^2$  is 0.256. The insignificance of the debt variables and quadratic terms would indicate that for 1986-90 column (iv) in Table VI.2 is a preferred specification.

part of the quadratic relationship in which deforestation increases with DTX. Examination of the constrained and unconstrained sample means for DTX shows that for 1980 the former is 211.47 % and the latter 132.96 % which implies the sub-sample means are either side of the turning point in the unanticipated direction. This would suggest that the distinction between these type of observations is indeed potentially important. In the 1986-90 period the parameter estimates for ARDT are reasonably close to those for 1981-85, but again a zero restriction cannot be rejected. With respect to DTX the estimated coefficients which have the reverse signs relative to 1981-85 are, like ARDT, not significantly different from zero. Thus there is some evidence of a debt deforestation relationship over the period 1981-85, but the hypothesis that deforestation is orthogonal to debt variables over 1986-90 cannot be rejected.

One final point on this extension to the basic model is that the findings in Table VI.2 are robust to the inclusion of the debt variables. The findings of a concave relationship with rural population and a convex relationship with real per capita incomes in 1981-85 are again observed, with parameter estimates close to those in Table VI.2. The marginal significance of timber prices is also observed again with  $t = 1.78$  for the (log)linear term and  $t = -1.61$  for the squared term. Moreover as reported in Table VI.4 the Wald test still weakly rejects a zero restriction on quadratic term parameters. This finding of robustness to the inclusion of debt variable is likewise found for 1986-90, where the real exchange rate is the only strongly significant explanatory variable ( $t=2.75$  for the log linear term and  $t=-1.98$  for quadratic term).<sup>45</sup> Finally, a test of

---

<sup>45</sup>There is an argument that this finding could be debt related since real exchange depreciations have been an element of the structural adjustment programmes undertaken throughout the 1980s. Recall earlier discussion in Section 6.1 with respect to the Capistrano and Kiker (1990 and 1995) studies

parameter stability between the cross-sections again indicates structural change. The test statistic (see footnote 39) under the null is  $\chi^2(17)$  with a computed value of 33.187 ( $P = 0.0107$ ).

*(c) Testing for the Absence of Debt Regimes*

This section presents the results of the empirical investigation of differences between constrained (i.e. problem) debtors and unconstrained (i.e. non-problem) debtors which are predicted by the theoretical model of chapter 5.

The set of instruments is now extended to include the interaction between the dummy indicator of borrowing constraints and the explanatory variables. Thus the statistics in Table VI.5 report tests of the validity of moment restrictions which restrict the covariance between these constrained group instruments and the error term of the null model to be zero. A more general point about the models is that the full set of explanatory variables from earlier sections is not considered here. Given the findings from Tables IV.2 - IV.4 variables which were found to be insignificant were dropped from the analysis. For the 1981-85 cross-section this applies to the regional dummies, agricultural prices and the real exchange rate. In 1986-90 the Latin American dummy, timber prices, rural population and real income are dropped from the analysis.

**Table VI.5**  
*Testing for Absence of Debt Regimes: Specification Tests*

	1981-85	1986-90
J-Statistic: $\chi^2$ (df)	211.4(31)	55.29(25)
p-value	0.000	0.000
Test of constrained group moment restrictions: $\chi^2$ (df)	116.5(21)	24.02(17)
p-value	0.000	0.119

The evidence presented in Table VI.5 indicates that the moment restrictions imposed on the constrained group variables are rejected over-whelmingly in 1981-85. For 1986-90 the statistics are to a degree ambiguous with the J-statistics rejecting the model at  $p=0.000$ , but the test of the debt moment restrictions would reject the null at only a 12 % level of significance.

Parameter estimates for the debt variables from the unrestricted model (see Eq. 6.19) for the periods 1981-85 and 1986-90 are provided in Table VI.6. The theoretical model from chapter 5 presents the hypotheses that deforestation is orthogonal to inherited debt and credit ceilings in the case of unconstrained borrowers, but is not orthogonal for constrained countries. In terms of the empirical model (6.20) these propositions have two aspects. The first is that the estimated constrained group deviation should be significantly different from zero, implying significant differences from unconstrained group parameters. The second is that the unconstrained group estimates should not, given the theoretical propositions, be significantly different from zero. Based on the evidence in Table VI.6 each hypothesis can be examined in turn.

**Table VI.6**  
*Testing for Absence of Debt Regimes: Parameter Estimates*

	1981-85		1986-90	
	coef	se	coef	se
$\ln\text{ARDT}_{i,1}-\ln\text{ARDT}_{i,2}$	+0.2116	(0.0362)	-0.1394	(0.0661)
Constrained group deviation	-0.1510	(0.0327)	+0.1207	(0.0702)
$\ln\text{ARDT}^2_{i,1}-\ln\text{ARDT}^2_{i,2}$	-0.0497	(0.0112)	+0.0384	(0.0199)
Constrained group deviation	+0.0290	(0.0103)	-0.0342	(0.0221)
$\ln\text{DTX}_{i,1}-\ln\text{DTX}_{i,2}$	-0.0679	(0.0545)	+0.3972	(0.1432)
Constrained group deviation	+0.3033	(0.1478)	-0.4679	(0.1820)
$\ln\text{DTX}^2_{i,1}-\ln\text{DTX}^2_{i,2}$	+0.0104	(0.0064)	-0.0390	(0.0152)
Constrained group deviation	-0.0306	(0.0150)	+0.0438	(0.0184)
			----	
J-statistic : $\chi^2$ (df)	12.44(21)	P=0.093	11.77(16)	P=0.763
Functional Form:				
$\chi^2(2)$	0.260	P=0.880	0.184	P=0.912
$\tau_{sq}$	0.490	P=0.619	0.226	P=0.821
$\tau_{cb}$	0.399	P=0.691	0.326	P=0.745
Wald 1 : $\chi^2$ (df):	63.29(4)	P=0.000	9.021(4)	P=0.061
Wald 2 : $\chi^2$ (df):	58.44(6)	P=0.000	23.70(4)	P=0.000
Wald 3 : $\chi^2$ (df):	196.73(10)	P=0.000	24.72(8)	P=0.002
$\bar{R}^2$	0.4125		0.0385	
s.e.e	0.0494		0.1332	

*Notes:*

1. Wald 1 is test of significance of constrained group debt parameters, Wald 2 is test of significance of non debt constrained group parameters, Wald 3 is test of all constrained group parameters.

2. See also notes to previous tables

Consider first the relationship between the DTX (ie inherited debt) variables and deforestation. For the 1981-85 period the unconstrained estimates for the log linear and quadratic terms are respectively -0.0679 ( $t=1.25$ ) and + 0.0104 ( $t=1.63$ ). Given these t-values, the null of a zero restriction on each parameter cannot be rejected at conventional significance levels. By comparison the constrained group deviations are significantly different from zero ( $t=2.05$  and  $t=2.04$ ) and in the anticipated direction. Based on these estimates computing

the constrained group turning point gives a value of 340.1 % (s.e. = 1.66). This compares with a constrained group mean for DTX (1980) of 186.1 %. Even allowing for the standard error in the turning point estimate, 35 from 37 constrained country observations lie to the left (i.e. on the positive slope of the concave curve) of a 95 % confidence interval around the turning point estimate. The 1981-85 evidence therefore is supportive of the prediction of the theoretical model that deforestation is increasing in inherited debt stocks for constrained observations. With respect to the hypothesis for the 1986-90 period at first sight the evidence seems contrary to that for 1981-85. For unconstrained observations there is evidence of a statistically significant concave curve, whilst the statistically significant constrained group deviations ( $t = -2.57$  for the log linear term and 2.38 for the quadratic terms) indicate a convex relationship. The turning point estimates are, however, of note. For the unconstrained group the concave turning point estimate is 162.3 % (s.e = 1.53) which compares with an unconstrained group mean for DTX (1985) of 261.4 % . In addition 87 % of the unconstrained group observations lie to the *right* of the 95 % confidence interval around the turning point estimate. The convex turning point for the constrained group by contrast is not significantly different from zero despite a high point estimate ( $\hat{\beta}^{TP} = 1614.8$  % s.e.=1413.3) Thus the hypothesis that all constrained observations lie on the positive slope of the convex curve cannot be rejected. This evidence together with that for the 1981-85 period provides an interesting contrast with the findings in Table VI.4 in which no distinction was made between types of borrower. There DTX variables were found to be statistically significant, but it was noted that the turning point for the estimated concave curve meant the mean unconstrained observation was to the left, whilst the mean constrained observation was to the right. Distinguishing

between constrained and unconstrained observations, as suggested by theory, would appear to resolve this anomaly and provide stronger evidence in support of the predicted debt-deforestation relationship.

The evidence on the credit ceiling hypothesis suggests that both constrained and unconstrained groups were operating on concave curves with the turning point estimates (unconstrained: 8.64 %, s.e. 1.20) and constrained: 4.51 %, s.e. 1.25) such that 94 % of unconstrained observations and 73 % of constrained observations were to the left of a 95 % confidence interval around the turning point i.e. the positive slope of the concave curve. The 1986-90 results reverse the estimated curves with both constrained and unconstrained operating on convex curves. Moreover, the constrained group deviations are marginal in their statistical significance (t-value = 1.73 for deviation from log linear ARDT parameter and  $t = -1.55$  for deviation from quadratic term parameter). Based on the estimates for the ARDT variables in the 1986-90 period, the unconstrained turning point is of 6.15 % (s.e. = 1.26), whilst, for the constrained group it is 9.31 % (s.e. = 59.65). Of interest here is that for a 95% confidence interval around the unconstrained turning point estimate of 6.15% the majority of observations for this group (60%) lie to the left of this interval. This corresponds to the negative slope of the convex relationship between deforestation and ARDT. In the constrained case, the null of a zero turning point cannot be rejected. As for the DTX variables in this period, the hypothesis that all constrained observations lie on the positive slope of the convex relationship between deforestation and ARDT, cannot be rejected

Finally, the null hypothesis of no differences between constrained and unconstrained debtors for the non debt parameters is clearly rejected. Table VI.6 reports Wald tests of equality restrictions on the non debt parameters for the two groups. These statistics have p-values of 0.000 for both periods indicating that the null is overwhelmingly rejected. This finding is consistent with the predictions from the model in chapter 5. ( See the results outlined in the appendix to chapter 5).

### 6.5 Conclusions.

This chapter has presented an econometric analysis of external indebtedness and deforestation for a sample of developing countries. The basic premise of the theoretical model presented in chapter 5 receives strongest support when deforestation over the period 1981-85 is considered. For the sub-sample of constrained debtors significant differences in debt parameter estimates in a direction consistent with theory were observed. A general result for this period is that lagged rural population growth and lagged real income per capita growth are the most important determinants of deforestation.<sup>46</sup>

The results provide less support for a debt-deforestation link in the 1986-90 period when the empirical model imposes an equality restriction on the parameters for unconstrained and constrained debtors.<sup>47</sup> More generally the

---

<sup>46</sup>It can also be noted from Table VI.6 that the fit of the model with the constrained / unconstrained distinction is markedly higher in 1981-85 ( $\bar{R}^2 = 0.4125$ ).

<sup>47</sup>One possible explanation for the 1986-90 differences is the effect of policy innovations such as "debt-for-nature swaps" during this period. These swaps provide a measure of debt relief and incentives for forest conservation. This was investigated by constructing a "debt-for-nature swap" dummy variable from data on such swaps documented in Deacon and Murphy (1995). This variable took the value one if a debt-for-nature swap was observed in 1990 or before. Of the 55 sample countries this condition was satisfied for Bolivia, Costa Rica, Dominican

model has very low explanatory power in this period. Allowing for differences between constrained and unconstrained parameters, as predicted by theory, did however receive statistical support. With respect to inherited debt, the estimated coefficients suggests a concave relationship with deforestation for unconstrained debtors. For the constrained group, the quadratic relationship is convex. Moreover, the turning point estimates are not sufficient to reject the hypothesis that the majority of unconstrained countries lie on the negative slope of the concave curve and the majority of constrained countries lie on the positive slope of the convex curve. With respect to credit ceilings, the estimated relationship between the proxy variable ARDT and deforestation is convex for both constrained and unconstrained debtors. However the evidence again would not reject the hypothesis of a negative relationship between the arrears proxy for credit ceilings and deforestation in unconstrained countries. Nor is it sufficient to reject the hypothesis of a positive relationship between the aforementioned variables for constrained countries.

Of more general note in the 1986-90 period is the evidence of structural change in the deforestation model. Rural population and real income per capita no longer provide statistically significant explanations for deforestation in this period. Real exchange depreciations, however, are consistently found to be a significant correlate of deforestation. This latter finding is of obvious interest in

---

Republic, Ecuador, Madagascar, Philippines and Zambia. The model from section (b) of 6.4.2 for the period 1986-90 was re-estimated with the debt-for-nature dummy. It is not clear, however, what sign should be expected for this variable. For example, a negative sign would indicate, *ceteris paribus*, deforestation is lower in swapping countries. Equally, from evidence of a positive correlation between the probability of a swap and debt servicing burdens provided by Deacon and Murphy (1995), a positive sign might be anticipated given the swap dummy could identify countries with particularly high debt burdens. The estimated parameter was 0.0314 favouring the latter interpretation, but was statistically insignificant ( $t$ -ratio = 0.7284). Thus, "debt-for-nature" swaps do not appear to have any explanatory power in the 1986-90 cross-section.

the context of the debt-deforestation link, since real exchange rate depreciations in the latter half of the eighties have become a component of the policy response (e.g. structural adjustment programs) to the debt problems which became evident earlier in the 1980s. This increase in the significance of real exchange rate adjustments in the explanation of deforestation over 1986-90 may also account for the less conclusive findings with respect to the (lagged) debt variables in the 1986-90 model.

## DATA APPENDIX

The sample used in estimation is outlined in Table VI.7 below. This table also indicates the periods in which each country was classified as constrained / unconstrained according to the Arrears and criteria.

**Table VI.7**  
*Countries (n=55) in Sample and Debt Regime Classifications*

Country	Constrained Periods	Country	Constrained Periods
Bangladesh	1, 4	Malaysia	0
Benin	1, 2, 3	Mali	1, 2, 3, 4
Bolivia	2, 3	Mexico	2
Brazil	1, 2, 3, 4	Myanmar	4
Burkina Faso	3, 4	Nepal	4
Cameroon	2, 3, 4	Nicaragua	2, 3, 4
Central African Republic	1, 2, 4	Nigeria	2, 3, 4
Chad	1, 2, 3	Panama	3
Colombia	3, 4	Papua New Guinea	3, 4
Congo	1, 3, 4	Paraguay	3, 4
Costa Rica	2, 3, 4	Peru	3, 4
Cote D'Ivoire	3, 4	Philippines	3, 4
Dominican Republic	1, 2, 3, 4	Rwanda	3, 4
Ecuador	4	Senegal	0
El Salvador	3, 4	Sierra Leone	1, 2, 3, 4
Ethiopia	1, 2, 4	Somalia	2, 3, 4
Gabon	3, 4	Sri Lanka	2, 3, 4
The Gambia	3	Sudan	2, 3, 4
Ghana	2, 3, 4	Tanzania	1, 2, 3, 4
Guatemala	3, 4	Thailand	1, 2, 3, 4
Guyana	1, 2, 3	Togo	2, 4
Honduras	2, 3, 4	Trinidad and Tobago	2, 4
India	0	Uganda	1, 2, 3, 4
Indonesia	0	Venezuela	2, 3, 4
Jamaica	2, 3, 4	Zaire	1, 2, 3, 4
Kenya	2, 3, 4	Zambia	1, 2, 3, 4
Madagascar	1, 2, 3, 4	Zimbabwe	2, 3, 4
Malawi	4		

*Notes:*

1. Codes for debt regimes are : 1 = Constrained in 1971-75 cross-section; 2 = Constrained in 1976-80 cross-section; 3 = Constrained in 1981-85 cross-section; 4 = Constrained in 1986-90 cross-section; 0 = Unconstrained in all cross-sections.

The explanatory variables (with units of measurement) used in the empirical investigations are defined as:

RP: Rural Population (millions)

The difference between total population and urban population figures. (source: *World Bank Socio-Economic Indicators 1990-91*.)

RY: Real Income per capita (US \$, 1987 prices)

Defined using data on nominal GNP per capita (source: *World Bank Socio-Economic Indicators 1990-91*) and converted to 1987 prices using the U.S. Wholesale Price Index (source: *International Financial Statistics*)

AP, TP: World prices for agricultural and timber exports (U.S.\$)

AP defined using export unit value index (1979-81 = 100) for agricultural commodities (source: *FAO Trade Yearbooks*, *FAO Quarterly Bulletin of Statistics*). TP defined using export unit value index (1979-81 = 100) for (non coniferous) Sawlogs and Veneer logs (source: *FAO Yearbooks of Forest Products*). Details of the construction of these export unit value indices are to be found in these aforementioned FAO sources.

With these price variables data was not available for some of the countries in the sample. In estimation these variables were treated as missing price observations and the zero-order approach was employed in computations. This

involves substituting the mean of the available observations for the missing observations, see Greene (1990) for further discussion.

RER: Real Exchange Rate Index (1987=100)

Defined by (6.21) in main text. (Nominal exchange rate source: *World Bank Socio-Economic Indicators and World Bank Tables*). The U.S. wholesale price index was used to proxy dollar prices. Domestic price indices were proxied by either domestic consumer price index or domestic GDP price deflator (source: *World Bank Socio-Economic Indicators 1990-91 and World Bank Tables*)

DTX: Debt-Export ratio (%)

Defined as total external debt (in U.S. \$) relative to export of goods and services (US \$) expressed as a percentage. (source: *World Debt Tables 1993-94*)

ARDT: Total Arrears-Debt Ratio (%)

Total arrears (U.S.dollars) obtained as a sum of principal and interest arrears on liabilities owed to official and private creditors. Official creditors are classed in terms of multilateral and bilateral lending. Multilateral lending includes loans and credits from the World Bank, Regional Development banks and other multilateral agencies. Bilateral lending includes loans from governments and their agencies (e.g. central banks) and official export credits. Private Creditors include bonds, commercial bank lending and private export credits. Debt

defined as total external debt in U.S. dollars (source: *World Debt Tables 1993-94*)

#### Africa, Latin America Dummies

Dummy variables for African (= 1, zero otherwise) and Latin American (= 1, zero otherwise) countries respectively. Latin American dummy includes countries in Central America and the Caribbean.

Full sample summary statistics for the years 1980, 1985, and 1990 are presented in Table VI.8.

**Table VI.8**  
*Explanatory variables: summary statistics for full sample*

Variable	1980	1985	1990
RP			
mean	21.99	23.89	25.77
std. dev	72.58	78.73	84.98
RY			
mean	1090.3	806.31	772.30
std. dev	1288.4	1010.6	812.37
TP			
mean	185.04	135.21	191.83
std. dev	108.41	102.50	132.99
AP			
mean	102.68	87.93	78.27
std. dev	17.57	22.57	32.70
RER			
mean	108.48	121.82	124.49
std. dev	211.18	113.98	163.95
DTX			
mean	171.50	346.54	448.32
std. dev	98.01	287.48	524.64
ARDT			
mean	2.14	4.96	10.92
std. dev	4.97	7.18	15.19

Table VI.9 presents summary statistics for the unconstrained and constrained sub-samples on the explanatory variables used in the estimation of the empirical models. Note therefore that for RP, RY, DTX and ARDT the statistics refer to the lagged cross-section, i.e. for these variables the 1990 column refers to the 1985 values.

**Table VI.9**  
*Explanatory variables: summary statistics for unconstrained and constrained sub-samples*

Variable	1980: mean (std. dev)		1985: mean (std. dev)		1990: mean (std. dev)	
	u (n=28)	c (n=27)	u (n=18)	c (n=37)	u (n=15)	c (n=40)
RP: Rural Population	29.98 (91.76)	9.99(13.95)	50.33 (123.1)	8.21 (12.36)	54.01 (147.1)	12.60 (18.31)
RY: Real income per capita	1166 (1348)	808.8 (670.9)	1040 (1513)	1115 (1186)	833 (933)	796 (1049)
AP: Index of agricultural export unit value	101.02 (20.38)	104.4 (5.1)	84.39 (24.38)	89.7 (17.9)	75.24 (16.28)	79.41 (32.5)
TP: Index of sawlogs/vlogs export unit value	182.4 (89.8)	187.8 (54.03)	131.84 (71.23)	136.9 (65.6)	148.9 (61.3)	207.93 (87.5)
RER: Real exchange rate	89.96 (94.56)	127.70 (301.9)	110.9 (29.6)	127.2 (137.8)	105.5 (173.3)	131.61 (192.2)
DTX: Debt to export ratio	106.1 (140.3)	140.3 (83.2)	141.59 (90.62)	186.1 (99.32)	261.4 (152.98)	378.5 (319.7)
ARDT: Total arrears to debt ratio	0.208 (0.94)	3.03 (5.38)	1.58 (6.55)	2.41 (4.08)	6.66 (9.78)	4.33 (5.97)

*Notes: u denotes unconstrained sample and c denotes constrained sample.*

## Chapter 7

### Conclusions

In chapter 1 it was suggested that the hypothesised relationship between indebtedness and resource use motivated two sets of questions. The first concerned the economics of a debt-resource link. That is, what kind of economic rationale could be offered to explain the mechanisms of a debt-resource link. The second set of questions were with regard to the empirical validity of the proposition. The economics of the debt-resources hypothesis were introduced in chapter 2 and then developed in two specific areas. Chapter 3 presented an intertemporal model of exhaustible resource extraction in an indebted economy, whilst chapter 5 analysed the relationship between the use of forest resources and external indebtedness within a static optimisation framework. The empirical significance of the debt-resources proposition was considered in Chapters 4 and 6 with econometric analysis in the respective contexts of mineral production (depletion) and deforestation. In the remainder of this concluding chapter the aim is two-fold. Firstly, to review and provide some discussion with regard to the insights / answers which chapters 3 and 5 provide with respect to the first set of questions which motivated this thesis and to reflect on the empirical findings of chapters 4 and 6 which allow for an assessment of the second set of questions. The second aim is to speculate with regard to future avenues of research and to consider areas where the analysis presented in this thesis could be extended. Again this discussion is framed in terms of the theoretical and empirical dimensions of the debt-resources issue.

## 7.1 Reflections on the main findings.

With respect to the economics of the debt-resources hypothesis it could be argued that the intuition which shaped a lot of the early thinking and views on the link between indebtedness and resource depletion can be formally demonstrated within the realm of economic theory. One approach to economic modelling is to view the problems of resource depletion and resource management as examples of a more general capital asset management problem with an intertemporal structure. The view of natural resources as capital implies that within the optimising framework of capital, equilibrium outcomes are determined by the equality of returns on respective capital assets. This was clearly expressed with the review of this approach provided in Chapter 2. In models with more than one asset such as a natural resource and foreign debt (which can be regarded as a negative asset, so the structure of the problem is in essence no different) the equilibrium outcome at the margin is to equate the return to holding natural resource capital with the cost (return) of holding foreign liabilities. Consequently when the shadow cost of foreign liabilities increases, thereby changing relative "returns" optimising behaviour would naturally lead to a re-allocation of existing capital portfolios. For example in chapter 3 the effect of the presence of binding credit ceilings which increases the cost of indebtedness can be understood in precisely these terms (recall eqs. 3.21 and 3.22). Thus the liquidity benefit of a unit of resource stock increases relative to its value as a capital asset.

The theoretical model of deforestation presented in chapter 5 offers a similar interpretation of the effect of binding credit ceilings, in this case on equilibrium

forest clearance. In an unconstrained equilibrium the standard efficiency condition of marginal costs equating price emerged, whilst in the constrained case this condition was modified to include the additional shadow value of producing the good requiring forest inputs. Thus the production of this good brings an extra liquidity benefit for the constrained economy (whether it is a net exporter or importer) which encourages a higher level of forest conversion.

A notable difference between the analysis of chapter 5 relative to chapter 3 is that this additional liquidity benefit is not relative to the capital value of the resource stock. Recall that in chapter 5 the idea of viewing the stock of forested land as a capital asset was ruled out explicitly. Decisions about the use of forested land were entirely in terms of current and competing uses for this resource. Thus it was assumed that the natural resource provided only a flow of services which could be consumed in the form of direct inputs to production or indirect uses such as ecological functions. Moreover it was further assumed that the decision problem facing agents could be narrowed to direct uses for forested land since various institutional factors could justify treating the stock and therefore indirect uses as fixed from the perspective of individual agents. Consequently, a distinction to be noted between chapters 3 and 5 concerns the role of the discount rate as a determinant of the optimal use of the resource stock. In chapter 5 the static analysis rules out consideration of the role of the discount rate. In chapter 3 the interesting result to emerge is that the discount rate is only relevant to the optimal extraction program in the case where constraints on foreign borrowing are binding. Akin to the earlier discussion in chapter 2, the model in chapter 3 demonstrates the standard open economy result that optimal extraction is independent of the discount rate when capital

markets are perfect (recall eqs. 3.17b and 3.29). Imperfections in the form of binding credit ceilings led to (3.27) which included the term  $(g_\mu - \rho)\mu_{t+1}(P_t - G^{Q_t})$  in the determination of extraction along an optimal path. A feature of (3.29) is that it would imply the usual comparative dynamics result that the rate of extraction along an optimal path is decreasing in the discount rate (recall for example the discussion in chapter 2). Of further note, however, is that (3.26) also implies that  $g_\mu$  relative to  $\delta$  has interesting implications. The analysis of chapter 3 focused on the role of a high  $g_\mu$  relative to  $\delta$  which was interpreted in terms of the severity of binding credit ceilings. An alternative view which can be offered is that where  $\delta$  is *low* relative to  $g_\mu$  then faster depletion will be observed in the constrained case relative to the unconstrained. Thus a shift of extraction from the future to the present may arise because of *relatively* low discount rates in constrained borrowers. In other words, relatively low discount rates place a burden on future generations (in constrained economies) in the form of lower stocks of natural resource given the potential to encourage higher extraction in the present. This to a degree is contrary to the standard view that it is high discount rates which are prejudicial against future generations, a theme which has resurfaced in the literature on Sustainable Development; see for example discussions in Pearce, Barbier and Markandya (1990), Clark (1991) and Toman (1994).

The role of the discount rate in determining the optimal intertemporal allocation of costs and benefits is however ambiguous and in the view of Heal (1993) the discounting debate has mostly been confused. Heal notes the distinction between the utility rate of discount (i.e. the time rate of preference used to discount future utilities) and the consumption rate of discount which

may be defined as:

$$(7.1) \quad \psi = \rho + \eta(C)\dot{C}/C,$$

where  $C$  denotes consumption and  $\eta(C) > 0$  is the elasticity of marginal utility of consumption with respect to consumption. Note therefore that if consumption grows over time and  $\delta = 0$  the consumption rate of discount is still positive, but of course may even be negative if consumption growth is negative. Thus as Heal would argue there is a case for discounting future consumption if future generations are going to be better off. This latter outcome of improved consumption possibilities for future generations moreover results in the long run from the investment activities of current generations which in an microeconomic framework are motivated by relative returns. This gives rise to a further ambiguity with respect to discounting in the sustainability debate since as noted by, for example, Norgaard and Howarth (1991) if the rate of return on investments (assume for the argument this equals the discount rate) which generate future environmental costs is low then such investment is less attractive to current generations which has a benefit to future generations in the form of lower environmental costs.

The role of the discount rate which emerges in the analysis of chapter 3 may therefore be interpreted as a further instance of this ambiguity. Moreover the reason for the ambiguity arises from the fact that future welfare costs are imposed by binding credit ceilings (relative to an unconstrained situation). When the (utility) discount rate is low, decision-makers in the present are in effect asking future generations to bear more of this welfare cost than would be the case if discount rates were high. Assuming that the existence of a binding

constraint reflects lender assessments of past and present circumstances (i.e. evidence of unproductive investments, low income growth and even political uncertainty) then a low discount rate (in relative terms given the analysis) would suggest that future generations are bearing the cost of actions attributable to the present. Interestingly this mirrors the logic that high discount rates prejudice the interests of future generations. The standard argument about discount rates, as noted above, arises because the future generations are given less weight in the present value calculation of net benefits. The alternative interpretation of the analysis presented in chapter 3 suggests that with low discount rates future generations may carry relatively more weight in the present value calculation of the welfare cost of constrained borrowing. At the very least it would appear that the issue of discounting in the management of natural resources is not simply about discount rates which are judged to be too high.

Turning to the empirical evidence presented in the thesis, the results of chapter 4 would suggest that the potential problem of relatively low discount rates does not arise since the null hypothesis of  $\tilde{\alpha} = 0$  was not rejected. Given the structure of the empirical model this may be equivalently interpreted as the non-rejection of  $g_{\mu} = \delta$ . More generally, the empirical findings suggest a contrast between the extraction of minerals and the clearance of forests. Based on a pooled sample of developing country mineral producers over the period 1973-1989, the econometric results of chapter 4 would not reject the hypothesis that resource extraction was orthogonal to constrained lending regimes. However, the evidence from chapter 6 supports the idea that the constrained / unconstrained distinction was important in explaining deforestation in a sample

of 55 developing countries over the periods 1981-85 and 1986-90.

Two observations on these contrasting results can be made. The first is that the Euler equation model of chapter 4 was specified in a way that meant debt variables did not enter the set of instruments. Indebtedness, therefore, was only relevant to the extent that the debt situation for each  $i$  at time  $t$  could be used to classify the associated borrowing regime. In chapter 6 the model framework permitted an explicit role for debt variables (i.e. DTX, ARDT) under the alternative. One unanswered question from chapter 4 therefore, is whether the findings are robust to augmented Euler equation specifications which include debt variables as explanatory variables.<sup>1</sup> A second observation follows from the assumption that the findings of chapter 4 would be robust to Euler equation models with debt variables. The failure to reject orthogonality in the case of minerals is perhaps not unexpected. An important reason for this would be the different nature of the processes leading to depletion of natural capital in the case of mineral extraction and forest clearance. Mining, unlike deforestation, is a capital-intensive activity which means capacity constraints may limit the ability of mineral producers to adjust extraction levels in response to an increase in the debt burden. A further point is that in mining, again unlike forest clearance, property rights are well defined. For resources where the legal framework is less well established, as with forests in developing countries, it would seem likely that agents would face less institutional constraints on the exploitation of natural capital. Thus for a given burden of debt, it may be easier for the economy to adjust through exploitation of forest resources than exploitation of minerals stocks.

---

<sup>1</sup>Whited (1992) and Bond and Meghir (1994) would be examples of this in different contexts.

## 7.2 Future avenues and extensions.

The analysis of the interaction between resource use and indebtedness remains in its infancy. It is hoped that this thesis has contributed somewhat to extending both the understanding and analysis of the debt-resource interaction. There are invariably, however, many issues which still require further study. The remainder of this chapter is therefore dedicated to outlining some of the more promising avenues.

### *(1) Endogenous credit limits.*

The analysis throughout has employed the assumption that borrowing limits are exogenously imposed. An obvious extension of the analysis would therefore be to relax this assumption. This would undoubtedly create, at the level of theory, more complex interactions between indebtedness and resource use. The approach employed by Eaton and Gersovitz (1981) to study the endogenous determinants of credit limits may offer scope for extension of the analysis in this thesis. This question would also offer scope for further empirical analysis. For example, the issue of endogeneity could be considered by investigating the hypothesis that stocks of natural capital are a determinant of developing country access to international capital markets. This could also be interpreted as a way of testing the theoretical proposition presented in Mohr (1988) and Mansoorian (1991) that resource capital provides collateral for international loans.

*(2) Dis-aggregating the level of analysis.*

The thesis has presented the debt-resources hypothesis at the macroeconomic level. There is in effect the representative agent lurking behind much of the theoretical modelling. But perhaps an interesting question with respect to the debt-resources issue concerns the mechanisms by which macro-level debt burdens lead agents operating at the micro-level to increase the exploitation of natural resources. The question is of further interest since it could be argued that it is not all clear that individual agents will respond in the "desired" manner. This could be interpreted in principal-agents terms. Supposing, in this case, the government is the principal with the objective of maximising social welfare in a resource-exporting economy. Achieving this objective depends on the effort of agents at the micro-level responsible for decisions about resource exploitation. These agents would presumably be interested in maximising their *private* returns from their exploitation of resources, not the net social benefits consistent with the overall maximisation of social welfare. Even if the economy would benefit from, say, increased resource exploitation in response to debt constraints, what incentives do private agents have to respond in the way consistent with the principal's objectives ? The analysis presented in this thesis has presented the hypothesis that agents do respond in the desired way, without specifying fully the mechanisms. Moreover, the finding that agents do not respond to debt constraints would require explanation. The frameworks considered here do not permit answers in this respect.

*(3) Open economy analysis of the use of environmental resources.*

The questions which motivated this research were framed in terms of the

standard interpretation of natural resources, e.g. forests, minerals. However, it would be of interest to consider other aspects of environmental resource management in the open economy context. For example, investment in pollution abatement. This could lead to investigations of, for example, the interaction between flows of foreign capital and pollution control decisions within borrowers.

The discussion in chapter 1 highlighted that the environmental crisis in developing countries took the form of degradation of environmental quality as well as the depletion of natural capital. Recent debate over the "sustainability" of development has been concerned with both these aspects of environmental degradation in developing countries. This suggests a more general issue worthy of investigation. That is, the nature of the interaction between indebtedness and sustainable development. In particular, do high debt burdens constrain the ability of developing economies to pursue development paths which are "sustainable".

To date, most of the analytical literature on sustainable development has been conducted within the closed economy context. One final extension therefore would be to consider the issue of indebtedness and sustainability within the open economy framework presented in this thesis.

### **7.3 A final few words.**

The broad theme of this thesis has been to consider the use of natural resources within an international macroeconomic context. More specifically, the focus

has been on the hypothesised relationship between external indebtedness and the depletion of natural resources. Economic models consistent with the hypothesis that increases in indebtedness lead to increases in the exploitation of natural resources were constructed. Although a link was not indicated for mineral depletion, empirical evidence was suggestive of a link in the context of deforestation. Given the global ramifications of continued deforestation these results would lend support for international initiatives to reduce debt burdens in developing economies. Such initiatives would have the desirable outcome of easing financial pressures in the poorest developing economies and providing developed economies with the benefit of forest conservation.

## References

- Aarrestad, J., (1978) Optimal savings and exhaustible resource extraction in an open economy. *Journal of Economic Theory*, 19, pp. 163-179.
- Aarrestad, J., (1979) Resource extraction, financial transactions and consumption in an open economy. *Scandinavian Journal of Economics*, 81(4), pp. 552-64.
- Abel, A. and O. Blanchard, (1983) An intertemporal equilibrium model of saving and investment. *Econometrica* 51(3), pp. 675-692.
- Agebeyegbe, T. D., (1989) Interest rates and metal price movements: further evidence. *Journal of Environmental Economics and Management*, 16, 184-192.
- Allen, J C. and D F. Barnes, (1985) The causes of deforestation in developing countries. *Annals of the Association of American Geographers*, 75(2), pp. 163-184.
- Allsopp, C. and I. Joshi, (1985) The international debt crisis. *Oxford Review of Economic Policy*, 2, pp. i-xxxiii.
- Anderson, T. W. and C. Hsiao, (1982) Formulation and estimation of dynamic models using panel data. *Journal of Econometrics*, 18, pp. 578-606.
- Andrews, D. W. K., (1991) Heteroskedasticity and autocorrelation consistent covariance matrix estimation. *Econometrica*, 59(3), pp. 817-858.
- Arellano, M. and S. Bond, (1988) Dynamic panel data estimation using DPD : a guide for uses. *Institute of Fiscal Studies Working Paper* 88/15
- Arellano, M. and S. Bond, (1991) Some tests of specification for panel data : Monte Carlo evidence and an application to employment equations. *Review of Economic Studies* 58, pp. 277-297.
- Barbier, E., (1989) *Economics, Natural Resource Scarcity and Development*. London: Earthscan.
- Barbier, E., (1991) Environmental degradation in the third world. In Pearce, D. W., ed., *Blueprint 2*. London: Earthscan, pp. 75-108.
- Bardhan, P. K., (1967) Optimal foreign borrowing. In Shell, K., ed., *Essays on the Theory of Optimal Economic Growth*. Cambridge, MA : MIT Press, pp. 117-128.

- Barnett, H. J., (1979) Scarcity and growth revisited. In Smith, V. K., ed., *Scarcity and Growth Reconsidered*. Baltimore: John Hopkins Press. pp 163-217.
- Barnett, H. J. and C. Morse, (1963) *Scarcity and Growth: The Economics of Natural Resource Availability*. Baltimore: John Hopkins Press.
- Barnett, S. and C. Storey, (1970) *Matrix Methods in Stability Theory*. London: Nelson.
- Barnett, S., (1971) *Matrices in Control Theory*. London: Van Nostrand Reinhold.
- Barrett, S., (1992) Economic growth and environmental preservation. *Journal of Environmental Economics and Management*, 23, pp. 289-300.
- Bergh, J. C. van den, and P. Nijkamp, (1991) Operationalising sustainable development : dynamic ecological economic models. *Ecological Economics*, 4 (1), pp. 11-34.
- Binswanger, H. P., (1991) Brazilian policies that encourage deforestation in the Amazon. *World Development*, 19(7), pp. 821-829.
- Bishop, R. C., (1982) Option value: an exposition and extension. *Land Economics*, 58(1), pp. 1-15.
- Blanchard, O. and S. Fischer, (1989) *Lectures on Macroeconomics*. Cambridge, Mass.: MIT Press.
- Bohi, D. R. and M. A. Toman, (1984) *Analysing Non-renewable Resource Supply*. Washington, D.C.: Resources for the Future.
- Bond, S. and C. Meghir, (1994) Dynamic investment models and the firm's financial policy. *Review of Economic Studies*, 61, pp. 197-222.
- Brown, G. M. and B. Field, (1978) Implications of alternative measures of natural resource scarcity. *Journal of Political Economy*, 86, pp. 229-243.
- Brown, K. and D. W. Pearce, eds., (1994) *The Causes of Tropical Deforestation*. London: UCL Press.
- Bruno, M., (1976) The two-sector open economy and the real exchange rate. *American Economic Review*, 66(4), pp. 566-577.

Burgess, J. C., (1992) *Economics of frontier agriculture expansion and tropical deforestation*. Department of Economics, University College London. Mimeo

Cairns, R. D., (1985) Nickel depletion and pricing: further considerations. *Journal of Environmental Economics and Management*, 12, pp. 395-396.

Cairns, R. D., (1986) More on depletion in the nickel industry. *Journal of Environmental Economics and Management*, 13, pp. 93-98.

Capistrano, A. D. and C. F. Kiker, (1990) *Global economic influences on tropical broad-leaved forest depletion : 1967-85*. Food and Resource Economics Department., University of Florida. Mimeo.

Capistrano, A. D. and C. F. Kiker, (1995) Macro-scale influences on forest depletion. *Ecological Economics*, 14(1), pp. 21-29.

Chamberlain, G., (1984) Panel data. In Griliches, Z. and M. D. Intriligator, eds., *Handbook of Econometrics*, Vol. II. Amsterdam: North-Holland. pp. 1247-1318.

Chang, P. H. K., (1987) *The role of developing country debt and currency devaluation in the current commodity slump*. World Bank Commodity Studies and Projections Division Working Paper No. 1987-1, World Bank.

Clark, C., (1976) *Mathematical Bioeconomics: The Optimal Management of Renewable Resources*. New York: John Wiley.

Clark, C., (1991) Economic biases against sustainability. In Costanza, R., ed., *Ecological Economics : The Science and Management of Sustainability*. New York: Columbia University Press. pp. 319-101.

Cline, W. R., (1985) International debt: analysis, experience and prospects. *Journal of Development Planning*, 16, pp. 25-55.

Cohen, D., (1991) *Private Lending to Sovereign States*. Cambridge, Mass.: MIT Press.

Cohen, D. and J. Sachs, (1986) Growth and external debt under risk of debt repudiation. *European Economic Review*, 30, pp. 529-560.

Dasgupta, P., (1995) Optimal development and the idea of net. national product. In Goldin, I. and L. A. Winters, eds., *The Economics of Sustainable Development*. Cambridge, U.K: Cambridge University Press. pp. 114-146.

Dasgupta, P., R. Eastwood and G. M. Heal, (1978) Resource management in a trading country. *Quarterly Journal of Economics*, 92, pp. 296-306.

Dasgupta, P. and G.M. Heal, (1974) The optimal depletion of exhaustible resources. *Review of Economic Studies, Symposium on the Economics of Exhaustible Resources*, pp. 3-28

Dasgupta, P. and G.M. Heal, (1979) *Economic Theory and Exhaustible Resources*. Cambridge, U.K.: Cambridge University Press.

Dasgupta, P. and K. G. Mäler, (1990) The environment and emerging development issues. *The Development Economics Research Programme, Discussion Paper No. 28*.

Davidson, R. and MacKinnon, J. G., (1993) *Estimation and Inference in Econometrics*. Oxford: Oxford University Press.

Deacon, R.T., (1994) Deforestation and the rule of law in a cross-section of countries. *Land Economics*, 70(4), pp. 414-30.

Deacon, R. T., (1995) Assessing the relationship between government policy and deforestation. *Journal of Environmental Economics and Management*. 28, pp. 1-18.

Deacon, R. T. and P. Murphy, (1995) *The structure of an environment transaction : the debt for nature swap*. Department of Economics, University of California, Santa Barbara. Mimeo

Devarajan, S. D. and A. Fisher, (1981) Hotelling's "Economics of exhaustible resources": fifty years later. *Journal of Economic Literature*, 19, pp. 65-73.

Devarajan, S. D. and A. Fisher, (1982) Exploration and scarcity. *Journal of Political Economy*, 90, pp. 1279-1290.

Dockner, E., (1985) Local stability analysis in optimal control models with two static variables. In Feichtinger, G., ed., *Optimal Control Theory and Economic Analysis*. Amsterdam: North Holland, pp. 89-103.

Dornbusch, R. and S. Fischer, (1985) The world debt problem : origins and prospects. *Journal of Development Planning*, 16, pp. 57-81.

Eaton, J., (1989) Foreign public capital flows. *In* Chenery, H. B. and T. N. Srinivasan, eds., *Handbook of Development Economics*. Amsterdam: North-Holland.

Eaton, J., (1993) Sovereign debt: a primer. *The World Bank Economic Review*, 7(2), pp. 137-172.

Eaton, J. and M. Gersovitz, (1981) Debt with potential repudiation: theoretical and empirical analysis. *Review of Economic Studies*, 48, pp. 289-309.

Eaton, J. and L. Taylor, (1986) Developing country finance and debt. *Journal of Development Economics*, 22, pp. 209-265.

Edwards, S., (1988) Real and monetary determinants of real exchange rate behaviour: theory and evidence from developing countries. *Journal of Development Economics*, 29, pp. 311-341.

Ehui, S. K., Hertel, T. K. and P. V. Preckel, (1990) Forest resource depletion, soil dynamics, and agricultural productivity in the tropics. *Journal of Environmental Economics and Management*, 18, pp. 136-154.

Epple, D., (1985) The econometrics of exhaustible resource supply: a theory and an application. *In* Sargent, T. J., ed., *Energy, Foresight and Strategy*. Washington D.C.: Resources for the Future. pp. 143-200.

Epple, D. and L. Hansen, (1981) An econometric framework for modelling exhaustible resource supply. *In* Ramsey, J. B., ed., *The Economics of Exploration for Energy Resources*. London : JAI Press, pp. 103-117.

Epple, D. and J. Londregan (1993) Strategies for modeling exhaustible resource supply. *In* Kneese, A. V. and J. L. Sweeney, eds., *Handbook of Natural Resource and Energy Economics Vol. III*. Amsterdam: Elsevier. pp. 1077-1107.

Farrow, S., (1985) Testing the efficiency of extraction from a stock resource. *Journal of Political Economy*, 93(1), pp. 452-487.

Favero, C. A., (1992) Taxation and the optimisation of oil exploration and production: the UK continental shelf. *Oxford Economic Papers*, 44, pp. 187-208.

Feichtinger, G. and A. Novak, (1991) A note on the optimal use of environmental resources by an indebted country. *Journal of Institutional and Theoretical Economics*, 147(3), pp. 547-555.

Fisher, A., (1981) *Resource and Environmental Economics*. Cambridge: Cambridge University Press.

Food and Agricultural Organisation of the United Nations, (1990) *Interim Report on Forest Resources Assessment 1990 Project*. (10th Session FAO Committee on Forestry, Rome 24-28 September). Rome: FAO.

Food and Agricultural Organisation of the United Nations, (1991a) *Yearbook of Forest Products, Volume 44 (1990)*. Rome: FAO.

Food and Agricultural Organisation of the United Nations, (1991b) *Production Yearbook, Volume 44 (1990)*. Rome: FAO.

Food and Agricultural Organisation of the United Nations, (1991c) *Trade Yearbook, Volume 44 (1990)*. Rome: FAO.

Food and Agricultural Organisation of the United Nations, (1993) *Forest Resources Assessment 1990: Tropical Countries*. Rome: FAO.

Food and Agricultural Organisation of the United Nations, (1995) *Quarterly Bulletin of Statistics*. Rome: FAO.

Food and Agricultural Organisation of the United Nations, Forestry Resources Division, (1988) *An Interim Report on the State of Forest Resources in the Developing Countries*. Rome: FAO.

Frank, J. and M. Babunovic, (1984) An investment model of natural resources markets. *Economica*, 51, pp. 83-95.

Gaudet, G. and P. Howitt, (1989) A note on uncertainty and the Hotelling rule. *Journal of Environmental Economics and Management*, 16, pp. 80-86.

George, S., (1989) *A Fate Worse than Debt*. Hammersworth : Penguin Books.

George, S., (1992) *The Debt Boomerang*. London : Pluto Press.

Ghysels, E. and A. Hall, (1990) A test for structural stability of Euler conditions parameters estimated via the generalized method of moments. *International Economic Review*, 31(2), pp. 355-364.

Gilbert, C. L., (1986) *The impact of exchange rates and developing country debt on commodity prices*. World Bank Commodity Studies and Projections Division Working Paper No. 1986-4, World Bank.

Gilbert, C. L., (1989) The impact of exchange rates and developing country debt on commodity prices. *The Economic Journal*, 99, pp. 773-784.

Gilbert, R. J., (1979) Optimal depletion of an uncertain stock. *Review of Economic Studies*, 46, pp. 47-58.

Gillis, M., (1988a) Indonesia: public policies, resource management and the tropical forest. In Repetto, R. and M. Gillis, eds., (1988) *Public Policies and the Misuse of Forest Resources*. pp. 43-113.

Gillis, M., (1988b) West Africa: Resource management policies and the tropical forest. In Repetto, R. and M. Gillis, eds., (1988) *Public Policies and the Misuse of Forest Resources*. pp. 299-351.

Glick, R. and H. J. Kharas, (1986) The costs and benefits of foreign borrowing: a survey of multi-period models. *Journal of Development Studies*, 24(4), pp. 279-299.

Goldin, I. and A. L. Winters, (1995) *The Economics of Sustainable Development*. Cambridge : Cambridge University Press.

Gregory, R. G., (1976) Some implications of the growth of the mineral sector, *The Australian Journal of Agricultural Economics*, 20, pp. 71-91.

Gullison, R. E. and E. C. Losos, (1993) The role of foreign debt in deforestation in Latin America. *Conservation Biology*, 7, pp. 146-147.

Guppy, N., (1984) Tropical deforestation: a global view. *Foreign Affairs*, 62(4), pp. 928-965.

Hamada, K., (1969) Optimal capital accumulation by an economy facing an international capital market. *Journal of Political Economy*, 77, pp. 684-697.

Hajivassiliou, V.A., (1987) The external debt repayment problems of LDC's: an econometric model based on panel data. *Journal of Econometrics*, 36, pp. 205-229.

Hall, D. C. and J. V. Hall, (1984) Concepts and measures of natural resource scarcity with a summary of recent trends. *Journal of Environmental Economics and Management*, 11, pp.363-379.

- Hall, R., (1978) Stochastic implications of the life-cycle-permanent income hypothesis: theory and evidence. *Journal of Political Economy*, 86, pp. 971-987.
- Halvorsen, R. and T. R. Smith, (1984) On measuring natural resource scarcity. *Journal of Political Economy*, 92(5), pp. 954-964.
- Halvorsen, R. and T. R. Smith, (1991) A test of the theory of exhaustible resources. *Quarterly Journal of Economics*, Feb., pp. 123-140.
- Hansen, L. P., (1982) Large sample properties of generalized method of moments estimators. *Econometrica*, 50, pp. 1029-1053.
- Hansen, L. P. and K. Singleton, (1982) Generalized instrumental variables estimation of non-linear rational expectations models. *Econometrica*, 50, pp. 1269-1286.
- Hansen, S., (1989) Debt for Nature Swaps: an overview of the issues. *Ecological Economics*, 1(1), pp. 77-95.
- Harris, DeVerle P., (1993) Mineral resource stocks and information. In Kneese, A. V. and J. L. Sweeney, eds., *Handbook of Natural Resource and Energy Economics Vol. III*. Amsterdam: Elsevier. pp. 1011-1076.
- Hartwick, J. M., (1978) Exploitation of many deposits of an exhaustible resource. *Econometrica*, 46(1), pp. 201-217.
- Heal, G. M., (1976) The relationship between price and extraction cost for a resource with a backstop technology. *Bell Journal of Economics*, 7(2), pp. 371-378.
- Heal, G. M., (1993) The optimal use of exhaustible resources. In Kneese, A. V. and J. L. Sweeney, eds., *Handbook of Natural Resource and Energy Economics vol. III*. Amsterdam: Elsevier, pp. 855-880.
- Heal, G. and M. Barrow, (1980) The relationship between interest rates and metal price movements. *Review of Economic Studies*, 47, pp. 161-181.
- Heal, G. and M. Barrow, (1981) Empirical investigation of the long-term movement of resources: a preliminary report. *Economic Letters*, 7, pp. 95-103.
- Hecht, S. and A. Cockburn, (1990) *The Fate of the Forest : Developers, Destroyers and Defenders of the Amazon*. London: Penguin Books.

Hirshleifer, J., (1970) *Investment, Interest and Capital*. Englewood Cliffs. New Jersey: Prentice-Hall.

Hoel, M., (1978) Resource extraction, uncertainty and learning. *Bell Journal of Economics*, 9(2), pp. 642-645.

Hoffman, D. and A. Pagan, (1989) Post-sample prediction tests for generalized method of moment estimators. *Oxford Bulletin of Economics and Statistics*, 51(3), pp. 333-343.

Holtz-Eakin, D., W. K. Newey and H. S. Rosen, (1988) Estimating vector autoregressions with panel data. *Econometrica*, 56(6), pp. 1371-1395.

Hotelling, H., (1931) The economics of exhaustible resources. *Journal of Political Economy*, 39, pp. 137-175.

Hotz, V. J., F. E. Kydland and G. L. Sedlacek, (1988) Intertemporal preferences and labor supply. *Econometrica*, 56(2), pp. 335-360.

Hsiao, C., (1986) *Analysis of Panel Data*. Cambridge, U.K.: Cambridge University Press.

International Monetary Fund, *International Financial Statistics*. New York: IMF Publications. (Various Issues).

Kahn, J. R. and J. A. McDonald, (1990) *Third world debt and tropical deforestation*. Department of Economics, SUNY -Binghamton, Binghamton, Mimeo.

Kahn, J. R. and J. A. McDonald, (1995) Third world debt and deforestation. *Ecological Economics*, 12(2), pp. 107-123.

Klaassen, G. A. J. and J. B. Opschoor, (1991) Economics of sustainability, or the sustainability of economics: different paradigms. *Ecological Economics*, 4(2), pp. 93-116.

Keane, M. P. and D. E. Runkle, (1990) Testing the rationality of price forecasts: new evidence from panel data. *American Economic Review*, 80(4), pp. 714-735.

Kharas, H. J., (1984) The long-run creditworthiness of developing countries: theory and practice. *Quarterly Journal of Economics*, 98 (Aug.), pp. 415-439

- Kletzer, K., (1984) Asymmetries of information and LDC borrowing with sovereign risk. *The Economic Journal*, 94, pp. 287-307.
- Kletzer, K., (1988) External borrowing by LDCs : a survey of some theoretical issues. In Ranis, G. and T. P. Schultz, eds., *The State of Development Economics : Progress and Perspectives*. Oxford: Basil Blackwell. pp. 579-616.
- Koopmans, T., (1973) Some observations on 'optimal' economic growth and exhaustible resources. In Bos, H. C., H. Linnerman and P de Wolff, eds. *Economic Structure and Development*, Essays in Honour of Jan Tinbergen. Amsterdam : North Holland, pp. 239-255.
- Krutilla, J. A., (1967) Conservation reconsidered. *American Economic Review*, 57, pp. 777-786.
- Lanly, J. P., (1982) *Tropical Forest Resources*. FAO Forestry Paper 30. Rome: FAO.
- Lensink, R. and P. A. G. van Bergeijk, (1991) The determinants of developing countries' access to the international capital market. *Journal of Development Studies*, 28(1), pp. 86-103.
- Léonard, D. and N. van Long, (1992) *Optimal Control Theory and Static Optimization in Economics*. Cambridge: Cambridge University Press.
- Levhari, D. and N. Liviatin, (1977) Notes on Hotelling's economics of exhaustible resources. *Canadian Journal of Economics*, 10(2), pp. 177-194.
- Lewis, T. R., (1977) Attitudes toward risk and the optimal exploitation of an exhaustible resource. *Journal of Environmental Economics and Management*, 4, pp. 111-119.
- Livernois, J. R. and R. S. Uhler, (1987) Extraction costs and the economics of non-renewable resources. *Journal of Political Economy*, 95(1), pp. 195-203.
- Long, N. van, (1974) International borrowing for resource extraction. *International Economic Review*, 15(1), pp. 168-183.
- Long, N. van, (1975) Resource extraction under uncertainty about possible nationalization. *Journal of Economic Theory*, 10, pp. 42-53.
- Long, N. van, (1984), On the short-run and long-run effects of a resource boom. In: Siebert, H., ed., *The Resource Sector in an Open Economy*. Berlin: Springer-Verlag. pp. 17-45.

Looney, R. and C. Knouse, (1987) Profiles of third world mineral producers. *Resources Policy*, 13, pp. 55-67.

Loury, G. C., (1978) The optimal exploitation of an unknown reserve. *Review of Economic Studies*, 45, pp. 621-636.

Mahar, D. J., (1989) *Government Policies and Deforestation in Brazil's Amazon Region*. Washington, D.C. : The World Bank.

Mansoorian, A., (1991) Resource discoveries and excessive external borrowing. *The Economic Journal*, 101, pp. 1497-1509.

Manthy, R., (1978) *Natural Resource Commodities - A Century of Statistics*. Baltimore: John Hopkins Press.

Martin, R and M. Selowsky, (1983) Energy prices, substitution and optimal borrowing in the short-run. *Journal of Development Economics*, 14, pp. 331-50.

Mathers, A. S., (1990) *Global Forest Resources*. Oregon: Timber Press.

McDonald, D. C., (1982) Debt capacity and developing country borrowing: a survey of literature. *IMF Staff Papers*, 29, pp. 603-646.

McFadden, D. et. al., (1985) Is there life after death ? An econometric analysis of the creditworthiness of developing countries. In Smith, G. W. and J. T. Cuddington, eds., *International Debt and the Developing Countries, A World Bank Symposium*. Washington D.C.: The World Bank.

Mendelsohn, R., (1994) Property rights and tropical deforestation. *Oxford Economic Papers*, 46, pp. 750-756.

Miller, M. H. and C. W. Upton, (1985) A test of the Hotelling valuation principle. *Journal of Political Economy*, 93(1), pp. 1-25.

Miller, M., (1991) *Debt and the Environment : Converging Crises* New York : United Nations Publications.

Mohr, E., (1988) International borrowing and exhaustible resources: note on a liquidity creditworthiness conflict. *European Economic Review*, 32(4), pp. 1385-92.

Murphy, P., (1994) *Debt and deforestation in developing countries*. Department of Economics, University of California, Santa Barbara. Working Papers in Economics, No. 9-94.

Myers, N., (1980) *Conversion of Tropical Moist Forests*. Washington, D.C.: National Academy of Science.

Myers, N., (1983) Conversion Rates in Tropical Moist Forests. In Golley, F. B., ed., *Tropical Rainforest Ecosystems: Structure and Function*. Amsterdam: Elsevier. pp. 289-300.

Neher, P., (1990) *Natural Resource Economics*. Cambridge, U.K : Cambridge University Press.

Newey, W. K., (1985) Generalized method of moments specification testing. *Journal of Econometrics*, 29, pp. 229-256.

Newey, W. K. and K. D. West, (1987a) A simple positive definite, heteroskedasticity and autocorrelation consistent covariance matrix. *Econometrica*, 55, pp. 703-708.

Newey, W. K. and K. D. West, (1987b) Hypothesis testing with efficient method of moments estimation. *International Economic Review*, 28(3), pp. 777-787.

Norgaard, R., (1990) Economic indicators of resource scarcity: a critical essay. *Journal of Environmental Economics and Management*, 19, pp. 19-26.

Norgaard, R. and R. Howarth, (1991) Sustainability and discounting the future. In Costanza, R., ed., *Ecological Economics : The Science and Management of Sustainability*. New York: Columbia University Press. pp. 88-101.

Nickell, S., (1981) Biases in dynamic models with fixed effects. *Econometrica*, 49(6), pp. 1417-1426.

Nunnenkamp, P., (1990) Determinants of voluntary and involuntary bank lending to developing countries in the 1980s. *Kyklos*, 43, pp. 555-577.

Nziramasanga, M. T. and C. Obideguu (1981) Primary commodity price fluctuations and developing countries: an econometric model of copper and Zambia. *Journal of Development Economics*, 9(1), pp. 89-119.

O'Faircheallaigh, C., (1985). Financial failures in mining. *Resources Policy*, 11, pp. 235-244.

Pagan, A., (1984) Econometric issues in the analysis of regressions with generated regressors. *International Economic Review*, 25, pp. 221-247.

Pagan, A., (1986) Two stage and related estimators and their applications. *Review of Economic Studies*, 53, pp. 517-538.

Pagan, A. and F. Vella, (1989) Diagnostic tests for models based on individual data: a survey. *Journal of Applied Econometrics*, 4, pp. S29-S59.

Panayotou, T., (1992) The economics of environmental degradation: problems, causes and responses. In Markandya, A. and J. Richardson, eds., *The Earthscan Reader in Environmental Economics*. London: Earthscan; 1992. pp. 316-363.

Panayotou, T. and S. Sungsuwan, (1994) An econometric analysis of the causes of tropical deforestation: the case of northeast Thailand. In Brown, K. and D. W. Pearce, eds., *The Causes of Tropical Deforestation*. pp. 192-210.

Pearce, D., (1991) An economic approach to saving the tropical forests. In Helm, D., ed., *Economic Policy Toward the Environment*. Oxford: Blackwell. pp. 239-262.

Pearce, D., E. Barbier and A. Markandya, (1990) *Sustainable Development: Economics and Environment in the Third World*. London: Edward Elgar.

Pesaran, M. H., (1990) An econometric analysis of exploration and extraction of oil in the UK continental shelf. *The Economic Journal*, 100, pp. 367-390.

Pesaran, M. H. and B. Pesaran, (1991) *Microfit 3.0 Users Manual*. Oxford: Oxford University Press.

Pesaran, M. H. and R. J. Smith, (1990) A unified approach to estimation and orthogonality tests in linear single-equation econometric models. *Journal of Econometrics*, 44, pp. 41-66.

Pezzey, J., (1989) *Economic analysis of sustainable growth and sustainable development*. Working Paper No. 15. Washington D.C. : The World Bank.

Pitchford, J. D., (1989) Optimum borrowing and the current account when there are fluctuations in income. *Journal of International Economics*, 26, pp. 345-358.

Pindyck, R. S., (1978) The optimal exploration and production of non-renewable resources. *Journal of Political Economy*, 86, pp. 841-861

Pindyck, R. S., (1980) Uncertainty and exhaustible resource markets. *Journal of Political Economy*, 88, pp. 1203-1225.

Ramsey, F., (1928) A mathematical theory of saving. *The Economic Journal*, 38, pp. 543-559.

Rauscher, M., (1989) Foreign debt and renewable resources. *Metroeconomica*, 40(1), pp. 57-66.

Rauscher, M., (1990) The optimal use of environmental resources by an indebted country. *Journal of Institutional and Theoretical Economics*, 146(3), pp. 500-517.

Repetto, R., (1988) Overview. In Repetto, R. and M. Gillis, eds., (1988) *Public Policies and the Misuse of Forest Resources*. pp. 1-41.

Repetto, R. and M. Gillis, eds., (1988) *Public Policies and the Misuse of Forest Resources*. Cambridge, U.K.: Cambridge University Press.

Sachs, J. and D. Cohen, (1985) LDC borrowing with default risk. In Krümmel, H. J., ed., *Internationales Bankgeschäft* (Beihefte zu Kredit und Kapital H8), Berlin. pp. 211-235.

Sachs, J. D., ed., (1989) *Developing Country Debt and the World Economy*. Chicago: Chicago University Press.

Sargan, J. D., (1958) The estimation of economic relationships using instrumental variables. *Econometrica*, 26, pp. 393-415.

Seldon, T. M. and D. Song, (1994) Environmental quality and development : is there a Kuznets curve for air pollution emissions ? *Journal of Environmental Economics and Management*, 27, pp. 147-162

Sen, S., (1993) The influence of external debt on Latin American metal and mineral exports, *Resources Policy*, 19, pp. 225-229.

Sevestre, P. and A. Trognon, (1992) Linear Dynamic Models. In Mátyás, L. and P. Sevestre, eds., *The Econometrics of Panel Data*. Dordrecht: Kluwer Academic Publishers. pp. 95-117.

Shafik, N., (1994) Macroeconomic causes of deforestation: barking up the wrong tree ? In Brown, K. and D. W. Pearce, eds., *The Causes of Tropical Deforestation*. pp. 81-95.

Shilling, J. D., (1992) Reflections on debt and the environment. *Finance and Development*, 29, pp. 28-30.

Siebert, H., (1985) *Economics of the Resource-Exporting Country : Intertemporal Theory of Supply and Trade*. Greenwood, Connecticut : JAI Press.

Slade, M. E., (1982) Trends in natural-resource commodity prices: an analysis of the time domain. *Journal of Environmental Economics and Management*, 9, pp. 122-137.

Slade, M. E., (1991) Do markets underprice natural-resource commodities ? Background paper prepared for *World Development Report 1992: Environment and Development*. Washington, D.C: The World Bank.

Smith, V. K., (1978) Measuring resource scarcity: theory and practice. *Journal of Environmental Economics and Management*, 5, pp. 150-171.

Smith, V. K., (1979) Natural resource scarcity: a statistical analysis. *Review of Economics and Statistics*, 61, pp. 423-427.

Smith, V. K., (1981) The empirical relevance of Hotelling's model for natural resources. *Resources and Energy*, 3, pp. 105-117.

Solow, R. M., (1974) The economics of resources and the resources of economics. *American Economic Review, Papers and Proceedings*, 64, pp. 1-14.

Solow, R. M. and F. Y. Wan, (1976) Extraction costs in the theory of exhaustible resources. *Bell Journal of Economics*, 7(2), pp. 359-370.

Southgate, D., (1991) *Tropical deforestation and agricultural development in Latin America*. Environment Department, Working Paper No. 1991-20. The World Bank.

Southgate, D. and D. Pearce, (1988) *Agricultural colonization and environmental degradation in frontier developing economies*. Environment Department Working Paper No.9; The World Bank.

Southgate, D., R. Sierra and L. Brown, (1991) The causes of tropical deforestation in Ecuador : a statistical analysis. *World Development*, 19(9), pp. 1145-1151.

- Stiglitz, J.E. and A. Weiss, (1981) Credit rationing in markets with imperfect information. *American Economic Review*, 71, pp. 393-410.
- Stollery, K. R., (1983) Mineral depletion with costs as the extraction limit: a model applied to the behavior of prices in the nickel industry. *Journal of Environmental Economics and Management*, 10, pp. 151-165.
- Stollery, K. R., (1985) User costs versus markups as determinants of prices in the nickel industry: reply. *Journal of Environmental Economics and Management*, 12, pp. 110-113.
- Summers, R. and A. Heston, (1991) The Penn world table (mark 5): an expanded set of international comparisons, 1950 - 1988. *Quarterly Journal of Economics*, May, pp. 327 - 368.
- Sweeney, J. L., (1993) Economic theory of depletable resources: an introduction. In Kneese, A. V. and J. L. Sweeney eds. *Handbook of Natural Resource and Energy Economics Vol. III*. Amsterdam: Elsevier. pp. 759-854.
- Toman, M. A., J. Pezzey and J. Krautkraemer, (1995) Neoclassical economic growth theory and "sustainability". In Bromley, D., ed., *Handbook of Environmental Economics*. Oxford: Blackwell.
- UNECE / Food and Agricultural Organisation of the United Nations, (1993) *The Forest Resources of the Temperate Zones. Volume 1: General Forest Resource Information*. Geneva: UNECE / FAO.
- Victor, P. A., (1991) Indicators of sustainable development : some lessons from capital theory. *Ecological Economics*, 4(3), pp. 191-214.
- Vousden, N., (1973) Basic theoretical issues in resource depletion. *Journal of Economic Theory*, 6(2), pp. 126-143.
- Vousden, N., (1974) International trade and exhaustible resources: a theoretical model. *International Economic Review*, 15(1), pp. 149-167.
- Warner, A., (1992) Did the debt crisis cause the investment crisis ? *Quarterly Journal of Economics*, Nov., pp. 1161-1186.
- Weinstein, M. C. and R J. Zeckhauser, (1975) The optimal consumption of depletable natural resources. *Quarterly Journal of Economics*, 89, pp. 371-392.
- Weitzman, M. L., (1976) The optimal development of resource pools. *Journal of Economic Theory*, 12, pp. 351-364.

- White, H., (1980) A heteroskedasticity-consistent covariance matrix estimator and a direct test for heteroskedasticity. *Econometrica*, 48, pp. 817-838.
- Whited, T. M., (1992) Debt, liquidity constraints and corporate investment: evidence from panel data. *Journal of Finance*, 47(4), Sept., pp. 1425-1459.
- World Bank, (1991) *Socio-Economic Indicators 1990*. Washington D.C. : The World Bank.
- World Bank, (1992) *World Development Report 1992*. Washington D.C. : The World Bank.
- World Bank, (1994) *World Debt Tables 1993-94*. Washington D.C.:The World Bank.
- World Commission on Environment and Development, (1987) *Our Common Future*. Oxford : Oxford University Press.
- World Resources Institute, (1994) *World Resources 1994-95*. Oxford: Oxford University Press.
- Young, D., (1992) Cost specification and firm behaviour in a Hotelling model of resource extraction. *Canadian Journal of Economics*, 25(1), pp. 41-59.
- Zeldes, S. P., (1989) Consumption and liquidity constraints: an empirical investigation. *Journal of Political Economy*, 97(2), pp. 305-345.