THE UNIVERSITY
OF ADELAIDE
AUSTRALIA

ENDOGENOUS GROWTH, INTERNATIONAL TRADE AND THE ENVIRONMENT

BY

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Submitted in partial fulfilment of the requirements for the degree of Master or Economics by research at the University of Adelaide.

August 2004

ACKNOWLEGEMENTS

My acknowledgments are many.

First of all, I would like to thank my supervisors, Professor Daniel Leonard for his compassionate care and his sharp supervision; and Associate Professor Richard Damania for his helpful guidance.

I am also grateful to The University of Adelaide for the Adelaide Scholarship International (ASI) that enables me to undertake the research. I also extend my thanks to all the staff, both academic and administrative, especially to Dr Ian W. Mc Lean for his invaluable advices in the last 5 years.

Finally, I wish to thank my family for their love, constant support and encouragement.

August 2004

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ABSTRACT

We develop a dynamic model that explicitly considers the trans-boundary pollution problem between two asymmetric countries. We found that the countries will enjoy higher long run growth rates and a higher environmental quality when they coordinate their environmental policies. Furthermore, the two countries suffer more heavily not cooperating with each other when their attitudes towards a cleaner environment differ greatly. The implication is that despite the inherent differences in their development level and in their environmental attitudes, developed and developing countries are strongly encouraged to cooperate environmentally. In the second part of the thesis, we turn the focus to the role of international trade in relation to economic growth and the environment. We found that the long run growth rates of the countries are lower when they engage in international trade, no matter whether the environmental externality is internalised or not. The impact of trade on welfare however is ambiguous.

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CHAPTER 1- INTRODUCTION AND LITERATURE REVIEW

Introduction

The traditional opposition to the current wave of trade liberalization is concerning with job losses and the influx of imported commodities. Environmentalists top up these reservations about globalisation by raising several issues regarding the harmful, sometimes detrimental impacts of globalisation and production expansion on environmental quality. Indeed, evidence of global warming, species extinction, and industrial pollution are rising. Environmentalists question if more trade and growth means more pollution, or demand the appropriate procedures to deal with trans-boundary pollution and global environmental problems.

While we have managed to reach a consensus about the roles of trade liberalization on rasing income and prosperity, the debate about the environment in relation with international trade and economic growth is at its most heated stage. Environmentalists start off the debate by stressing the sustainability concept and expressing the concern over possible negative impacts of the current expansion in trade and growth on the environmental and ecological system. Trade community provides feedback to that statement. They argue that if the environment is a normal good, higher income induced by trade and/or growth will boost demand for a cleaner environment, and therefore allow the government to afford costly investment in environmental protection and cleaner production technologies. The environmentalists respond with the exact same argument. Due to stricter environmental regulations imposed by now richer and more environmentally sensitive economies, polluting industries may migrate to poorer countries where regulation is somewhat less stringent, which actually worsens the global environment. This phenomenon is referred to as the “pollution haven hypothesis” and is said to have an adverse effect on the global environment. Furthermore, it might create a competition in which countries lower their environmental standard to attract foreign investors (widely known as the “race to the bottom”). Interaction between economic growth, international trade and the environment, particularly within the relationship of developed and developing countries is very interesting and the main motivation of thesis.

1.1 Empirical evidence regarding trade, growth and the environment:

1.1.1. Growth and the environment

Empirical evidence regarding growth in relation with the environment has mainly centred on the Environmental Kuznets Curve (EKC) literature. In his study Kuznets (1955) showed an inverted U-shaped relationship between income inequality and economic growth. That means, income inequality first increases at low level of national income then decreases at higher level. Economists found a very similar relationship between income and various measures of environmental quality, after controlling for potentially interfering variables such as population, openness to trade, income distribution and other institutional characteristics.

The best known EKC study is by Grossman and Kruger (1995). They showed an estimated EKC for SO_2, smoke and suspended particles using GEMS (Global Environmental Monitoring System) data for 52 cities in the period 1977-1988 in relation with PPP-adjusted per capita GDP. Selden and Song (1994) used data on emission in developed countries to find a turning point of $8 709 for SO_2; of $11217 for NO_x and of $5963 for CO. Shafik (1994); Holtz-Eakin and Selden (1995); Hilton and Levinson (1998); Bradford et al, 2000 are among many empirical studies of EKC.

Copeland and Taylor in their recently published paper (Copeland and Taylor, 2004) mentioned four explanations for the shape of the EKC. These are: (1) sources of growth; (2) income effect (3) threshold effect and (4) increasing returns to abatement. ‘Sources of growth’ refers to the fact that countries grow via capital accumulation in the early stages, which causes pollution and via human capital accumulation in the later stage, which reduces it. ‘Income effect’ refers to the change in the demand for good environmental quality as income rises. According to Copeland and Taylor, whether pollution rises and falls with income depends on the so-called income elasticity of marginal damages. Another EKC explanation is about the pollution thresholds or ‘threshold effects’. In the early stage, pollution may be neglected and unregulated for the sake of economic activities. However, after some thresholds have been breached, necessary abatement activities and regulations are imposed and implemented, which helps to mitigate the environmental problems. Finally, ‘increasing return to abatement’ is based on the argument that technological level and efficiency of abatement activities might rise over time along with the higher development stage of the countries.

The major contribution of EKC literature is to predict a strong environmental policy response to growth. To many, this suggests growth is the key to solving environmental problem. If environmental quality is a normal good, an increase in income brought by growth will both increase the demand for cleaner environment and enhance the ability of governments to afford costly measures to reduce pollution and to protect various aspects of the environment. Though providing no explicit connection between trade and the environment, EKC literature has strong implications for the empirical investigations of the effects of trade on the environment (due to the arguably positive correlation between trade and growth).

However we should not overemphasize the importance of income on polluting level. Income inequality, unequal power distribution, population densities and other institutional measures (political rights, literacy and civil properties…) are also significant in the polluting outcomes of countries. [Selden and Song(1994); Torras and Boyce(1998); Cropper and Griffiths(1994)].

Copeland and Taylor (2003) in their review about trade, growth and the environment mentioned a striking weakness of the EKC literature: there is very limited role of theoretical guidance to this empirical stream. They challenged a simple stable relationship between income and pollution, given that each is a function of more primitive determinants such as technologies and primary factors of production.

1.1.2 Trade and the environment

Copeland and Taylor (2004) mentioned the key role of international trade as an alternative abatement mechanism for rich countries. With economic integration, dirty goods at home can be taxed heavily and moved abroad. In other words, trade makes pollution demand more elastic and domestic environmental pollution more effective. However, polluting industries may migrate to poorer countries –referred as "pollution havens"- where stringent regulation may not apply. Various test regarding the 'pollution haven hypothesis' and the 'race to the bottom' hypothesis are the main focus of the empirical literature on trade and the environment. However, they often come up with conflicting results.

The evidence in support of the two hypotheses is mainly found in the background papers prepared for World Development Report (World Bank 1992). [Birdsall and Wheeler (1992); Lucas et at (1992); Low and Yeats (1992)]. Birdsall and Wheeler (1992) found that dirty industries developed faster in relatively closed Latin American economies than in the open ones. Pollution intensity of toxic emissions and a number of dirty industries grew rapidly in developing countries between 1960 and 1988 (Lucas et, at (1992)). Low and Yeats (1992) showed that developing countries tend to be attracted to polluting industries as opposed to non-polluting ones. They claimed support for the 'pollution haven' and the 'race to the bottom' hypothesis.

Counter-evidence is abundant. Leonard (1988) found no evidence for the claim that pollution cost are taken into account in location decision of multinational firms. Tobey (1990) found that variables representing stringency of environmental regulations in 23 countries fail to explain the export of five most "dirty" commodities. Wheeler (2000) in an attempt to test the pollution hypothesis, examined air pollution in main cities of China, Mexico and Brazil, which are the three biggest recipient of foreign investment in the developing world. He observed declining trends in most major forms of air pollution as these countries develop, implying a rejection of the hypothesis.

In an attempt to reconcile these differences, it is necessary to note that most of the studies are either country-specific or confined into pollution policy analysis. They seem to neglect the conventional comparative advantages that determine the export pattern of dirty goods. As a consequence, their results are not expected to be precise and consistent. These studies do present evidence in favour of one hypothesis or the other, but no one so far has conducted a formal systematic test of the hypotheses in a cross-country framework with information on technologies, factor endowments as well as environmental regulations (Copeland and Taylor (2003)). Again, on the other side of the coin, this unsatisfactory progress is not intentional but the consequence of several limitations, first and foremost the availability of panel data on pollution.

The second stream of the literature attempts to address directly the fundamental question: "Is free trade good for the environment?" A pioneering systematic analysis of the relationship between trade and the environment is by Grossman and Krueger (1991) who broke down the impact into three separate components. The *scale effect* is the likely increase in pollution due to an expansion of trade and production. The *technique effect* refers the changing techniques of production, including environmentally friendly production technologies, generated by trade and international spill-over effect. Finally, the *composition effect* refers to the changing composition of an economy that increasingly specialises on production activities that it enjoys a comparative advantage. Antweiler et al (1998) investigated how openness to international goods markets affects pollution concentrations. They incorporated Grossman and Krueger's scale, technique, and composition effects into their formal model and then tested the theory using data on sulphur dioxide concentrations. They found international trade creates relatively small changes in pollution concentrations when it alters the composition of national output. Estimates of the trade-induced technique and scale effects imply a net reduction in pollution from these sources. Combining their estimates of all three effects yields a somewhat surprising conclusion: freer trade appears to be good for the environment.

1.2 Theoretical evidence regarding trade, growth and the environment

1.2.1. Trade and the environment: static models

A majority of trade-environmental theoretical analysis employs static models to explain the one-off effect of trade liberalization on environmental quality. Simple two-product, two-country models in a partial or general equilibrium context are widely used. Some authors also integrate the comparative advantage trade theory (H—O model) in their analysis. Siebert(1992) extended a H-O framework to analyse the interaction between national environmental endowment and trade. He argued that a country with less environmental and natural resources would export less polluting intensity products. Only with appropriate environmental measures, the country's comparative advantage in pollution intensive commodities will decline. Anderson and Blackhurst (1992) investigated the effect of trade on environmental quality of a small country, then of a large country using partial equilibrium analysis. They showed that only appropriate environmental policies will improve welfare and environmental quality when a small country takes part in some forms of trade liberalization. Non-environmental policies in attempts to cut pollution, such as trade sanction will reduce welfare. If stricter environmental policies are imposed in rich countries, dirty goods production will move to poor country (as per the 'pollution haven hypothesis'). Antweiler et al (1998) showed for two countries with similar incomes and scale, openness is associated with lower pollution in the country that has a comparative advantage in polluting goods and the reverse for the other countries. However, Perroni and Wigle (1994) with a general equilibrium framework managed to show that trade liberalization has little impact on the environmental quality.

Copeland and Taylor (1994,1995) developed the static two-country general equilibrium model to illustrate North-South Trade and the environment. They also incorporated scale, technique, and composition effects into their model and derived that free trade raises world pollution if incomes differ substantially across countries. In their 1994 paper, environmental quality is assumed as a local public good and the two countries differ in their endowment of human capital. They showed that trade shifts polluting production into human capital scarce country and increases world pollution; and unilateral transfers from the human-capital rich to the poor will reduce world wide pollution (Copeland and Taylor, 1994). In their 1995 paper, Copeland and Taylor modified their 1994 paper and placed a strong emphasis on income effects. They also made a major realistic change allowing the environment to be a global public good. They also found that free trade raises world pollution if incomes differ substantially across countries, however, income transfer may not affect world pollution. In our model, international transfer under the form of an abatement subsidy improves environmental quality and welfare.

By working on mostly static models, theorists seem to concentrate on the short run effect of the pollution (via the disutility of consumers being exposed to pollution). The long run impact on the natural environment, viewed as a stock, is usually ignored. It is one of the most serious weaknesses of the current approach to environment-economic interaction modelling. The major aim of the thesis is to reconsider trade, growth and pollution in a dynamic long run framework. Hence a more detailed literature review is given in an effort to address the different types of dynamic model; and to discuss their strengths and weaknesses.

1.2.2. Growth and the environment: dynamic models

1.2.2.1 Endogenous growth theory:

In 1956 Robert Solow with his paper "A Contribution to the theory of Economic Growth" has laid the foundation for Neo-classical growth theory. In his article, production function takes the form $Y = F(K, L)$ where $F(\bullet)$ exhibits positive and diminishing marginal return with respect to each output. $F(\bullet)$ also exhibits constant return to scale. The economy converges to the steady state where per capita variables do not grow ($\dot{k} = \dot{y} = \dot{c} = 0$).

One result of this model relates to the concept of conditional convergence. The lower the starting level of real per capita GDP relative to the long run steady state, the higher is the growth rate. This prediction has been proved empirically to have some power in explaining the difference in economic growth rates across countries.

The second result of the Solow model is that long run growth eventually ceases. This is clearly unsatisfactory since it does not match the empirical evidence. For example, in the US, positive growth rate of output has persisted for two centuries and has no clear tendency to decline (Barro and Xala-I-Martin, 1995).

To overcome this problem, neoclassical economists in the 1950s and 1960s introduced exogenous technological progress into the model. They found that in the steady state, per capita capital, output and consumption grow at the rate of the given technological progress. This method allows for a constant positive long run growth and hence is in line with empirical evidence. Still, it also exposes a deficiency. The long run growth rate is entirely determined by an element that is given from outside the model (i.e. exogenous). There is no policy implication to control and improve the technical progress and economic growth.

Cass (1965) and Koopmans (1965) brought Ramsay's utility maximisation back and thereby introduced the endogeneity of the savings rate into this neoclassical model, but failed to correct the problem of long run growth being contingent on exogenous technological progress. For this reason, neo-classical theory is criticised as an inadequate explanation of economic growth. Growth theory, as a consequence, lost its contact with empirical application and received little attention in the next two decades.

In the late 1980's, growth theory returned to the centre stage of economic research with a new approach in which long run growth can be determined endogenously –i.e. within the model. Hence, it is often referred as "endogenous" growth. Four typical approaches of endogenous growth are the AK approach (Rebelo,1991), the learning by doing approach (Romer,1986), the human capital approach (Lucas, 1988) and the Schumpeterian approach(Aghion and Howitt, 1998).

It is proved that persistent positive long run growth is possible in situations where returns to accumulated factors are not diminishing. The simplest model that satisfies non-diminishing return is due to Rebelo (1991), where production function is specified as Y=AK (that's why the approach is named AK). K is understood as broad capital, including not only physical capital but also human capital and as can be seen, the return to scale for K is constant. The derived market driven endogenous growth is Pareto optimal.

The second approach is learning by doing approach (Arrow, 1962 and Romer, 1986). The production function of firm i is specified as a labour-augmenting technology $Y_i = F(K_i, A_i L_i)$ where K_i and L_i are capital and labour respectively, and A_i is the knowledge stock of that firm. This model is based on two assumptions. The first one is learning by doing i.e. an increase in any particular firm's capital stock (K_i) leads to a proportional increase in its knowledge (A_i). Secondly, each firm's knowledge is a public good that can be used by other firms at zero cost. These particular assumptions eliminate the diminishing return to capital and create endogenous growth in the framework of perfect competition. However, as shown by Romer (1990), the decentralised outcome is not Pareto optimal.

While the learning by doing approach identifies the engine for long run growth which is the technical progress as an unintended by- product of capital accumulation, human capital approach (Uzawa, 1965 and Lucas,1988) introduces human capital accumulation as a purposeful activity. Human capital is a set of intangible skills such as knowledge or technical experience that is embodied in each individual. Human capital can be gained by formal education, learning or on-the-job training. In this model, those activities take place in the human capital sector, which is a second sector beside the traditional final good sector. Agents distribute their time to participate in economic activities or to accumulate human capital, which in turn improves the productivity of the production process. The production function takes the form $Y = F(K, HL)$ where K and L are defined as before, and H is human capital. Along with physical capital, human capital is presented here as the driving force of endogenous growth and therefore, the role of formal and informal education is particularly emphasized in growth maximizing strategies.

Another typical approach of the new growth theory is the Schumpeterian approach. It stresses the importance of entrepreneurship and innovation in the face of competition and falling profit to economic growth. It is named after Joseph A. Schumpeter, 1883-1950, an

Austrian academic who first mentioned the theory of entrepreneurship (Schumpeter, 1934). A simple model of Schumpeterian approach is presented in Aghion and Howitt (1998) where final output is produced using labour and an intermediate good. Research activities generate a sequence of better and newer intermediate goods, which renders their predecessors obsolete. Firms are motivated to devote resources to research for the prospect of monopoly rent. Firm who discovers new intermediate product gets monopoly rent until its product is wiped out by a newer good. This continuous quality improvement is the cause of economic growth.

1.2.2.2 Endogenous growth and the environment:

Interactions between growth and the environment are various and interrelated. Economic activities cause pollution and degrade the environment. The effects of the latter on human activities, in turn, are diverse and have been thoroughly discussed in the literature. Smulders and Gradus (1996) pointed out at least three. Firstly, the environment acts as a life-support system. If environmental quality is critically low, life could not exist and neither could production or consumption. Hence, growth is zero. Secondly, they mentioned the effect of the environment on individual's utility. People have higher utility with a better environment. One feels better to breathe fresh air or to observe spectacular natural beauty. Thirdly, the environment acts as a public production factor. Moreover, the environment also has some regenerative capacity, as mentioned by Hofkes(1996).

Endogenous growth theorists have been able to take into account various interactions that have been discussed above and allow for long run growth to be determined endogenously. The basis for these models is described as follows. The classical utility optimisation problem is applied to an economy where pollution is an unavoidable side effect of economic activity. The representative agent's utility function includes both consumption and environmental quality. Environmental quality also makes a positive contribution to the production process. Some models take pollution as a flow instead of environmental quality as a stock in their analysis. If this is the case, pollution is assumed to have a positive marginal product. Eventually, the typical problem of various models is to choose the optimal level of consumption, abatement and investment so that utility is maximised. However, detailed model specifications differ from one researcher to another. Interestingly enough, they have been able to exploit all conventional approaches of endogenous growth theory (the AK approach, the Schumpeterian approach and the human capital approach) in their environment-incorporated models.

A typical example of the AK approach is the work of Stokey (1998). She modified the basic AK model to Y=AKz, where z $\in [0,1]$ is a measure of "dirtiness" of the existing technology (as can be seen, a cleaner technology, ceteris paribus, is associated with a lower output). Pollution is assumed to be proportional to the level of production $P = Yz^{\gamma}$ (γ>0). This means a more environmentally friendly method being put into use will reduce the pollution/output ratio. What she found is that growth is unsustainable in the long run. The cost of an increasingly cleaner technology will continuously reduce the social marginal product of capital until long run growth ceases.

Another approach to incorporate environmental issues is the Schumpeterian approach (Aghion and Howitt, 1998). They adapted Stokey's idea into their traditional Schumpeterian production function as follow $Y = K^{\alpha}(BL)^{1-\alpha}z$, where K and L are capital and labour respectively, B is the quality of intermediate goods, and z is also "dirtiness" of the technology. It is proved that sustainable development under some particular assumptions is possible, but not guaranteed.

The human capital approach has been adopted by many authors (Gradus and Smulders,1993; Bovenberg and Smulders,1996; Hofkes,1996; Hettich,1998). The traditional Lucas human capital sector is interpreted as a learning sector-producing knowledge about environmental technology. The production technology for the final good is given by $Y(K, Z, E)$ where K is physical capital, Z is human capital and E is the quality of the environment. Their results allow for sustainable development being feasible and socially optimal under some specific constraints on the production function. Still, the impact of increasing environmental concern on long run growth is mixed. Gradus and Smulders (1993) found that the optimal growth rate is independent of environmental preference. Others (e.g. Hofkes, 1996) showed the growth effect of greener preference is ambiguous and depends on the relative importance of the interdependencies between the environment and the economy.

1.2.2.3 Endogenous growth theory and the environment: an international perspective

The previous section summarizes the endogenous models that explain the interaction between the environment and long run growth. The interesting thing here is that mainstream research has been heavily devoted to environmental issues in a single economy. The analysis of this interaction in an international perspective has been largely ignored, despite the fact that most current ecological problems are ones that involve open access common property and require international cooperation. Examples are many. The rise in emission of greenhouse gases and the depletion of the ozone layer are two typical global issues; regional trans-boundary pollution problems include waterway pollution and acid rain. Still, study of growth-environment interaction in an international perspective is admittedly difficult. It is technically complicated to incorporate endogenous growth, endogenous environmental change and endogenous international trade into one single mathematical model. Nevertheless, in the words of Aghion and Howitt (1998), ”constructing such situations is the most interesting and challenging problem facing those interested in sustainable development”.

So far only a little work has been done on this problem. There are two approaches to modeling interaction between growth and the environment in a multi-regional context. One approach is to describe a region as an open system (Elbasha and Roe, 1995). The second approach is to describe a multi-regional system completely and explicitly. The very first attempt to investigate the interrelationship between endogenous growth, trade and environment in a system of two regions is by Van Den Berg et al (1998). They set up a very general framework of two regions where regional environmental processes interact through the global environment, endogenous technology allows for more efficient use of resources and there is diffusion of technology from one region to another. The model is too complicated to be solved, however, numerical exercises are provided. Nevertheless, this model's implication is comprehensive: growth is determined not only by technology but also driven by trade, technology diffusion and global environment improvement.

The thesis aims to develop a model that incorporates various roles of the environment in the production process and human activities; subsequently we attempt to illustrate the intricate and interrelated long run relationships between economic growth, international trade and the environmental quality. The model explicitly considers the trans-boundary pollution problem between two separated economies and allows for asymmetries between them. In chapter 2 of the thesis, the two countries are different in their environmental preferences. In chapter 3, we analyse the case where technologies are different and subsequently we consider the trading situation between countries.

CHAPTER 2- ENVIRONMENTAL POLLUTION, ASYMMETRIC ENVIRONMENTAL PREFERENCES AND ECONOMIC GROWTH

2.1 Motivation

Existing models incorporating the environment do not totally reflect and explain the current issue concerning trade, a common environment and growth, especially between developed and developing countries. The inherent differences in characteristics between developed and developing countries and in particular their attitudes towards environmental issues are ignored. Building a dynamic model that describes this asymmetry is very exciting and challenging. This is the main motivation of the thesis.

Differences between developed and developing countries concern their final products, their production and abatement technologies as well as public altitudes toward environmental pollution. In the first chapter we will consider the difference in environmental preference only, and leave other features of the economy identical for the two countries.

The idea of modelling different attitudes and preferences towards the environment is not far off reality. Empirical studies have indeed confirmed a clear disparity of environmental preferences of people belonging to different income groups. Unemployment rate, population density, proportion of population that has college level education or local environmental conditions are among other factors (Inglehart,1995; Ellis and Thompson, 1997; Dunlap and Mertig, 1995). At national level, according to the EKC-related analysis, countries tend to adopt a higher environmental preference at their later stage of development. However, this endogeny of environmental preference is ignored in the model. Each country is assumed to have an exogenous and fixed value of the environmental preference.

2.2 The basic model

We consider a hypothetical world that consists of two countries that are only different in their environmental preferences. For country *i*:

Utility function:

The economy *i* is populated by identical infinitely-lived individuals who seek to maximise total discounted lifetime utility:

$$U_i = \int_0^{\infty} e^{-\rho t} L_0 e^{\mu t} U_i(c_i, E)dt$$

where c_i is the level of per capita consumption

E is the stock of environment stock, common to both countries.

ρ is the constant positive discount rate

L_0 is population at time t=0

μ is the constant population growth rate

We assume no change in population and normalize the population of the economy to unity. Lifetime utility can be rewritten as:

$$U_i = \int_0^{\infty} e^{-\rho t} U_i(c_i, E)dt$$

Utility depends on consumption as well as environmental quality. The individual prefers higher levels of both consumption and environmental quality. A balanced growth solution can be obtained only if the utility function is of a special form (King et al, 1988).The utility function takes a logarithmic form as :

$$U_i(c_i, E) = \ln(c_i E^{\alpha_i}) = \ln c_i + \alpha_i \ln E$$

where α_i is the relative importance of the environment in the utility of country *i*.

Production function:

The production function takes the form $y_i = A_0 f(L)E$ where y is output, A_0 is technology proxy, *f(L)* represents some function of labour (*L*, normalised to 1, is the constant labour force) and E is the environmental quality. Denoting $A \equiv A_0 f(L)$, the production function can be written as $y_i = AE$,which resemble the linear CRS form.[1]

Final outputs are either consumed or used to abate the environment.

$$c_i = AE - a_i$$

In summary, in country 1:

$$\begin{aligned} &y_1 = AE \\ &c_1 = AE - a_1 \\ &U_1(c_1, E) = \ln c_1 + \alpha \ln E \end{aligned}$$

Similarly in country 2:

$$\begin{aligned} &y_2 = AE \\ &c_2 = AE - a_2 \\ &U_2 = \ln c_2 + \beta \ln E \end{aligned}$$

We assume that β<α, in words, country 2 cares less to the environment.

The environment:

Environmental quality changes as follow:

$$\dot{E} = nE - B(y_1 + y_2) + D(a_1 + a_2)$$

where n: rate of natural regenerative capacity of the environment

B: polluting effect of the production process to the environment.

D: effectiveness of abatement activities

The environmental equation considers the situation where both countries share a common environment. It is a very typical circumstance in reality. For instance, six countries Bulgaria, Georgia, Romania, Russian Federation, Turkey, and Ukraine surround the Black Sea and share the possibility of maintaining its ecosystem. In this common system, the polluting effect caused by one country is shared by every country involved. In addition, the effort to clean up the environment of one country also benefits others. As a result, countries

[1] In this production function we do not employ physical capital. It is because only one state variable is allowed for a tractable differential game. Here it is neatly used by E (environmental stock), which is the main interest of the model. See Dockner et. al.(2000) for more about differential games.

have an incentive to over pollute and under-abate the environment. This is usually referred to as the “tragedy of the commons”. The conventional expectation in these circumstances is that the environmental quality deteriorates and countries suffer the sub-optimal long run growth rates.

We assume $D>B$, indicating that the abatement activities are more effective than the polluting process. Given a negligible self-regeneration capability of the environment, the assumption is necessary for positive long run growth; since otherwise (i.e. $B>D$), the countries even with their entire output used for abatement would not be able to fix the damage the production causes to the environment.

The simple basic model set up might as well fit the real world example of two major players in the world economy: the United States and the European Union. Both are considerably equal in their size and in production and abatement technology. Their sheer economy sizes are not too far off the model assumption of the two-economy world. Interestingly, reality shows they have quite different approaches to global common environmental issues. Observers often said the EU is more environmentally protective than the US and that stylized fact fits well with the asymmetric environmental preference assumption of the model.

2.3 Basic results:

2.3.1 Non-cooperative solution

We first investigate the case where the two countries do not cooperate. One country cannot control the other’s production and abatement activities. Each country will single-handedly maximise their lifetime utility taking the other’s activities as given. The result will be a Nash-equilibrium of this differential game.

The social-planer problem of country 1 is to choose $\{a_1, c_1\}$ to maximise the representative agent’s utility subject to the environmental quality accumulation constraint and production constraint:

$$Max\int_0^{\infty} e^{-pt}(\ln c_1 + \alpha \ln E)dt$$

subject to $\dot{E} = nE - B(y_1 + y_2) + D(a_1 + a_2)$

or $\dot{E} = nE - 2ABE + D(a_1 + a_2)$

and $c_1 = AE - a_1$

Rewrite the problem:

$$Max\int_0^{\infty} e^{-pt}(\ln(AE - a_1) + \alpha \ln E)dt$$

subject to $\dot{E} = nE - 2ABE + D(a_1 + a_2)$

The social planner of country 1 will choose a_1 given a_2 and y_2. Consumption level c_1 will be chosen accordingly.

$$H_1 = \ln(AE - a_1) + \alpha \ln E + \varphi[nE - ABE - By_2 + D(a_1 + a_2)]$$

The maximum principle states that the solution satisfies the environmental constraint and the following:

$$\frac{\partial H_1}{\partial a_1} = 0 : \frac{1}{AE - a_1} = \varphi D \qquad \text{or } \frac{1}{c_1} = \varphi D \qquad (2.1)$$

$$\dot{\varphi} = -\frac{\partial H}{\partial E} + \rho\varphi = \frac{-A}{AE - a_1} - \frac{\alpha}{E} - \varphi(n - AB - \rho) \qquad (2.2)$$

Transversality condition:

$$\lim_{t \to \infty} \varphi(t) e^{-\rho t} E(t) = 0$$

Substitute (2.1) into (2.2):

$$\dot{\varphi} = -\frac{\alpha}{E} - \varphi(n - AB + AD - \rho) \qquad (2.2b)$$

Similarly, the Hamiltonian expression for country 2 is:

$$H_2 = \ln(AE - a_2) + \beta \ln E + \lambda[nE - ABE - By_2 + D(a_1 + a_2)]$$

$$\frac{\partial H_2}{\partial a_2} = 0 : \frac{1}{AE - a_2} = \lambda D \qquad \text{or } \frac{1}{c_2} = \lambda D \qquad (2.3)$$

$$\dot{\lambda} = -\frac{\beta}{E} - \lambda(n - AB + AD - \rho) \tag{2.4}$$

Transversality condition:

$$\lim_{t\to\infty} \lambda(t)e^{-\rho t}E(t) = 0$$

Rewrite the environmental equation:

$$\dot{E} = nE - 2ABE + D(a_1 + a_2)$$

$$\dot{E} = nE - 2ABE + D(AE - c_1 + AE - c_2)$$

$$\dot{E} = E(n - 2AB + 2AD) - D(c_1 + c_2) \tag{2.5}$$

Substitute (2.1) and (2.3) into (2.5)

$$\dot{E} = E(n - 2AB + 2AD) - \frac{1}{\lambda} - \frac{1}{\varphi} \tag{2.6}$$

Solve the system of (2.2b) (2.4) and (2.6)

$$\dot{\varphi} = -\frac{\alpha}{E} - \varphi(n - AB + AD - \rho)$$

$$\dot{\lambda} = -\frac{\beta}{E} - \lambda(n - AB + AD - \rho)$$

$$\dot{E} = E(n - 2AB + 2AD) - \frac{1}{\lambda} - \frac{1}{\varphi}$$

and the initial condition $E(0)=E_0$, we obtain the solution:

$$E(t)=E_0\exp(\gamma_1 t)$$

$$\varphi(t) = \varphi_0 \exp(-\gamma_1 t)$$

$$\lambda(t) = \lambda_0 \exp(-\gamma_1 t)$$

where $\boxed{\gamma_1 = n + 2(AD - AB)\left(2 - \frac{\alpha+\beta}{\alpha+\beta+\alpha\beta}\right) - \frac{\rho(\alpha+\beta)}{\alpha+\beta+\alpha\beta}}$

and $\varphi_0 = \frac{\alpha+\beta+\alpha\beta}{E_0\beta(\rho + AD - AB)}$; $\lambda_0 = \frac{\alpha+\beta+\alpha\beta}{E_0\alpha(\rho + AD - AB)}$

Note that $\varphi(t)E(t) = \varphi_0 E_0$ and $\lambda(t)E(t) = \lambda_0 E_0$. This follows the well-known result of Rebelo model (Rebelo, 1991) that when the utility function is in the log form, the total value of the state variable (in this case is the environmental quality) is constant over time. This also implies the tranversality condition is satisfied.
(The details are given in appendix A1)

Some basic insights can be drawn from these results. The two countries enjoy the same growth rates of γ_1. It is because of the assumption of the environmental quality being the only input of the production functions in both countries. Hence, the outputs of the two countries grow at the same rate as the environmental quality does. In addition, the growth rate is positively correlated with the technology proxy *A* and *D*-*B*, which is the difference between the abatement effective and severity of pollution. Rewrite the growth rate as follow:

$$\gamma_1 = n - 2AB + 2AD - (AD - AB + \rho)\left(1 - \frac{1}{1 + \frac{1}{\alpha} + \frac{1}{\beta}}\right)$$

As α and β increase, so would the growth rate, this shows a positive relationship between the environmental preferences and the growth rate. It helps mitigate the concern from the pro-business lobby that high environmental preference damages the country's competitiveness, thereby lowering economic growth. However, it is worthwhile to notice that the result is due to the environmental quality being the sole input in the production process.

Consumptions of country 1 and 2 are :

$$c_1 = \frac{1}{\varphi D} = \frac{E_0 \beta(\rho + AD - AB)}{D(\alpha + \beta + \alpha\beta)} \exp(\gamma_1 t) ;$$

$$c_2 = \frac{1}{\lambda D} = \frac{E_0 \alpha(\rho + AD - AB)}{D(\alpha + \beta + \alpha\beta)} \exp(\gamma_1 t)$$

In addition, it can be observed from the two consumption paths in previous page that the country with greener preference consumes less. If we assume $\alpha > \beta$, $c_1 < c_2$ will be obtained, implying a smaller consumption for country 1. Intuitively, the country with higher environmental preference will abate more and therefore have a smaller level of consumption, given the rigid assumption of symmetric output. The other country partially free rides on the efforts made by the first country.

2.3.2 Cooperative solution

The two countries choose c_1, c_2, a_1, a_2 to jointly maximise the total utility.

$$Max\int_0^\infty e^{-pt}(\ln c_1 + \alpha \ln E + \ln c_2 + \beta \ln E)dt$$ [2]

subject to: $\dot{E} = nE - 2ABE + D(a_1 + a_2)$

Since the two countries are coordinating their activities, it is sensible to assume that they know each other's budget constraints (i.e. $c_1 = AE - a_1$ and $c_2 = AE - a_2$).

Substitute the two budget constraints into the environmental equation and rewrite the social's planner problem:

$$Max\int_0^\infty e^{-pt}(\ln c_1 + \alpha \ln E + \ln c_2 + \beta \ln E)dt$$

subject to: $\dot{E} = nE - 2ABE + D(AE - c_1 + AE - c_2)$

The Hamiltonian is:

$$H = \ln c_1 + \alpha \ln E + \ln c_1 + \beta \ln E + \varphi\left[nE - 2ABE + D(AE - c_1 + AE - c_2)\right]$$

$$H = \ln c_1 + \alpha \ln E + \ln c_1 + \beta \ln E + \varphi E(n - 2AB + 2AD) - \varphi D(c_1 + c_2)$$

Now the two countries choose c_1 and c_2 (a_1 and a_2 will be chosen accordingly):

$$\frac{\partial H_1}{\partial c_1} = 0 : \frac{1}{c_1} = \varphi D \tag{2.7}$$

$$\frac{\partial H_1}{\partial c_2} = 0 : \frac{1}{c_2} = \varphi D \tag{2.8}$$

[2] Clearly the result would be different if each country's utility were given different weights, but there is no basis for such discrimination here. This will be taken up in the next chapter. This is only one Pareto efficient solution.

$$\dot{\varphi} = -\frac{\partial H}{\partial E} + \rho\varphi = -\frac{\alpha+\beta}{E} - \varphi(n - 2AB + 2AD - \rho) \quad (2.9)$$

Transversality condition:

$$\lim_{t\to\infty} \varphi(t) e^{-\rho t} E(t) = 0$$

Rewrite $\dot{E} = nE - 2ABE + D(a_1 + a_2)$ as

$$\dot{E} = (n - 2AB + 2AD)E - D(c_1 + c_2)$$

Substitute (2.7) and (2.8) in to the above:

$$\dot{E} = (n - 2AB + 2AD)E - \frac{2}{\varphi} \quad (2.10)$$

Solve the system of (2.9) and (2.10)

$$\dot{\varphi} = -\frac{\alpha+\beta}{E} - \varphi(n - 2AB + 2AD - \rho)$$

$$\dot{E} = (n - 2AB + 2AD)E - \frac{2}{\varphi}$$

and the initial condition $E(0)=E_0$, we obtain the solution:

$$E(t)=E_0\exp(\gamma_2)$$

$$\varphi(t) = \varphi_0 \exp(-\gamma_2 t)$$

where

$$\boxed{\gamma_2 = n - 2AB + 2AD - \frac{2\rho}{\alpha+\beta+2}}$$

$$\varphi_0 = \frac{\alpha+\beta+2}{E_0\rho} \text{ and}$$

$$c_1 = c_2 = \frac{1}{\varphi D} = \frac{E_0\rho}{D(\alpha+\beta+2)}\exp(\gamma_2 t)$$

(the details are given in appendix A2)

Again, $\varphi(t)E(t) = \varphi_0 E_0$, which implies the transversality condition is satisfied.

It also can be seen that the two economies grow exponentially at the same rate γ_2. The growth rate is again positively correlated with n, A, D-B, α and β and is negatively correlated with ρ. The two countries choose the same abatements level at every period (because after substituting the budget constraint into the objective function, a_1 and a_2 have the same weight). Consequently, they maintain the same consumption level.

Under the cooperative policy scenario we observe that the initial consumption level does not depend on the overall productivity parameter A. In other words a larger A will increase gross output but this increase will only result in higher abatement activities. This one-sided result is the consequence of the log form of the utility function. Had we used the more general form $U = \frac{\left(cE^{\alpha}\right)^{1-\theta}}{1-\theta}, \theta \neq 1$, this result would not have occurred. Unfortunately we can not obtain the analytical solution when $\theta \neq 1$.

2.3.3 Comparison of the two scenarios:

2.3.3.1 Comparison of growth rates:

Consider the non-cooperative and cooperative growth rates:

Non-cooperative: $\gamma_1 = n - 2AB + 2AD - \frac{(AD - AB + \rho)(\alpha + \beta)}{\alpha + \beta + \alpha\beta}$

Or $\gamma_1 = n - 2AB + 2AD - \frac{\rho(\alpha + \beta)}{\alpha + \beta + \alpha\beta} - \frac{(AD - AB)(\alpha + \beta)}{\alpha + \beta + \alpha\beta}$

Cooperative: $\gamma_2 = n - 2AB + 2AD - \frac{2\rho}{\alpha + \beta + 2}$

Simple algebra shows $\frac{2\rho}{\alpha + \beta + 2} < \frac{\rho(\alpha + \beta)}{\alpha + \beta + \alpha\beta}$ with $\alpha \neq 0$ and $\beta \neq 0$, hence $\gamma_2 > \gamma_1$.

When the two countries were not cooperating, they would suffer lower growth rate and the environmental quality is also growing more slowly. The result is exactly what we expected from "the tragedy of the commons".

More careful analysis provides some additional insights. The gap between the two growth rates depends on the size of $A(D\text{-}B)$, *ceteris paribus*. The larger the difference between D and B coefficients, the wider is the gap. That is, countries with cleaner production and advanced abatement technology have stronger incentives to co-ordinate their environmental policies than they would otherwise. Advanced abatement and clean production technology might provide strong incentives for the two countries to internalise the environmental externality. In addition, algebraic exercise also proves that the gap is larger when there is large discrepancy between α and β ([3]). Two countries suffer more heavily not cooperating with each other when their attitudes toward a cleaner environment differ greatly. This result was not expected. We traditionally think that two similar countries will have stronger incentives to coordinate their environmental activities because they share the same interest. In fact, most trade blocks and environmental protocols have been traditionally signed by countries that have similar sizes, development levels and common concerns. The model however stresses the importance of cooperation from countries with different environmental attitudes. The implication is very clear. Despite the inherent differences in their development level and in their environmental attitudes, developed and developing countries are strongly encouraged to discuss common environmental issues, to co-ordinate their activities to inform and educate public to understand and support the environmental initiatives, and to devote more resources to abate the environment.

2.3.3.3 Comparison of consumption paths:

Consumptions when the two countries do not cooperate (indicated by the N subscript)

$$c_{1N} = \frac{1}{\varphi D} = \frac{E_0\beta(\rho + AD - AB)}{D(\alpha+\beta+\alpha\beta)}\exp(\gamma_1 t);$$

$$c_{2N} = \frac{1}{\lambda D} = \frac{E_0\alpha(\rho + AD - AB)}{D(\alpha+\beta+\alpha\beta)}\exp(\gamma_1 t)$$

Consumptions when the two countries cooperate (indicated by the C subscript)

$$c_{1C} = c_{2C} = \frac{1}{\varphi D} = \frac{E_0\rho}{D(\alpha+\beta+2)}\exp(\gamma_2 t)$$

Firstly, we have proved that the cooperative growth rate is larger than the non-cooperative one, thus in the very long run, the ‘cooperative’ consumptions will definitely surpass the

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[3] If $\alpha+\beta=R,$ the ratio $\dfrac{\dfrac{(AD-AB+\rho)(\alpha+\beta)}{\alpha+\beta+\alpha\beta}}{\dfrac{2\rho}{\alpha+\beta+2}} = \dfrac{(AD-AB+\rho)R}{R+\alpha\beta}\times\dfrac{R+2}{2\rho}$, hence the smaller $\alpha\beta$, the larger is the ratio and the larger is the gap. In the context of $\alpha+\beta=R,$ $\alpha\beta$ gets smaller when α and β are wider apapt.

'non-cooperative' ones, which means countries by cooperating with each other will consume more in the long run. In other words, cooperation has positive growth effect. This was expected.

The level effect of cooperation of country 2 is examined by looking at consumption levels of c_{2N} and c_{2C} at time t=0.

We will prove that $c_{2N(t=0)} > c_{2C(t=0)}$:

Since $\frac{2\rho}{\alpha+\beta+2} < \frac{\rho(\alpha+\beta)}{\alpha+\beta+\alpha\beta}$ and $\alpha > \beta$, $\frac{E_0\alpha\rho}{D(\alpha+\beta+\alpha\beta)} > \frac{E_0\rho}{D(\alpha+\beta+2)}$.

Hence $\frac{E_0\alpha(\rho+AD-AB)}{D(\alpha+\beta+\alpha\beta)} > \frac{E_0\rho}{D(\alpha+\beta+2)}$ or $c_{2N(t=0)} > c_{2C(t=0)}$.

Country 2 chooses to initially consume less and abate more in cooperation than they would otherwise because in cooperation it is bound to do so. In the case of non-cooperation, country 2 with their little care to the environment puts less resources for abatement, consumes more and free-rides on the cleaning efforts of country 1. For country 2 the level effect and the growth effect of cooperation go in opposite directions, as is often the case.

The comparison of initial consumption levels of country 1 is more difficult. Consumption levels at time zero are rewritten below:

$$c_{1N(t=0)} = \frac{E_0\beta\rho}{D(\alpha+\beta+\alpha\beta)} + \frac{E_0\beta A(D-B)}{D(\alpha+\beta+\alpha\beta)}$$

$$c_{1C(t=0)} = \frac{E_0\rho}{D(\alpha+\beta+2)}$$

$$c_{1N(t=0)} - c_{1C(t=0)} = \frac{E_0\beta\rho}{D(\alpha+\beta+\alpha\beta)} - \frac{E_0\rho}{D(\alpha+\beta+2)} + \frac{E_0\beta A(D-B)}{D(\alpha+\beta+\alpha\beta)}$$

$$= \frac{E_0\rho}{D}\left(\frac{\beta+\beta^2-\alpha}{(\alpha+\beta+\alpha\beta)(\alpha+\beta+2)}\right) + \frac{E_0\beta A(D-B)}{D(\alpha+\beta+\alpha\beta)}$$

$$= \frac{E_0}{D(\alpha+\beta+\alpha\beta)}\left(\frac{\rho\left(\beta+\beta^2-\alpha\right)}{(\alpha+\beta+2)} + \beta A(D-B)\right)$$

The relative sizes of country 1's initial consumptions depend on the values of the parameters. If $A(D-B)$ is small enough, β is small enough and α is large enough, we would expect $c_{1N(t=0)} < c_{1C(t=0)}$.[4] *If this is the case, the level effect and the growth effect of cooperation go in the same direction for country 1*. The inequality is reversed if there is a small difference between α and β, but a large difference between D and B. Note that the larger the $A(D\text{-}B)$ is, the larger is the cooperative growth rate γ_2 relative to γ_1.

2.3.3.4 Comparison of welfare levels:

The welfare of country i is expressed as a total discounted life time utility of the infinitely–lived representative agent.

$$W_i = \int_0^\infty \{Ui\} \times e^{-\rho t} dt$$

$$W_i = \int_0^\infty \{\ln[c_i] + \alpha_i \ln E_i\} \times e^{-\rho t} dt$$

$$W_i = \int_0^\infty \{\ln[c_{0i} \exp(\gamma t)] + \alpha_i \ln[E_0 \exp(\gamma t)]\} \times e^{-\rho t} dt$$

$$= \int_0^\infty \{\ln c_{0i} + \alpha_i \ln E_0\} \times e^{-\rho t} dt + \int_0^\infty (\alpha_i + 1)\gamma t \times e^{-\rho t} dt$$

$$= \frac{\ln c_{0i} + \alpha_i \ln E_0}{\rho} + \frac{(\alpha_i + 1)\gamma}{\rho^2} \quad \text{where } \alpha_i = \alpha, \beta \text{ when } i = 1,2.$$

The initial environmental component can be ignored since countries have the same environmental starting point. Effectively, the welfare consists of one consumption component and one growth component. Firstly, cooperation brings a positive growth effect for both countries. For country 2, cooperation unambiguously causes a negative consumption effect, making the comparison of welfare levels ambiguous. For country 1, we have just shown in section 2.3.3.3 that a negative consumption effect is likely to occur as a result of cooperation when countries do not diverge significantly in their environmental preference and the values of pollution and abatement proxies are largely different. Otherwise, cooperation would bring country 1 a positive consumption effect, making an unambiguous boost in welfare level. Country 1 then would have every reason to engage in the environmental cooperation.

[4] An example of which is obtained when $n=0.02; \rho=0.02; A=0.1; D\text{-}B=0.1; \beta=0.5; \alpha=2$. At these values of parameters, the cooperative growth rate and non-cooperative growth rate are still positive.

2.3.4 Possible fiscal scheme to improve the non-cooperative solution:

In practice, countries do not always come up with an agreement on their environmental policies. Even if they do, there always exist incentives to cheat and free ride on the other country's efforts[5]. The consequence of this free riding is lower environmental quality and lower economic growth. This is not very satisfactory especially in the perspective of the country with higher environmental preference. The natural question in this context is therefore, given cooperating is not always practicable, are there any circumstances under which the non-cooperative solution can be improved to ideally match the optimal growth rate. In fact, developed countries with higher environmental preference and abundant capital resources have been aiding and subsidising developing countries that care less about the common global environment. Whether those schemes help improve economic growth remain the subject of further empirical research. In this thesis, we try to investigate the problem theoretically by developing a fiscal scheme or a transfer of payment from the more environmentally sensitive country (country 1) to the less sensitive (country 2). The fiscal scheme is designed as follows. Country 1 promises to pay a portion for every unit of country 2's abatement. Given the publicly-announced rate s, country 2 will choose a_2 to maximise its utility. The total subsidy then is financed by an income tax in country 1. In this simple dynamic model, given a subsidy rate s, a constant tax rate τ can be calculated. By encouraging country 2 to abate more, country 1 hopes to improve the environmental quality and therefore the growth rate in both countries.

The model

Formally, the model with subsidy is constructed as follow:

Country 1:

$$\begin{aligned} y_1 &= AE \\ c_1 &= (1-\tau)AE - a_1 \\ U_1 &= \ln c_1 + \alpha \ln E \end{aligned}$$

Country 2:

[5] We can think of it as a simple prisoner's dilemma type game.

$$y_2 = AE$$
$$c_2 = AE - (1-s)a_2$$
$$U_2 = \ln c_2 + \beta \ln E$$

Fiscal constraint: $\tau AE = sa_2$

Each country will again single-handedly maximise their lifetime utility taking the other's activities as given. The result will be a Nash-equilibrium. The rates of tax and subsidy are treated as given for now.

The social-planer problem of country 1 is to choose $\{a_1\}$ to maximise the representative agent's utility subject to physical capital and environmental quality accumulation constraints:

$$Max \int_0^{\infty} e^{-pt} (\ln c_1 + \alpha \ln E) dt$$

subject to $\dot{E} = nE - ABE - By_2 + D(a_1 + a_2)$

with $c_1 = (1-\tau)AE - a_1$

Rewrite the problem so that country 1 chooses a_1, given a_2 and τ:

$$Max \int_0^{\infty} e^{-pt} (\ln((1-\tau)AE - a_1) + \alpha \ln E) dt$$

subject to $\dot{E} = nE - ABE - By_2 + D(a_1 + a_2)$

The Hamiltonian expression:

$$H_1 = \ln\big((1-\tau)AE - a_1\big) + \alpha \ln E + \varphi\big[nE - ABE - By_2 + D(a_1 + a_2)\big]$$

$$\frac{\partial H_1}{\partial a_1} = 0 : \frac{1}{(1-\tau)AE - a_1} = \varphi D \qquad \text{or } \frac{1}{c_1} = \varphi D \qquad (2.11)$$

$$\dot{\varphi} = -\frac{\partial H}{\partial E} + \rho\varphi = \frac{-(1-\tau)A}{(1-\tau)AE - a_1} - \frac{\alpha}{E} - \varphi(n - AB - \rho) \qquad (2.12)$$

Transversality condition:

$$\lim_{t\to\infty} \varphi(t) e^{-\rho t} E(t) = 0$$

Substitute (2.11) to (2.12):

$$\dot{\varphi} = -\frac{\alpha}{E} - \varphi(n - AB + (1-\tau)AD - \rho) \qquad (2.12b)$$

Similarly, country 2 chooses a_2 given a_1 and s.The Hamiltonian expression for country 2 is:

$$H_2 = \ln\big(AE-(1-s)a_2\big)+\beta\ln E+\lambda\big[nE-ABE-By_1+D(a_1+a_2)\big]$$

$$\frac{\partial H_2}{\partial a_2}=0:\frac{1-s}{AE-(1-s)a_2}=\lambda D \qquad \text{or } \frac{1}{c_2}=\frac{\lambda D}{1-s} \tag{2.13}$$

$$\dot{\lambda}=-\frac{\beta}{E}-\lambda(n-AB+\frac{AD}{1-s}-\rho) \tag{2.14}$$

Rewrite the environmental equation:

$$\dot{E}=nE-2ABE+D(a_1+a_2)$$

$$\dot{E}=nE-2ABE+D((1-\tau)AE-c_1+\frac{AE}{1-s}-\frac{c_2}{1-s})$$

$$\dot{E}=E(n-2AB+AD(1-\tau+\frac{1}{1-s}))-Dc_1-\frac{Dc_2}{1-s}$$

Substituting (2.11) and (2.13) into the above

$$\dot{E}=E\left[n-2AB+AD(1-\tau+\frac{1}{1-s})\right]-\frac{1}{\varphi}-\frac{1}{\lambda} \tag{2.15}$$

Solving the system of (2.12b) (2.14) (2.15)

$$\dot{\varphi}=-\frac{\alpha}{E}-\varphi(n-AB+(1-\tau)AD-\rho)$$

$$\dot{\lambda}=-\frac{\beta}{E}-\lambda(n-AB+\frac{AD}{1-s}-\rho)$$

$$\dot{E}=E\left[n-2AB+AD(1-\tau+\frac{1}{1-s})\right]-\frac{1}{\varphi}-\frac{1}{\lambda}$$

and the initial condition $E(0)=E_0$, we obtain the solution:

$E(t)=E_0\exp(\gamma_3 t)$

$$\varphi(t)=\varphi_0\exp(-\gamma_3 t)$$

$$\lambda(t)=\lambda_0\exp(-\gamma_3 t)$$

where

$$\boxed{\gamma_3=n-2AB+(1-\tau)AD+\frac{AD}{1-s}+\frac{(AB-\rho)(\alpha+\beta)}{\alpha+\beta+\alpha\beta}-\left[\frac{(1-\tau)}{\beta}+\frac{1}{(1-s)\alpha}\right]\times\frac{AD}{\alpha+\beta+\alpha\beta}}$$

Note that when $s=\tau=0$, $\gamma_3=\gamma_1$.

Also the values of the shadow prices are obtained:

$$\frac{1}{\varphi_0}=E_0\times\left((AB-\rho)\left(\frac{\alpha+\beta-\alpha\beta}{\alpha^2\beta}\right)-\left[\frac{1-\tau}{\beta}+\frac{1}{(1-s)\alpha}\right]\times\frac{AD\beta}{\alpha+\beta+\alpha\beta}+\frac{AD}{\alpha(1-s)}\right)$$

$$\frac{1}{\lambda_0}=E_0\times\left((AB-\rho)\left(\frac{\alpha+\beta-\alpha\beta}{\alpha\beta^2}\right)-\left[\frac{1-\tau}{\beta}+\frac{1}{(1-s)\alpha}\right]\times\frac{AD\alpha}{\alpha+\beta+\alpha\beta}+\frac{AD(1-\tau)}{\beta}\right)\quad(2.16)$$

(details are given in appendix A3)

In the other hand, from $a_2=\frac{AE}{1-s}-\frac{c_2}{1-s}$ and $c_2=\frac{1-s}{\lambda D}=\frac{1-s}{\lambda_0 D}\exp(\gamma_3 t)$, we derive

$$a_2=\frac{AE}{1-s}-\frac{1}{\lambda_0 D}\exp(\gamma_3 t)\quad(2.17)$$

Substitute (2.16) into (2.17) we obtain:

$$a_2=\frac{AE}{1-s}-\left[\frac{E_0}{D}\times\left((AB-\rho)\left(\frac{\alpha+\beta-\alpha\beta}{\alpha\beta^2}\right)-\left[\frac{1-\tau}{\beta}+\frac{1}{(1-s)\alpha}\right]\times\frac{AD\alpha}{\alpha+\beta+\alpha\beta}+\frac{AD(1-\tau)}{\beta}\right)\right]\exp(\gamma_3 t)\quad(2.18)$$

Substitute (2.18) into the fiscal constraint $\tau AE=sa_2$:

$$\tau AE=s\left[\frac{AE}{1-s}-\frac{1}{\lambda_0 D}\exp(\gamma_3 t)\right]$$

$$=\frac{sAE}{1-s}-s\left[\frac{E_0}{D}\times\left((AB-\rho)\left(\frac{\alpha+\beta-\alpha\beta}{\alpha\beta^2}\right)-\left[\frac{1-\tau}{\beta}+\frac{1}{(1-s)\alpha}\right]\times\frac{AD\alpha}{\alpha+\beta+\alpha\beta}+\frac{AD(1-\tau)}{\beta}\right)\right]\exp(\gamma_3 t)$$

hence

$$\tau=\frac{sAE}{1-s}-s\left(\frac{(AB-\rho)}{AD}\left(\frac{\alpha+\beta-\alpha\beta}{\alpha\beta^2}\right)-\left[\frac{1-\tau}{\beta}+\frac{1}{(1-s)\alpha}\right]\times\frac{\alpha}{\alpha+\beta+\alpha\beta}+\frac{(1-\tau)}{\beta}\right)$$

Rearrange the above, we obtain the expression of $1-\tau$ in terms of s:

$$1-\tau=\frac{1-\frac{s}{1-s}+s\frac{(AB-\rho)}{AD}\left(\frac{\alpha+\beta-\alpha\beta}{\alpha\beta^2}\right)-\frac{s}{1-s}\times\frac{1}{\alpha+\beta+\alpha\beta}}{g(s)}\quad(2.19)$$

where $g(s) = 1 - \frac{s}{\beta} + \frac{s\alpha}{(\alpha + \beta + \alpha\beta)\beta}$

Substitute (2.19) into γ_3, we can derive the growth rate as a function of *s*, which we denote by $\gamma(s)$.

We argue that the problem of country 1 is to choose *s* to maximise the growth rate γ_3. Alternatively, it can choose *s* to maximise its own welfare, measured as the function $W(s) = \int_0^\infty \{\ln[c_0 \exp(\gamma_3 t)] + \alpha \ln[E_0 \exp(\gamma_3 t)]\} \times e^{-\rho t} dt$

The problem is solved by taking the first derivative of $\gamma(s)$ or $W(s)$ with respect to *s*. However, it is too complicated to solve the problem analytically hence we are currently confined to investigate the problem numerically.

2.3.5 Numerical example:

In this example, we illustrate numerically the fiscal subsidy situation that has been discussed above. The problem for the more environmental sensitive country is whether the subsidy scheme pays dividend. In other words, if country 1 decides to subsidise abatement activities of country 2, will the common long run growth rate be higher, or alternatively, in terms of welfare, will the welfare of the donor country be improved?

The bench mark values for the exercise are given below. E_0 and *A* are arbitrary so they are assigned the unity value. The environment's regeneration capability is 3% per annum (n=0.03) and the long-term discount rate is around 2% (ρ=0.02). α and β also take arbitrary value with $\alpha > \beta$. *B* and *D* are then carefully chosen so that $B<D$, the optimal growth rate is in a reasonable range and the non-cooperative rate is positive.

Bench mark values: E_0=1, A=1, n=0.02, ρ=0.02, α=1.2, β=0.8, B=0.1, D=0.14.

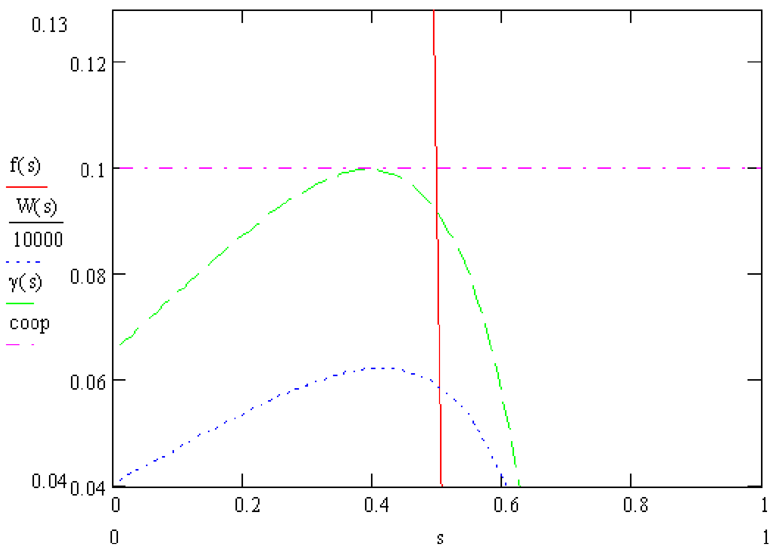

Figure 2.1a: Optimal values of s associated with welfare maximising and growth rate maximising.

There are four lines in the diagram. The first line is almost vertical in the diagram. It represents *f(s)*, which is 1-τ as a function of s (i.e. equation 2.19) ; and is inserted to insure the optimal value of s is in the range of τ<1 or *f(s)*>0 (i.e. in the left hand side of the *f(s)* line). Practically the output tax rate τ has to be smaller than 50%. *Coop* represents the cooperative rate γ_2. This function is independent of *s* therefore the line of *coop*(*s*) is a straight horizontal line near the top of the diagram. In this example, the cooperative growth rate is approximately 10% per annum. $\gamma(s)$ and $\frac{W(s)}{10000}$ are the growth rate and of country one's welfare divided by 10000 respectively when the subsidy scheme is undertaken. Obviously $\gamma(s)$ and $\frac{W(s)}{10000}$ are functions of the subsidy rate *s*. Notice that $\gamma(0)$ is the non-cooperative growth rate γ_1 when there is no subsidy scheme. γ_1 is around 6.5% in this example.

It can be seen from the diagram that the two alternative values of *s* corresponding to maximum welfare of country 1 and maximum growth rate γ_3 exist in the acceptable range. In this particular illustration, the growth-maximising subsidy scheme significantly improves the non-cooperative growth rate. The rate almost matches the optimal one.

If we enlarge the diagram, the difference between two values of *s* becomes more observable. The subsidy rate *s* corresponding to welfare maximising is approximately 0.41, which means country 1 subsidises 41c for every 1 dollar used for abatement at country 2; the corresponding tax rate is 44.4%. The subsidy rate corresponding to growth rate maximising is around 0.39 with the corresponding tax rate in country 1 is 37.1%. The tax rates are above realistic average but still in an acceptable range. Calculations show that when we narrow the gap of the environmental preferences, the subsidy rate and the tax rate seems to diminish. This suggest a more costly subsidy if the environmental preferences of the countries differ greatly. This is not an unexpected result.

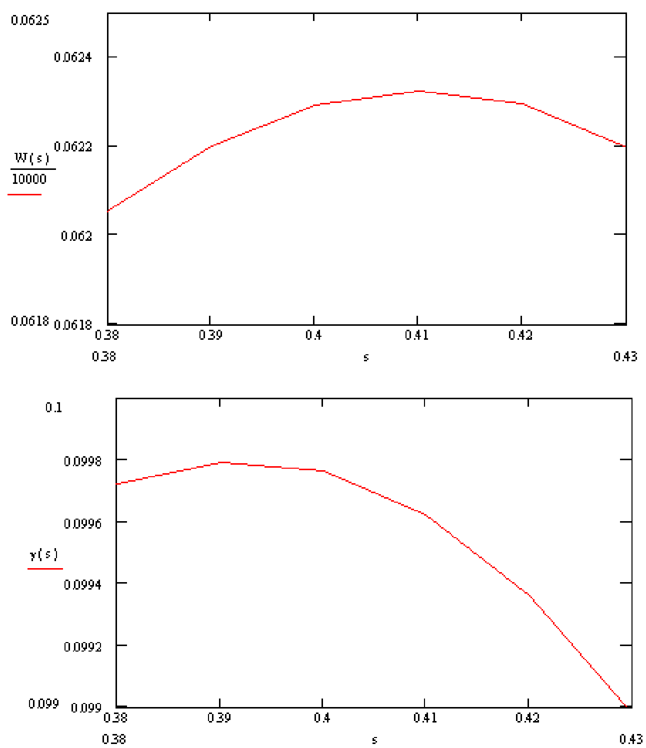

Figure 2.1b: Optimal values of s associated with welfare maximising and growth rate maximising.

The numerical exercise provides the example whereby one country can single-handedly improve its well-being (in terms of growth rate or welfare). Although this is only a numerical example, it does establish that a tax/subsidy scheme exists in some cases and with a carefully chosen rate to subsidise other countries' abatement activities, a more environmentally sensitive country, usually richer, will boost growth of improve its welfare. The welfare of the recipient country will likely to be improved as well.

2.4. Conclusion

We developed an endogenous growth model to incorporate the environment as the international externality. The two countries in the model are identical except for their environmental preferences. Two scenarios are considered: when the two countries coordinate and do not coordinate their environmental policies. The results fulfil the expectations. That is, the countries will enjoy higher growth rates and a higher environmental quality when they cooperate. The reason is that by coordinating their activities countries are able to fully internalise the international environmental externality. We also examine possible factors that can influence the gap of the growth rates and compare consumption and abatement levels in the two scenarios. One result that stands out is that for some configurations of the parameters, country 1 benefits from cooperation from both growth and level effects.

In the case of non-cooperation, we have also investigated the scheme whereby a country single-handedly seeks to improve either the growth rate or its own welfare. The result shows that with a well-chosen subsidy applied to the other country's abatement activities, the country with higher environmental preference could improve the non-cooperative growth rate. This is illustrated by a numerical example.

Various extensions to the model are possible. First of all, the idea of incorporating international trade into the model is very appealing. The asymmetry of the countries will eventually leads to different products and thereby possible gains from trade. Being able to consider the complicated interactions between international trade, environmental externality and growth is indeed extremely interesting but presents technical difficulties. However, a very preliminary effort is still undertaken in the next chapter to investigate this extension.

CHAPTER 3 –ENVIRONMENTAL POLLUTION AND TRADE WITH DISCREPANCY IN TECHNOLOGY

3.1 Motivation

The relationship between trade and growth has created a massive literature. Many theoretical and empirical international trade studies have been able to show a positive correlation between trade volume and the economy's performance. However, the impact of trade on growth in the framework of sustainable development is not clear. In general, trade is associated with an increase in output. However, the impact of output expansion on the environment is obscured. On the one hand, a higher production level brings more pollution; on the other hand, higher output enables people to devote more resources to abate the environment. Which effect is dominant is not known.

In this chapter, we turn the focus on the relationship between trade and growth and the environment. The usual distinction between trade and growth is that trade involves the change in the relative goods' prices while growth implies the gross output increase or technological advancement. However, trade liberalization also can stimulate growth if it helps to bring capital, technology or management skills from overseas.

In the context of our model, in order to incorporate trade and to keep the model as simple as possible, we assume the two countries produce two different products. The good produced by one country cannot be produced by or used to abate the environment of the other country. This is not an excessively unrealistic assumption as in reality, many foreign goods cannot be produced domestically due to lack of know-how, or differences in geographical conditions. In this version of the model, the only purpose to import goods from the other country is to satisfy consumer demand. The agent's utility function is modified to include the foreign good. We also consider a differentiation in the technology of the two countries in an attempt to bring the flavour of the interaction between developed countries and developing countries into the model. Environmental-economic interactions between developed and developing countries are indeed becoming a very topical issue now.

The rich countries complain that poor countries with lower environmental standard lure dirty but productive manufacturing sectors which were traditionally located in the rich countries. The poorer countries are referred to as “pollution havens”. Goods are exported to the rich; the global environmental quality is not improved and the cost of job losses is borne by the developed world. The poorer countries however are not content with the criticism. In their point of view, the richer countries in effect limit manufacturing imports from the developing world under the umbrella of environmental and labour standards. Modelling these dynamic asymmetric interactions is extremely difficult yet interesting. This chapter is one attempt to put these policy issues into mathematical modelling. For simplicity and to focus on the analysis of the technological discrepancy, environmental preferences for the two countries are now assumed identical.

Admittedly the incorporation of trade into the model lacks many crucial features of a complete trade model. Firstly unlike the usual definition of trade that trade liberalization involves change in the goods’ prices, we do not see that phenomenon here. The reason being simply is that before opening to trade, each country only produces and consumes one product. Secondly, the model fails to consider key positive aspects of trade such as capital accumulation from abroad or technology spill over, because of which trade might create adverse result. Nevertheless, in a first attempt to bring international trade into a dynamic growth-environment model and with the concern of the model’s tractability, these drawbacks seem unavoidable.

The chapter is organized as follow: section 3.2 provides the basic setup of the model; section 3.3 considers the case where the two countries in autarky cooperate with each other; section 3.4 looks at the case of autarky and non-cooperation; 3.5 and 3.6 respectively are analyses of the circumstances when the two countries either coordinate or do not coordinate their environmental policies but trade with one another. In section 3.7 we compare the growth rates and welfare levels in various scenarios.

3.2 The basic model

In order to incorporate trade, we assume the two countries produce two different products. The good produced by one country cannot be produced by or used to abate the environment by the other country. In this version of the model, the only purpose to import goods from the other country is to satisfy consumer demand. Hence, the agent's utility function is modified to include the foreign good.

Country 1:

$$U_1 = \ln c_1 + \alpha \ln E + \ln(m_1 + K) \tag{3.2.1}$$

$$y_1 = AE \tag{3.2.2}$$

$$x_1 + c_1 + a_1 = AE \tag{3.2.3}$$

where m_1 and x_1 are the import and export of country 1 respectively.

The basic setup in chapter 2 is brought over here with one exception. The consumption of imports is taken into the utility function. Note that the utility function is carefully modified so that it can be used in both autarky and in the event of international trade. Thus $\ln(m_1+K)$ is defined even if $m_1=0$. The value of K has no bearing on the outcome of the games. Its significance will be discussed in section 3.7.2.

Country 2

$$U_2 = \ln c_2 + \alpha \ln E + \ln(m_2 + K) \tag{3.2.4}$$

$$y_2 = zAE \tag{3.2.5}$$

$$x_2 + c_2 + a_2 = zAE \tag{3.2.6}$$

where m_2 and x_2 are the import and export of country 2 respectively. z is assumed greater than 1, indicating that country 2 is more technologically advanced than country 1.

The environment:

$$\dot{E} = nE - B(y_1 + y_2) + D(a_1 + a_2) \tag{3.2.7}$$

We still assume D>B.

3.3 Cooperative environmental policies in autarky

We first consider the situation whereby no trade takes place. However, the two countries still share the common environment and therefore interact environmentally. It is the standard starting point of the analysis about impact of openness to trade on growth in the context of polluting production. From now on, this case will be referred as *'coop-autarky'*.

Firstly, consider the case when two countries co-ordinate their environmental policies perfectly. This is very similar to the model of section 2.3.2 except that the countries now differ in technologies (1,*z*) and not environmental preference (α,β). This perfection is not likely to happen in the real world because inadequate supporting institutions and regulations do not allow countries to fully internalise their environmental externality. However, in a hypothetical mathematical model, we allow for this extreme case here.

This is very similar to the model in section 2.3.2 except that the countries now difer in technology (z) and not environmental preference. When no trade takes place, import and export of the two countries are zero: $m_1 = m_2 = 0$ and $x_1 = x_2 = 0$. Rewrite the utility functions of the two countries:

Country 1:

$$U_1 = \ln c_1 + \alpha \ln E + \ln(K) \tag{3.3.1}$$

$$y_1 = AE \tag{3.3.2}$$

$$c_1 + a_1 = AE \tag{3.3.3}$$

Country 2:

$$U_2 = \ln c_2 + \alpha \ln E + \ln(K) \tag{3.3.4}$$

$$y_2 = zAE \tag{3.3.5}$$

$$c_2 + a_2 = zAE \tag{3.3.6}$$

The environment evolves as follow:

$$\dot{E} = nE - B(y_1 + y_2) + D(a_1 + a_2) \tag{3.3.7}$$

Two countries jointly maximize their total utility. However, the weights of the two utilities are not necessarily equal. In this chapter we explicitly consider one country as more technological advanced than the other country. The advantage in the technological level of one country may well lead to the increased power at the negotiation table. It does make sense for example in practice that rich and powerful countries do not consider the poorer ones as equal and tend not to seriously put as much weight on the well-being of the poorer countries as on their own. For the poor country, the huge potential benefit gained when trading with the rich country is too much to resist and they are likely to accept unequal arrangements provided that the deal will help to improve their current position. Examples are many. Vietnam, for instance, in order to gain access to the huge U.S market had to agree to join UPOV (one WTO's agency that promotes plant variety protection and is widely believed to protect the right of breeding companies in developed countries and to neglect the well-being of subsistence farmers in developing countries).

In our model, this stylized fact is brought in by assuming that the weights of the two countries' utility in the joint utility are the technology levels of each country.

$$U = U_1 + zU_2$$

The social planner's problem is to choose c_1 ,c_2 and a_1,a_2 to maximize the discounted joint utility.

$$Max\int_0^\infty e^{-pt}(U_1 + zU_2)dt$$

subject to production constraint and $\dot{E} = nE - B(y_1 + y_2) + D(a_1 + a_2)$ (3.3.7)

and also to (3.3.2), (3.3.3),(3.3.5) and (3.3.6)

Since the two countries are cooperating, it is reasonable to assume they know each other's production functions and budget constraints. Substituting the two production function (3.3.1), (3.3.4) and the two budget constraints (3.3.3), (3.3.6) into (3.3.7) we obtain:

$$\dot{E} = nE - ABE(1+z) + D(AE - c_1 + zAE - c_2) \quad (3.3.7b)$$

The Hamiltonian expression is:

$$H = \ln c_1 + \alpha \ln E + z(\ln c_2 + \alpha \ln E) + \varphi[nE - ABE(1+z) + D(AE - c_1 + zAE - c_2)]$$

$$H = \ln c_1 + \alpha \ln E + z(\ln c_2 + \alpha \ln E) + \varphi[nE + AE(D-B)(z+1) - D(c_1 + c_2)]$$

The maximum principle states that the solution must obey (3.3.7b) and:

$$\frac{\partial H}{\partial c_1} = 0 : \frac{1}{c_1} = \varphi D \qquad (3.3.8)$$

$$\frac{\partial H}{\partial c_2} = 0 : \frac{z}{c_2} = \varphi D \qquad (3.3.9)$$

$$\dot{\varphi} = -\frac{\delta H}{\delta E} + \varphi\rho \qquad (3.3.10)$$

$$\dot{\varphi} = -\frac{\alpha(z+1)}{E} - \varphi[n + A(D-B)(z+1)] + \rho\varphi \qquad (3.3.11)$$

Transversality condition: $\lim_{t\to\infty} \varphi(t) e^{-\rho t} E(t) = 0$.

Substitute (3.3.8) and (3.3.9) into (3.3.7), we obtain:

$$\dot{E} = E[n + A(D-B)(z+1)] - \frac{1+z}{\varphi} \qquad (3.3.12)$$

Denote G $\equiv n + A(D-B)(z+1)$, the system of (3.3.11) and (3.3.12) becomes:

$$\dot{\varphi} = -\frac{\alpha(z+1)}{E} - \varphi(G-\rho)$$

$$\dot{E} = EG - \frac{1+z}{\varphi}$$

or $\qquad \dot{\varphi} E = -\alpha(z+1) - \varphi E(G-\rho)$

$$\dot{E}\varphi = \varphi EG - (1+z)$$

Add them up we obtain: $\qquad \frac{d(E\varphi)}{dt} = -(z+1)(\alpha+1) + E\varphi\rho$

Solving the above differential equation we obtain the solution:

$$E\varphi = \frac{(z+1)(\alpha+1)}{\rho} \qquad (3.3.13)$$

This also implies the transversality condition of $\lim_{t\to\infty} \psi(t) e^{-\rho t} E(t) = 0$ is satisfied.

Substitute (3.3.13) into (3.3.12)

$$\dot{E} = nE + A(D-B)(z+1)E - \frac{E\rho(1+z)}{(1+z)(\alpha+1)}$$

or $\dot{E} = E\left(n + (D - B)(z+1) - \dfrac{\rho}{\alpha+1}\right)$

Hence, $\dfrac{\dot{E}}{E} = n + A(D - B)(z+1) - \dfrac{\rho}{\alpha+1}$

If we denote γ_1 as the growth rate then $\boxed{\gamma_1 = n + A(D - B)(z+1) - \dfrac{\rho}{\alpha+1}}$

The two countries grow at the same rate, which is also the growth rate of the environmental quality. This is due to the environmental quality being the only input in both production functions. For of the exact same reason, the relative significance of polluting and abatement process is very clearly seen. The long run growth rate again depends upon the difference between abatement technology and the polluting effect of the production. γ_1 also increases with *z*; however it does not increase with a shift of technology weight from one country to the other. In other words, it only depends on the total technology. This suggests that disparity in technology does not drive growth for both countries. In the context of no knowledge spill-over and endogenous technological advancement, the result is perfectly understandable.
The standard result in our models of the long run growth rate being positively correlated with the environmental preference α is also observed here.

The long run environmental quality, consumptions of the two countries are derived below:
$E = E_0 \exp(\gamma_1 t)$.

From (3.3.13): $\varphi = \dfrac{(z+1)(\alpha+1)}{\rho E_0} \exp(-\gamma_1 t)$

From (3.3.8) and (3.3.9)

$c_1 = \dfrac{1}{D\varphi} = \dfrac{\rho E_0}{D(z+1)(\alpha+1)} \exp(\gamma_1 t)$ and $c_2 = \dfrac{z}{\varphi D} = \dfrac{z\rho E_0}{D(z+1)(\alpha+1)} \exp(\gamma_1 t)$

Country 2 consumes *z* times more than country 1 does and also abates more with the same proportion. Intuitively, country 2 with its technological dominance has obtained a higher weight in the joint utility function, making it consume at a higher level than country 1 does.

Consumptions at time zero positively depends on the initial value of the environment and negatively depends on the abatement technology and the environmental preference. Consumption then grows exponentially after that at the rate of γ_1. Interestingly, the environmental preference has a positive growth effect and a negative level effect on the consumption levels of two countries.[6]

3.4 Non-cooperative environmental policies in autarky:

We turn to the case where the two countries do not co-ordinate their environmental policies and still live with autarky (referred as *'noncoop-autarky'*). One country cannot control the other's production and abatement activities. Their only interaction (not internalized) is through the environment. Each country will single-handedly maximize its lifetime utility taking the other's activities as given. The result will be a Nash-equilibrium. Their only interaction (not internalised) is through the environment.

Firstly we consider country 1. The social-planer problem of country 1 is to choose $\{a_1\}$ to maximise representative agent's utility subject to environmental quality accumulation constraints:

$$Max\int_0^{\infty} e^{-pt}(\ln c_1 + \alpha \ln E)dt$$

$$\text{subject to} \qquad \dot{E} = nE - B(y_1 + y_2) + D(a_1 + a_2) \qquad (3.4.1)$$

$$\text{with} \qquad c_1 + a_1 = AE \text{ and } y_1 = AE\,.$$

Since the two countries do not co-ordinate their policies, one country is not aware of the other's production and budget constraint. As said, it takes the other's activities as given. Rewrite the problem as follow:

$$Max\int_0^{\infty} e^{-pt}(\ln(AE - a_1) + \alpha \ln E)dt$$

$$\text{subject to} \qquad \dot{E} = nE - ABE - By_2 + D(a_1 + a_2)$$

[6] Level effects and growth effects usually work in opposite directions.

The Hamiltonian expression is:

$H_1 = \ln(AE - a_1) + \alpha \ln E + \varphi[nE - ABE - By_2 + D(a_1 + a_2)]$

The maximum principle states that the solution must obey (3.4.1) and:

$$\frac{\delta H_1}{\delta a_1} = 0 : \frac{1}{AE - a_1} = \varphi D \tag{3.4.2}$$

$$\dot{\varphi} = -\frac{\delta H_1}{\delta E} + \varphi\rho$$

$$\dot{\varphi} = -\frac{A}{AE - a_1} - \frac{\alpha}{E} - \varphi\left[n - AB - \rho\right] \tag{3.4.3}$$

Transversality condition: $\underset{t\to\infty}{Lim}\, \varphi(t)e^{-\rho t}E(t) = 0$.

Substitute (3.4.2) into (3.4.3): $\dot{\varphi} = -\frac{\alpha}{E} - \varphi\left[n - AB + AD - \rho\right]$ (3.4.4)

Now we consider country 2. The social-planer problem of country 2 is to choose $\{a_2, c_2\}$ to maximise representative agent’s utility subject to environmental quality accumulation constraints:

$$Max \int_0^\infty e^{-pt}(\ln c_2 + \alpha \ln E)dt$$

subject to $\dot{E} = nE - B(y_1 + y_2) + D(a_1 + a_2)$ (3.4.1)

with $c_2 + a_2 = zAE$ and $y_2 = zAE$.

Rewrite the problem:

$$Max \int_0^\infty e^{-pt}(\ln(zAE - a_2) + \alpha \ln E)dt$$

subject to $\dot{E} = nE - zABE - By_1 + D(a_1 + a_2)$

The Hamiltonian expression is:

$H_2 = \ln(zAE - a_2) + \alpha \ln E + \lambda[nE - zABE - By_1 + D(a_1 + a_2)]$

The maximum principle states that the solution must obey (3.4.1) and:

$$\frac{\delta H_2}{\delta a_2} = 0 : \frac{1}{zAE - a_2} = \lambda D \qquad \text{or} \qquad \frac{1}{c_2} = \lambda D \tag{3.4.5}$$

$$\dot{\lambda} = -\frac{\delta H_2}{\delta E} + \lambda\rho$$

$$\dot{\lambda} = -\frac{zA}{zAE - a_2} - \frac{\alpha}{E} - \lambda[n - zAB - \rho] \tag{3.4.6}$$

Substitute (3.4.5) into (3.4.6): $\dot{\lambda} = -\frac{\alpha}{E} - \lambda[n - zAB + zAD - \rho]$ (3.4.7)

Rewrite (3.4.1): $\dot{E} = nE - B(y_1 + y_2) + D(a_1 + a_2)$

or $\dot{E} = nE - ABE(1+z) + D(AE - c_1 + zAE - c_2)$

Substitute (3.4.2) and (3.4.5) into the above we obtain:

$$\dot{E} = E\big(n - AB(1+z) + AD(z+1)\big) - \frac{1}{\varphi} - \frac{1}{\lambda} \tag{3.4.1b}$$

The system of (3.4.1b),(3.4.4) and (3.4.7) is the subject of interest:

$$\dot{E} = E\big(n - AB(1+z) + AD(z+1)\big) - \frac{1}{\varphi} - \frac{1}{\lambda} \tag{3.4.1b}$$

$$\dot{\varphi} = -\frac{\alpha}{E} - \varphi[n - AB + AD - \rho] \tag{3.4.4}$$

$$\dot{\lambda} = -\frac{\alpha}{E} - \lambda[n - zAB + zAD - \rho] \tag{3.4.7}$$

Solving the system we obtain the solution:

$E = E_0 \exp(\gamma_2 t)$ where $\boxed{\gamma_2 = n + (AD - AB)(z+1)\left(1 - \frac{1}{\alpha+2}\right) - \frac{2\rho}{\alpha+2}}$ (see appendix A4)

Although the two countries are not co-ordinate their policies, they enjoy the same growth rate. It is again because the environmental quality is the sole input in both production functions.

The consumption paths of the two countries also have been derived:

$$\frac{1}{c_1}=\varphi D \text{ hence } c_1=\frac{1}{\varphi D}=\frac{1}{D\varphi_0\exp(-\gamma_2 t)}=\frac{E_0}{D}\left[\frac{(AD-AB)\left(z-\frac{z+1}{\alpha+2}\right)}{\alpha}+\frac{\rho}{\alpha+2}\right]\exp(\gamma_2 t)$$

$$\frac{1}{c_2}=\lambda D \text{ hence } c_2=\frac{1}{\lambda D}=\frac{1}{D\lambda_0\exp(-\gamma_2 t)}=\frac{E_0}{D}\left[\frac{(AD-AB)\left(1-\frac{z+1}{\alpha+2}\right)}{\alpha}+\frac{\rho}{\alpha+2}\right]\exp(\gamma_2 t)$$

The details are shown in appendix A4

We can see that the total technology advancement ($z+1$) is good for growth. It is not quite an obvious statement as it seems to be, especially in the context of polluting production. In all endogenous growth models, the advancement of productivity level boosts long run growth (in fact, it is one engine for long run growth) since technological improvement allows for higher levels of output being produced using the same levels of inputs. However, in this model, an output expansion is accompanied by a more polluted environment that requires extra resources for abatement. Hence, the anticipation about the impact of productivity improvement on growth is generally not clear. In our model, provided that $D>B$, we can show a positive correlation between productivity level (z+1) and long run growth. Further more, it is worth mentioning that disparity in technology does not drive growth here, which is the same result we obtain in ‘coop-autarky’ case.

Provided that z>1, it is clear that $c_1>c_2$. This counter-intuitive result is initially quite puzzling. Since country 2 is producing more than country 1 does, it is not expected to consume less given that both countries have identical environmental preferences. Mathematically we have been able to show that $\lambda>\varphi$ (see appendix A4). What the inequality indicates is the shadow price of the environment to country 2 is higher than that to country 1 at every instant, implying that country 2 values the environment as a more important asset than country 1 does. This is very stimulating result, given the fact that both countries have the same environmental preference. It seems that being richer is enough to indirectly yield a different evaluation of the environment. As a consequence of this high appraisal, country 2 will spend more on abatement and to put it simply, disregard the cleaning effort of country 1. Seeing a_2 so big, country 1 chooses an even smaller a_1, hence boosting c_1 to exceed c_2. This is an unexpected free riding outcome.

3.5 Cooperative environmental policy with international trade:

After analysing the autarky situation, we examine to the situation whereby the two countries trade with each other and coordinate their environmental policies (referred as '*coop-trade*' situation). By looking at the growth rate and welfare of the two countries after they open up their economy, we can make some conjecture about the impact of international trade on the economy in the context of polluting production. Firstly, the setup is briefly stated here.

Country 1:

$$U_1 = \ln c_1 + \alpha \ln E + \ln(m_1 + K) \qquad (3.5.1)$$

$$y_1 = AE \qquad (3.5.2)$$

$$x_1 + c_1 + a_1 = AE \qquad (3.5.3)$$

Country 2

$$U_2 = \ln c_2 + \alpha \ln E + \ln(m_2 + K) \qquad (3.5.4)$$

$$y_2 = zAE \qquad (3.5.5)$$

$$x_2 + c_2 + a_2 = zAE \qquad (3.5.6)$$

The environment evolves as follows:

$$\dot{E} = nE - B(y_1 + y_2) + D(a_1 + a_2)$$

We assume perfect trading information. The two countries are aware that one country will import all of the other's export (i.e. $m_1=x_2$ *and* $x_1=m_2$). They also know the trade balance ($p_1x_1 = p_2m_1$ or $p_1m_2 = p_2x_2$; where p_1 and p_2 are prices of goods produced by country 1 and 2 respectively).

Substitute $x_1 = \frac{p_2}{p_1} m_1$ and $x_2 = \frac{p_1}{p_2} m_2$ in to (3.5.3) and (3.5.6)

$c_1 = AE - \frac{p_2}{p_1} m_1 - a_1$ (3.5.7) and $c_2 = zAE - \frac{p_1}{p_2} m_2 - a_2$ (3.5.8)

The social planner's problem is to choose m_1, a_1 and m_2, a_2 to maximize the discounted joint utility with weights 1 and z as before.

$$Max \int_0^\infty e^{-pt} (U_1 + zU_2) dt$$

subject to $\quad \dot{E} = nE - B(y_1 + y_2) + D(a_1 + a_2)$

with $\quad c_1 = AE - \frac{p_2}{p_1} m_1 - a_1$ and $c_2 = zAE - \frac{p_1}{p_2} m_2 - a_2$

The Hamiltonian expression is:

$$H = \ln c_1 + \alpha \ln E + \ln(m_1 + K) + z[\ln c_2 + \alpha \ln E + \ln(m_2 + K)] +$$
$$\varphi[nE - B(y_1 + y_2) + D(a_1 + a_2)]$$

with $c_1 = AE - \frac{p_2}{p_1} m_1 - a_1$ and $c_2 = zAE - \frac{p_1}{p_2} m_2 - a_2$

Rewrite the Hamiltonian expression :

$$H = \ln c_1 + \alpha \ln E + \ln(m_1 + K) + z \ln c_2 + z\alpha \ln E + z \ln(m_2 + K)] +$$
$$\varphi[nE - ABE(1+z) + D(a_1 + a_2)]$$

or

$$H = \ln\left[AE - \frac{p_2}{p_1} m_1 - a_1 \right] + \alpha \ln E + \ln(m_1 + K)$$
$$+ z \ln\left[zAE - \frac{p_1}{p_2} m_2 - a_2 \right] + z\alpha \ln E + z \ln(m_2 + K)] +$$
$$+ \varphi[nE - ABE(1+z) + D(a_1 + a_2)]$$

First-order conditions:

$$\frac{\delta H}{\delta a_1} = 0 : \frac{1}{AE - \frac{p_2}{p_1} m_1 - a_1} = \varphi D \tag{3.5.9}$$

$$\frac{\delta H}{\delta m_1} = 0 : \frac{1}{AE - \frac{p_2}{p_1} m_1 - a_1} \times \frac{p_2}{p_1} = \frac{1}{m_1 + K}$$

or $$\frac{1}{AE - \frac{p_2}{p_1} m_1 - a_1} \times \frac{m_2}{m_1} = \frac{1}{m_1 + K} \quad \left(\text{since } \frac{p_2}{p_1} = \frac{m_2}{m_1}\right) \tag{3.5.10}$$

$$\frac{\delta H}{\delta a_2} = 0 : \frac{z}{zAE - \frac{p_1}{p_2} m_2 - a_2} = \varphi D \tag{3.5.11}$$

From (3.6.9) and (3.5.11), we have c_2=zc_1

$$\frac{\delta H}{\delta m_2} = 0 : \frac{z}{zAE - \frac{p_1}{p_2} m_2 - a_2} \times \frac{p_1}{p_2} = \frac{1}{m_2 + K}$$

or $$\frac{z}{zAE - \frac{p_1}{p_2} m_2 - a_2} \times \frac{m_1}{m_2} = \frac{1}{m_2 + K} \tag{3.5.12}$$

$$\dot{\varphi} = -\frac{\delta H}{\delta E} + \varphi\rho$$

$$\dot{\varphi} = -\frac{\alpha(z+1)}{E} - \varphi[n - AB(z+1)] - \frac{A}{AE - \frac{p_2}{p_1} m_1 - a_1} - \frac{z^2 A}{zAE - \frac{p_1}{p_2} m_2 - a_2} + \rho\varphi \tag{3.5.13}$$

Substitute (3.5.9) and (3.5.11) in (3.5.13)

or $$\dot{\varphi} = -\frac{\alpha(z+1)}{E} - \varphi[n - AB(z+1) + AD(z+1) - \rho] \tag{3.5.14}$$

$$\dot{E} = nE - ABE(z+1) + D(a_1 + a_2) \tag{3.5.15}$$

At this stage, we use the long-run approximation that greatly simplifies the calculations without being applicable to the short-run dynamics.

Providing positive growth, in the very long run the following is true:

$$\frac{1}{m_2 + K} \approx \frac{1}{m_2} \text{ and } \frac{1}{m_1 + K} \approx \frac{1}{m_1}$$

The first order condition becomes:

$$(3.5.10) \rightarrow \frac{1}{AE - m_2 - a_1} \times \frac{m_2}{m_1} = \frac{1}{m_1}$$

$$(3.5.12) \rightarrow \frac{z}{zAE - m_1 - a_2} \times \frac{m_1}{m_2} = \frac{1}{m_2}$$

or $\begin{matrix} AE - m_2 - a_1 = m_2 \\ zAE - m_1 - a_2 = zm_1 \end{matrix}$ (3.5.16) $\qquad \begin{matrix} c_1 = m_2 \\ c_2 = zm_1 \end{matrix}$ (3.5.17)

From (3.5.17) $\qquad \begin{matrix} m_1 = \dfrac{c_2}{z} \\ m_2 = c_1 \end{matrix}$ (3.5.18)

From (3.5.16) and (3.5.17) $a_1 + a_2 = (z+1)AE - 2m_1 - (1+z)m_2$

or $a_1 + a_2 = (z+1)AE - (3+z)c_1$ (3.5.19)

Substitute (3.5.19) into (3.5.15)

$$\dot{E} = nE - AB(z+1)E + AD(z+1)E - D(3+z)c_1 \qquad (3.5.20)$$

Substitute (3.5.9) and (3.5.11) into (3.5.20)

$$\dot{E} = nE - AB(z+1)E + AD(z+1)E - \frac{3+z}{\varphi} \qquad (3.5.21)$$

(3.5.21) and (3.5.14) make up the system of interest.

Denote $G \equiv n - AB(z+1) + AD(z+1)$, we can rewrite the system as follows:

$$\begin{aligned} \dot{E} &= GE - \frac{3+z}{\varphi} \\ \dot{\varphi} &= -\frac{\alpha(z+1)}{E} - \varphi(G - \rho) \end{aligned} \qquad (3.5.\text{I})$$

Solving the system (3.5.I)

$$\dot{\varphi} E = -\alpha(z+1) - E\varphi(G - \rho)$$

$$\dot{E}\varphi = E\varphi G - (3+z)$$

or $\frac{d(E\varphi)}{dt} = -[(z+1)(\alpha+1)+2] + E\varphi\rho$

Solving that first order differential equation we obtain:

$$E\varphi = \frac{(z+1)(\alpha+1)+2}{\rho} \qquad (3.5.22)$$

Note that this also implies the tranversality condition is satisfied.

Substitute (3.5.22) into (3.5.21)

$$\dot{E} = nE - AB(z+1)E + AD(z+1)E - \frac{E\rho(3+z)}{(1+z)(\alpha+1)+2}$$

Hence, $\frac{\dot{E}}{E} = n + A(D-B)(z+1) - \frac{\rho(3+z)}{(1+z)(\alpha+1)+2}$

If we denote γ_3 as the growth rate then $\boxed{\gamma_3 = n + A(D-B)(z+1) - \frac{p(3+z)}{(1+z)(\alpha+1)+2}}$

The long run environmental quality, consumption, import and export paths of the two countries are derived below:

$E = E_0 \exp(\gamma_3 t)$ and from (3.5.22): $\varphi = \frac{(z+1)(\alpha+1)+2}{\rho E_0}\exp(-\gamma_3 t)$

From (3.5.9) and (3.5.11)

$$c_1 = \frac{1}{D\varphi} = \frac{\rho E_0}{D[(z+1)(\alpha+1)+2]}\exp(\gamma_3 t) \text{ and } c_2 = zc_1 = \frac{z\rho E_0}{D[(z+1)(\alpha+1)+2]}\exp(\gamma_3 t) \qquad (3.5.23)$$

Country 2 consumes z times more than country 1 does. Intuitively, country 2 with its technological dominance has obtained a higher weight in the joint utility, making it consume at a higher level than country 1 does. This result is similar to the one in the ‘coop-autarky’ scenario.

The analysis on import levels will be discussed in section 3.7.2

3.6 Non-cooperative environmental policies with international trade:

This situation is referred as *"noncoop-trade'*. Consider country 1:

$$U_1 = \ln c_1 + \alpha \ln E + \ln(m_1 + K) \tag{3.5.1}$$

$$y_1 = AE \tag{3.5.2}$$

$$x_1 + c_1 + a_1 = AE \tag{3.5.3}$$

Country 2

$$U_2 = \ln c_2 + \alpha \ln E + \ln(m_2 + K) \tag{3.5.4}$$

$$y_2 = zAE \tag{3.5.5}$$

$$x_2 + c_2 + a_2 = zAE \tag{3.5.6}$$

The environment evolves as follow:

$$\dot{E} = nE - B(y_1 + y_2) + D(a_1 + a_2)$$

We also assume perfect trading information. That is countries are aware that $m_1=x_2$ and $x_1=m_2$. They also know the trade balance ($p_1 x_1 = p_2 m_1$ or $p_1 m_2 = p_2 x_2$).Hence (3.5.7) and (3.5.8) are maintained:

$$c_1 = AE - \frac{p_2}{p_1} m_1 - a_1 \text{ and } c_2 = zAE - \frac{p_1}{p_2} m_2 - a_2 .$$

However, the two countries are not co-ordinating their policies, one country is not aware of the other's production and budget constraint. As said, it takes the other's activities as given.

Firstly we consider country 1. The social-planer problem of country 1 is to choose $\{a_1, m_1\}$ to maximise representative agent's utility subject to environmental quality accumulation constraints:

$$Max \int_0^\infty e^{-pt} (\ln c_1 + \ln(m_1 + K) + \alpha \ln E) dt$$

$$\text{subject to} \qquad \dot{E} = nE - B(y_1 + y_2) + D(a_1 + a_2) \tag{3.6.1}$$

with $$c_1 = AE - \frac{p_2}{p_1} m_1 - a_1$$

Country 1 does not take into account country 2's budget constraint and production function; hence we rewrite the problem as follows:

$$Max \int_0^{\infty} e^{-pt} (\ln(AE - \frac{p_2}{p_1} m_1 - a_1) + \ln(m_1 + K) + \alpha \ln E)dt$$

subject to $$\dot{E} = nE - ABE - By_2 + D(a_1 + a_2)$$

The Hamiltonian expression is:

$$H_1 = \ln\left[AE - \frac{p_2}{p_1} m_1 - a_1\right] + \alpha \ln E + \ln(m_1 + K) + \varphi[nE - ABE - By_2 + D(a_1 + a_2)]$$

The maximum principle states that the solution must obey (3.6.1) and:

$$\frac{\delta H_1}{\delta a_1} = 0 : \frac{1}{AE - \frac{p_2}{p_1} m_1 - a_1} = \varphi D \qquad \text{or } \frac{1}{c_1} = \varphi D \tag{3.6.2}$$

$$\frac{\delta H_1}{\delta m_1} = 0 : \frac{1}{AE - \frac{p_2}{p_1} m_1 - a_1} \times \frac{p_2}{p_1} = \frac{1}{m_1 + K}$$

or $$\frac{1}{AE - \frac{p_2}{p_1} m_1 - a_1} \times \frac{m_2}{m_1} = \frac{1}{m_1 + K} \tag{3.6.3}$$

$$\dot{\varphi} = -\frac{\delta H_1}{\delta E} + \varphi\rho$$

$$\dot{\varphi} = -\frac{A}{AE - \frac{p_2}{p_1} m_1 - a_1} - \frac{\alpha}{E} - \varphi[n - AB - \rho] \tag{3.6.4}$$

Substitute (3.6.2) into (3.6.4)

or $$\dot{\varphi} = -\frac{\alpha}{E} - \varphi[n - AB + AD - \rho] \tag{3.6.5}$$

Now we consider country 2. The social-planer problem of country 2 is also to choose $\{a_2, c_2, m_2\}$ to maximize the representative agent's utility subject to environmental quality accumulation constraints:

$$Max\int_0^\infty e^{-pt}(\ln c_2 + \ln(m_2 + K) + \alpha \ln E)dt$$

$$\text{subject to} \qquad \dot{E} = nE - B(y_1 + y_2) + D(a_1 + a_2) \qquad (3.6.1)$$

$$\text{with} \qquad c_2 = zAE - \frac{p_1}{p_2}m_2 - a_2$$

Rewrite the problem:

$$Max\int_0^\infty e^{-pt}(\ln(zAE - \frac{p_1}{p_2}m_2 - a_2) + \ln(m_2 + K) + \alpha \ln E)dt$$

$$\text{subject to} \qquad \dot{E} = nE - zABE - By_1 + D(a_1 + a_2)$$

The Hamiltonian expression is:

$$H_2 = \ln\left[zAE - \frac{p_1}{p_2}m_2 - a_2\right] + \alpha \ln E + \ln(m_2 + 1) + \lambda[nE - zABE - By_1 + D(a_1 + a_2)]$$

The maximum principle states that the solution must obey (3.6.1) and:

$$\frac{\delta H_2}{\delta a_2} = 0 : \frac{1}{zAE - \frac{p_1}{p_2}m_2 - a_2} = \lambda D \quad \text{or} \quad \frac{1}{c_2} = \lambda D \qquad (3.6.6)$$

$$\frac{\delta H_2}{\delta m_2} = 0 : \frac{1}{zAE - \frac{p_1}{p_2}m_2 - a_2} \times \frac{p_1}{p_2} = \frac{1}{m_2 + K}$$

$$\text{or} \quad \frac{1}{zAE - \frac{p_1}{p_2}m_2 - a_2} \times \frac{m_1}{m_2} = \frac{1}{m_2 + K} \qquad (3.6.7)$$

$$\dot{\lambda} = -\frac{\delta H_2}{\delta E} + \lambda\rho$$

$$\dot{\lambda} = -\frac{Az}{zAE - \frac{p_1}{p_2} m_2 - a_2} - \frac{\alpha}{E} - \lambda[n - zAB - \rho] \tag{3.6.8}$$

Substitute (3.6.6) into (3.6.8)

$$\dot{\lambda} = -\frac{\alpha}{E} - \lambda[n - zAB + zAD - \rho] \tag{3.6.9}$$

We use the same approximation in section 3.5. In the very long run, m_1 and m_2 are large , hence:

$$\frac{1}{m_2 + K} \approx \frac{1}{m_2} \text{ and } \frac{1}{m_1 + K} \approx \frac{1}{m_1}$$

The first order condition becomes:

$$(3.6.3) \rightarrow \frac{1}{AE - \frac{p_2}{p_1} m_1 - a_1} \times \frac{m_2}{m_1} = \frac{1}{m_1} \text{ hence } AE - \frac{p_2}{p_1} m_1 - a_1 = m_2 \text{ or } c_1 = m_2 \tag{3.6.11}$$

$$(3.6.7) \rightarrow \frac{1}{zAE - \frac{p_1}{p_2} m_1 - a_2} \times \frac{m_1}{m_2} = \frac{1}{m_2} \text{ hence } c_2 = m_1 \tag{3.6.12}$$

From (3.6.11) and (3.6.12) $a_1 + a_2 = (z+1)AE - 2(m_1 + m_2) = (z+1)AE - 2(c_1 + c_2)$

(3.6.13)

Substitute (3.6.13) into (3.6.1)

$$\dot{E} = nE - AB(z+1)E + AD(z+1)E - 2D(c_1 + c_2) \tag{3.6.14}$$

Substitute (3.6.2) and (3.6.6) into (3.6.14)

$$\dot{E} = nE - AB(z+1)E + AD(z+1)E - \frac{2}{\varphi} - \frac{2}{\lambda} \tag{3.6.15}$$

The system of (3.6.5),(3.6.9) and (3.6.15) is the subject of interest:

$$\dot{E} = E\left(n - AB(1+z) + AD(z+1)\right) - \frac{2}{\varphi} - \frac{2}{\lambda} \tag{3.6.15}$$

$$\dot{\varphi} = -\frac{\alpha}{E} - \varphi[n - AB + AD - \rho] \tag{3.6.5}$$

$$\dot{\lambda} = -\frac{\alpha}{E} - \lambda[n - zAB + zAD - \rho] \tag{3.6.9}$$

Solve the system we obtain the solution:

$E = E_0 \exp(\gamma_4 t)$ where $\boxed{\gamma_4 = n + (AD - AB)(z+1)\left(1 - \frac{2}{\alpha+4}\right) - \frac{4\rho}{\alpha+4}}$

The consumption paths of the two countries have been also derived:

$$c_1 = \frac{1}{D\varphi} = \frac{E_0}{D}\left[\frac{(AD-AB)\left[z - \frac{2(z+1)}{\alpha+4}\right]}{\alpha} + \frac{\rho}{\alpha+4}\right]\exp(\gamma_4 t)$$

$$c_2 = \frac{1}{D\lambda} = \frac{E_0}{D}\left[\frac{(AD-AB)\left[1 - \frac{2(z+1)}{\alpha+4}\right]}{\alpha} + \frac{\rho}{\alpha+4}\right]\exp(\gamma_4 t) \qquad (3.6.16)$$

The detailed calculations are shown in appendix A5

We obtained a similar result to that of 'noncoop-autarky' case, which is $c_1 > c_2$. Because of its sheer size, country 2 would single-handedly spend more on its abatement and to some extent, disregard the cleaning effort of country 1. Seeing a_2 so big, country 1 chooses an even smaller a_1, and this allows c_1 to exceed c_2.

The analysis on import levels will be discussed in section 3.7.2.

3.7 Comparison of the four scenarios:

In this section we attempt to compare the performance of the economies under various scenarios. There are four sub-cases depending on whether countries cooperate (C) or not (N) and whether they operate in autarky (A) or trade (T). We are particularly interested in comparing the performances of countries in autarky verus with trade.

The ideal comparison would be that of welfare levels (total discounted utility of the representative individual). However, this proves intractable[7] and we focus on the two components of the welfare level: the long run growth rate component and the initial utility level component. Typically policy changes affect these two components in opposite way; this is not always true here as we will demonstrate.

3.7.1 Comparisons of the growth rates:

Firstly, we compare the growth rates of countries in four sub-cases, depending on whether countries cooperate (indicated by C subscript) or not (subscripted N) and whether they operate in autarky (subscripted A) or trade (subscripted T). For convenience, the four long run growth rates in the four different scenarios are rewritten here:

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[7] The welfare level of country *i* is:

$$W_i = \int_0^\infty \{Ui\} \times e^{-\rho t} dt$$

$$W_i = \int_0^\infty \{\ln[c_i] + \ln(m_i + K) + \alpha \ln E_i\} \times e^{-\rho t} dt$$

$$W_i = \int_0^\infty \{\ln c_{0i} + \ln(m_{0i} + K) + \alpha \ln E_0\} \times e^{-\rho t} dt + \int_0^\infty (\alpha + 1)\gamma t \times e^{-\rho t} dt$$

$$= \frac{\ln c_{0i} + \ln(m_{0i} + K) + \alpha \ln E_0}{\rho} + \frac{(\alpha + 1)\gamma}{\rho^2}$$

As the starting point of the environment quality is the same in all circumstances, the relative welfare levels of countries depend on their initial utility levels ($\ln c_{0i} + \ln(m_{0i} + K)$) and the long run growth rates. However, the comparison of welfare levels is not possible.

Cooperative environmental policies in autarky:

$$\gamma_1 \equiv \gamma_{C-A} = n + A(D-B)(z+1) - \frac{\rho}{\alpha+1}$$

Non-cooperative environmental policies in autarky:

$$\gamma_2 \equiv \gamma_{N-A} = n + (AD - AB)(z+1)\left(1 - \frac{1}{\alpha+2}\right) - \frac{2\rho}{\alpha+2}$$

Cooperative environmental policy with international trade:

$$\gamma_3 \equiv \gamma_{C-T} = n + A(D-B)(z+1) - \frac{\rho(3+z)}{(z+1)(\alpha+1)+2}$$

Non-cooperative environmental policies with international trade:

$$\gamma_4 \equiv \gamma_{N-T} = n + (AD - AB)(z+1)\left(1 - \frac{2}{\alpha+4}\right) - \frac{4\rho}{\alpha+4}$$

The initial expectation is $\gamma_{C-A} > \gamma_{N-A}$ and $\gamma_{C-T} > \gamma_{N-T}$. This chapter examines the hypothetical two-country world where they share the same environment. In this common system, the pollution caused by one country is shared by the other country involved. In addition, the effort to clean up the environment of one country also benefits the other. As a result, if they do not co-ordinate their environmental policies, countries have the incentive to over pollute or under-abate the environment. The conventional wisdom in these circumstances is that the environmental quality deteriorates; and countries experience the sub-optimal long run growth rates.

We have to see if the algebra confirms our expectations.

$$\gamma_{C-A} - \gamma_{N-A} = \left[n + A(D-B)(z+1) - \frac{\rho}{\alpha+1}\right] - \left[n + (AD - AB)(z+1)\left(1 - \frac{1}{\alpha+2}\right) - \frac{2\rho}{\alpha+2}\right]$$

$$= -\frac{\rho}{\alpha+1} + (AD - AB)(z+1)\left(\frac{1}{\alpha+2}\right) + \frac{2\rho}{\alpha+2}$$

$$= (AD - AB)(z+1)\left(\frac{1}{\alpha+2}\right) + \frac{\rho\alpha}{(\alpha+2)(\alpha+1)} > 0$$

$\gamma_{C-T} - \gamma_{N-T}$

$$\left[n + A(D-B)(z+1) - \frac{\rho(3+z)}{(z+1)(\alpha+1)+2}\right] - \left[n + (AD - AB)(z+1)\left(1 - \frac{2}{\alpha+4}\right) - \frac{4\rho}{\alpha+4}\right]$$

$$= -\frac{\rho(3+z)}{(z+1)(\alpha+1)+2} + (AD-AB)(z+1)\left(\frac{2}{\alpha+4}\right) + \frac{4\rho}{\alpha+4}$$

$$= (AD-AB)(z+1)\left(\frac{2}{\alpha+4}\right) + \frac{\rho(3\alpha z+\alpha)}{(\alpha+4)[(z+1)(\alpha+1)+2]} > 0$$

Hence $\gamma_{C-A} > \gamma_{N-A}$ and $\gamma_{C-T} > \gamma_{N-T}$ as expected.

More careful analysis provides some additional insights. The gaps between cooperative and non-cooperative growth rates depend upon total technology parameter (*z*+1). What can be inferred is the two countries with more advanced technology are penalised more heavily not cooperating with each other. However, the gaps do not increase with a shift of technology weight from one country to the other. This suggests that disparity in technology does not drive growth for both countries, as noted in section 3.3.

The gaps also depend on the size of *A(D-B)*, *ceteris paribus*. The larger the difference between *D* and *B* coefficients, the wider is the gap. This is the result also obtained in the previous chapter. That is, countries with cleaner production and advanced abatement technology are better off co-operating their environmental policies than they would otherwise. Advanced abatement and clean production technology might well provide strong tools for the two countries to internalise the environmental externality.

The influence of the environmental preference on growth is less clear.

Consider $\gamma_{C-A} - \gamma_{N-A} = (AD-AB)(z+1)\left(\frac{1}{\alpha+2}\right) + \frac{\rho\alpha}{(\alpha+2)(\alpha+1)}$.

It is easy to see that $(AD-AB)(z+1)\left(\frac{1}{\alpha+2}\right)$ is a decreasing function of α.

The second term $\frac{\alpha}{(\alpha+2)(\alpha+1)}$ is a decreasing function if and only if $\alpha \geq \sqrt{2}$.

Hence in the range of $\alpha \geq \sqrt{2}$, $\gamma_{C-A} - \gamma_{N-A}$ is decreasing in α, i.e. stronger environmental preference mitigates the environmental externality. However in the range of $\alpha < \sqrt{2}$, systematic relationship between the growth rate and the environmental preference can not be drawn. Furthermore, it seems difficult in practice to pin point the exact realistic size of the environmental preference, as the measures of one unit of the environmental quality and one unit of consumption are not known. A similar conclusion is reached for the case of γ_{C-T} - γ_{N-T} .

Now we turn to the comparison between the growth rates in the autarky situation and in the one when countries are opening up their economies to trade. Essentially we compare γ_{C-A} and γ_{C-T} ; γ_{N-A} and γ_{N-T} .

Comparing γ_{C-A} and γ_{C-T} is straightforward.

$$\gamma_{C-A} - \gamma_{C-T} = \left[n + A(D-B)(z+1) - \frac{\rho}{\alpha+1}\right] - \left[n + A(D-B)(z+1) - \frac{\rho(3+z)}{(z+1)(\alpha+1)+2}\right]$$

$$= \frac{\rho[(3+z)(\alpha+1)-(z+1)(\alpha+1)+2]}{(\alpha+1)[(z+1)(\alpha+1)+2]} = \frac{2\rho\alpha}{(\alpha+1)[(z+1)(\alpha+1)+2]} > 0.$$

γ_{N-A} - γ_{N-T} =

$$= \left[n + (AD-AB)(z+1)\left(1-\frac{1}{\alpha+2}\right) - \frac{2\rho}{\alpha+2}\right] - \left[n + (AD-AB)(z+1)\left(1-\frac{2}{\alpha+4}\right) - \frac{4\rho}{\alpha+4}\right]$$

$$= (AD-AB)(z+1)\left(\frac{2}{\alpha+4} - \frac{1}{\alpha+2}\right) + \frac{4\rho}{\alpha+4} - \frac{2\rho}{\alpha+2}$$

$$= (AD-AB)(z+1)\left(\frac{\alpha}{(\alpha+4)(\alpha+2)}\right) + \frac{2\alpha}{(\alpha+4)(\alpha+2)} > 0$$

Interestingly countries enjoy higher long run growth rate in autarky than they do when engage in international trade. Traditionally, trade is said to support growth. Many theoretical international trade studies have been able to show a positive correlation between trade volume and the economy’s performance. In our model the opposite result is observed. One possible interpretation of this result is that in our modelling of trade we introduce a second consumption good into each country. Previously each country spent its income on two goods: the home-produced consumption good and the environment enhancing abatement good. Now that there are three goods to spend income on, spending on the previous two goods is expected to diminish. If spending on abatement diminishes, so does the level of environmental quality in the long run, hence the growth rate.

Nevertheless, the implication of the model is clear. It suggests a negative environmental externality that counteracts the positive effect of trade on growth. In reality it might not be easily observed since the environmental contribution to economic activities is at a much lesser scale than theoretically presumed.

Note also that when $\alpha = 0$, hence when people only care to the environment as a factor of production and when the countries cooperate with each other, they have the same long run growth rates whether they operate under trade or autarky. The result also holds for the non-cooperative scenario.

3.7.2 The comparison of initial utility levels:

We have shown in 3.7.1 that the countries enjoy higher long run growth rates in autarky than in trade, now we turn our comparison into the second component of the welfare level, which is the initial utility level ($\ln c_{0i} + \ln(m_{0i} + K)$) .

When comparing initial utility levels under autarky and trade, we must make allowances for the fact that the consumption bundle will become two dimensional under trade. Therefore it would not be unexpected that the consumption of the home produced good decreases under trade.

The initial consumption levels of the home produced goods are:

Cooperative environmental policies in autarky:

$c_{1(C-A)}(t=0) = \dfrac{\rho E_0}{D(z+1)(\alpha+1)}$ and $c_{2(C-A)}(t=0) = \dfrac{z\rho E_0}{D(z+1)(\alpha+1)}$

Non-cooperative environmental policies in autarky:

$$c_{1(N-A)}(t=0)=\frac{E_0}{D}\left[\frac{(AD-AB)\left(z-\frac{z+1}{\alpha+2}\right)}{\alpha}+\frac{\rho}{\alpha+2}\right]$$

$$c_{2(N-A)}(t=0)=\frac{E_0}{D}\left[\frac{(AD-AB)\left(1-\frac{z+1}{\alpha+2}\right)}{\alpha}+\frac{\rho}{\alpha+2}\right]$$

Cooperative environmental policy with trade:

$c_{1(C-T)}(t=0)=\frac{\rho E_0}{D[(z+1)(\alpha+1)+2]}$ and $c_{2(C-T)}(t=0)=\frac{z\rho E_0}{D[(z+1)(\alpha+1)+2]}$

Non-cooperative environmental policies with trade:

$$c_{1(N-T)}(t=0)=\frac{E_0}{D}\left[\frac{(AD-AB)\left[z-\frac{2(z+1)}{\alpha+4}\right]}{\alpha}+\frac{\rho}{\alpha+4}\right]$$

$$c_{2(N-T)}(t=0)=\frac{E_0}{D}\left[\frac{(AD-AB)\left[1-\frac{2(z+1)}{\alpha+4}\right]}{\alpha}+\frac{\rho}{\alpha+4}\right]$$

As noted in chapter 2, under cooperative environmental policies, while the growth rates are affected by the overall technological parameter *A*, the initial consumption levels are not.

Calculations of the initial values of foreign-produced goods:

Cooperative environmental policy with trade:

Note that in all scenarios involving international trade, we use the long run approximation method as the only way to derive analytically the long run growth rates. The values of $\gamma_{\text{C-T}}$, $\gamma_{\text{N-T}}$ are therefore approximate values. The values of the costate variables are also approximate ones. When we derived the initial values of consumption we used the first order condition that involved only the costate variables[8], therefore the approximation of consumption is as good as γ and the costates. However in order to derive the initial values of m , we must not use the modified FOC that assimilates m to $m+K$, but rather the true FOC.

Rewrite the correct FOC:

$$\frac{1}{AE-\frac{p_2}{p_1}m_1-a_1}\times\frac{m_2}{m_1}=\frac{1}{m_1+K} \qquad \text{(from 3.5.10)}$$

$$\frac{z}{zAE-\frac{p_1}{p_2}m_2-a_2}\times\frac{m_1}{m_2}=\frac{1}{m_2+K} \qquad \text{(from 3.5.12)}$$

or
$$\begin{aligned}\frac{1}{c_1}\times\frac{m_2}{m_1}&=\frac{1}{m_1+K}\\ \frac{z}{c_2}\times\frac{m_1}{m_2}&=\frac{1}{m_2+K}\end{aligned} \qquad (3.7.2.1)$$

The two equations give the values of initial imports.

Cooperative environmental policy with trade:

Similarly we also rewrite the correct FOCs:

$$\frac{1}{AE-\frac{p_2}{p_1}m_1-a_1}\times\frac{m_2}{m_1}=\frac{1}{m_1+K} \qquad \text{(from 3.6.3)}$$

$$\frac{1}{zAE-\frac{p_1}{p_2}m_2-a_2}\times\frac{m_1}{m_2}=\frac{1}{m_2+K} \qquad \text{(from 3.6.7)}$$

or
$$\begin{aligned}\frac{1}{c_1}\times\frac{m_2}{m_1}&=\frac{1}{m_1+K}\\ \frac{1}{c_2}\times\frac{m_1}{m_2}&=\frac{1}{m_2+K}\end{aligned} \qquad (3.7.2.2)$$

[8] See (3.5.9) and (3.5.11)

We would need to solve the two equations we also obtain the values of initial import in the non-cooperative case.

However, our ultimate interest is to compare the initial utility levels of each country in autarky versus with trade, and we will focus on doing so and ignore the calculation of m_i. We compare the initial utility level in the next section in the special case of identical countries (*z=1*) since we have now shifted our focus onto the trade versus autarky question. When doing the comparison, there are two sub-cases: when the countries coordinate their environmental policies or when they do not.

3.7.2.1 Comparison of initial utility levels when the countries cooperate with each other:

The initial utility level of country *i* is expressed as $\ln c_{0i} + \ln(m_{0i} + K)$ where c_i was written in page 62 and m_i is the solution of (3.7.2.1). The calculations show that in the general case ($z \neq 1$) we can not draw any analytical result about the comparison of the initial levels of countries in the two scenarios, with and without trade. Hence we focus on the special case of *z*=1 (the countries have the same technological level, which effectively makes the two countries identical). We can indeed do so without significant loss of generalisation since the technological asymmetry does not influence the growth rate, in other words, disparity does not drive growth (as it was discussed in page 59 , section 3.7.1). The choice of the value of K will be discussed shortly .

If *z=1*, the two countries are identical and $m_1=m_2$, from (3.7.2.2) we have $c_1=m_1+K$.

Since the countries are identical, we consider the initial levels of country 1 only, note that z has been replaced 1 in all expressions below.

In autarky:

$$L_{1((C\text{-}A)}= \ln c_{01} + \ln(m_{01} + K) = \ln(c_{1(C-A)}(t=0)) + \ln K = \ln\left(\frac{\rho E_0}{2D(\alpha+1)}\right) + \ln K$$

With international trade:

$$L_{1(C\text{-}T)} = \ln c_{01} + \ln(m_{01} + K)$$

Since $c_1=m_1+K$, $L_{1(C\text{-}T)} = 2\ln(c_{01}) + \ln K = 2\ln\left(\frac{\rho E_0}{2D(\alpha+2)}\right)$.

The difference between the two levels is:

$L_{1(C-T)}$ - $L_{1(C-A)}$ $=2\ln\left(\dfrac{\rho E_0}{2D(\alpha+2)}\right)-\ln\left(\dfrac{\rho E_0}{2D(\alpha+1)}\right)-\ln K$

$$= \ln\left(\frac{\rho E_0}{2D}\right) - 2\ln(\alpha+2) + \ln(\alpha+1) - \ln K \qquad \text{(with } z=1\text{)}$$

$$= \ln\left(\frac{\rho E_0}{2DK}\right) + \ln(\alpha+1) - 2\ln(\alpha+2) \qquad (3.7.2.3)$$

In order to choose a 'neutral' value of K to calibrate the model, we assume that K is such that country 1 is indifferent between trade and autarky when they view the quality of the environment only as a factor of production ($\alpha = 0$) (recall that under cooperation the growth rates are identical under autarky and trade when $\alpha = 0$). Therefore we choose the 'neutral' K such that:

$L_{1(C-T)}$ - $L_{1(C-A)}$ $=\ln\left(\dfrac{\rho E_0}{2DK}\right)-2\ln(2)=0 \qquad (\alpha = 0)$

Hence, $K=K_0=\left(\dfrac{\rho E_0}{8D}\right)$ and with that value, (3.7.2.3) becomes:

$L_{1(C-T)}$ - $L_{1(C-A)}$ $=2\ln 2+\ln(\alpha+1)-2\ln(\alpha+2)= \ln[4(\alpha+1)]-\ln[(\alpha+2)^2]$

Under this neutral calibration, we see that trade is worse than autarky in terms of initial utility levels if and only if $\ln[4(\alpha+1)] < \ln[(\alpha+2)^2]$, which holds for any positive α. Hence under our calibration autarky is unambiguously better than trade as long as people care about the environment as a factor in their utility.

3.7.2.2 Comparison of initial utility levels when the countries do not cooperate with each other:

Similarly, if $z=1$, from (3.7.2.2) we have $c_1=m_1+K$. We again use the neutral K_0 value in what follows.

Since the countries are identical, we consider the initial levels of country 1 only.

In autarky:

L$_{1(N\text{-}A)}$= $\ln c_{1(N-A)}(t=0)+\ln K_0 = \ln\left\{\frac{E_0}{D}\left[\frac{(AD-AB)\left(1-\frac{2}{\alpha+2}\right)}{\alpha}+\frac{\rho}{\alpha+2}\right]\right\}$ +lnK_0

or L$_{1(N\text{-}A)}$ $=\ln\left\{\frac{E_0}{D}\left[\frac{(AD-AB)+\rho}{\alpha+2}\right]\right\}$ +ln$\left(\frac{\rho E_0}{8D}\right)$

With international trade:

L$_{1(N\text{-}T)}$=$\ln c_{01}+\ln(m_{01}+K_0)=2\ln(c_{1(N-T)}(t=0))$

$$=2\ \ln\left\{\frac{E_0}{D}\left[\frac{(AD-AB)+\rho}{\alpha+4}\right]\right\}$$

The difference between the two levels is:

L$_{1(C\text{-}T)}$ - L$_{1(C\text{-}A)}$ =2 $\ln\left\{\frac{E_0}{D}\left[\frac{(AD-AB)+\rho}{\alpha+4}\right]\right\}$ - $\ln\left\{\frac{E_0}{D}\left[\frac{(AD-AB)+\rho}{\alpha+2}\right]\right\}$ -ln$\left(\frac{\rho E_0}{8D}\right)$

$$= \ln\left(\frac{AD-AB+\rho}{\rho}\right)\text{-ln }\left((\alpha+4)^2\right)+\text{ ln }(8(\alpha+2))$$

$$=\ln\left(1+\frac{AD-AB}{\rho}\right)\text{-ln }\left(1+\frac{\alpha^2}{8\alpha+16}\right)$$

The value of the overall technology *A* matters here and it enhances the initial utility level in the trade situation in relation to the autarky one.

If $\frac{AD-AB}{\rho}<\frac{\alpha^2}{8\alpha+16}$, autarky is ambiguously preferred to trade as level effect and growth effect favour it. Trade is worse than autarky in terms of initial utility level when the environmental preference is large enough.

If $\frac{AD-AB}{\rho}>\frac{\alpha^2}{8\alpha+16}$, the comparison is ambiguous. A large overall technology (*A*) and good cleaning technology (*D-B* large), combined with a small environmental preference will have trade favoured in terms of the initial level effect, although autarky have a superior growth effect.

3.8 Conclusion:

In this chapter we changed our focus to the impact of international trade on the economy. The incorporation of trading is simplistic, in the sense that we assume the two countries produce two different products and imports are to satisfy consumers' demand. Various side-effects of international trade such as technology spill-over and capital accumulation from overseas are not included in the model.

We found that *the long run growth rates of countries are lower when they engage in international trade, no matter whether the environmental externality is internalised or not*. One possible interpretation of this result is that in our modelling of trade we introduce a second consumption food into each country. Previously each country spent its income on two goods: the home-produced consumption good and the environment enhancing abatement good. Now that there are three goods to spend income on, spending on the previous two goods is expected to diminish. If spending on abatement diminishes, so does the level of environmental quality in the long run, hence the growth rate.

The effect on welfare level is not known due to the ambiguity of the level effects. For simplicity, we focused the analysis on the special case of identical countries and calibrate the model so that in the 'neutral' case, i.e. when countries are identical and the environmental preference is nil, countries are indifferent to trading. With that calibration, *we found that when the two countries cooperate, autarky is always preferred to trade as long as people take the environment into their utility. When the countries do not coordinate their environmental policies, provided that abatement is efficient enough compared to pollution, trade has better initial utility level than autarky when the environmental preference is small enough. However, due to the negative growth effect, the effect of trade on welfare level is a subject of empirical studies.*

When the externality is not internalised, the result is not at all surprising as the well-known second-best policy work in the 1970s has indicated that trade needs not be welfare enhancing when externality exists. Here, the result shows that even the two countries coordinate their environmental policy perfectly, their welfare level does not improve. Furthermore, with positive environmental preference, the welfare level clearly declines as a result of trading. It is a very undesirable and disappointing result to the dominant pro-trade community, but worth noting. We should note that the model differs from previous trade models in the way that we consider trade in the context of the polluting production. Indeed, for the sake of tractability the impact of the environment on the production process is over-emphasized (the environment is made the sole input of the production) and that might well be the reason for such a result. In addition, the model fails to take into account the possible effects resulting from trading such as economies of scale and technology spill-over effect. Nevertheless, the implication of the model is clear. It suggests a negative environmental shock that works against the positive effect of trade on growth. In reality it might not be easily observed since the environmental contribution to economic activities is at a much lesser scale than theoretically presumed.

CHAPTER 4 –CONCLUSION

We develop a dynamic model that incorporates various roles of the environment in the production process and human activities; we subsequently attempt to illustrate the intricate and interrelated long run relationships between economic growth, international trade and environmental quality. The dynamic model is being used here to stress the long run impact on the natural environment, viewed as a stock, and also on the long run influence of the environment on the economy. The model explicitly considers trans-boundary pollution problems between two separate economies and to some extents allows for asymmetries between them.

The asymmetry is brought in as an effort to reflect the inherent differences in characteristics between developed and developing countries and in their attitudes towards environmental issues, which are usually ignored in previous long run dynamic models. The asymmetry allows us to explain the interaction concerning trade, common environment and growth, especially between developed and developing countries.

In the first part of the thesis, the two countries in the model are identical except for their environmental preferences. Two scenarios are considered: whether the two countries coordinate or do not coordinate their environmental policies. The results fulfil the expectations. That is, *the countries will enjoy higher growth rates and a higher environmental quality when they cooperate.* The reason is that by coordinating their activities countries are able to fully internalise the international environmental externality. Interestingly, *we found that two countries suffer more heavily not cooperating with each other when their attitudes toward a cleaner environment differ greatly.* The implication is very clear. Despite the inherent differences in their development level and in their environmental attitudes, developed and developing countries are strongly encouraged to cooperate environmentally.

Given that perfect cooperation is not always possible, we have also investigated the scheme whereby a country single-handedly seeks to improve either the growth rate or its own welfare. The mathematical result and the numerical exercise show that when a well-chosen subsidy is applied to the other country's abatement activities, the country with higher environmental preference could improve the non-cooperative growth rate and its own welfare.

In chapter 3, we turn the focus to the role of international trade in relation to economic growth and the environment. In our model, we assume the two countries produce two different products. The good produced by one country cannot be produced or used to abate the environment by the other one. For simplicity and for the concentration on the analysis of the technological discrepancy, the environmental preferences for the two countries are assumed identical. We then compare the welfare levels of the countries in various scenarios: with or without trade; and under cooperation or non-cooperation. Comparison of the welfare levels is analytically intractable. Consequently we analyse the effect of the various scenarios on the long run growth rate and the initial level effects separately. In terms of the growth rate, we found *the long run growth rates of the countries are lower when they engage in international trade, no matter whether the environmental externality is internalised or not, while the effect on initial utility levels is ambiguous.* However, under cooperation and when people only care about the environment as a factor of production, the countries have the same long run growth rates in both autarky and trade.

When comparing the initial utility levels, we only consider the special case of identical countries and calibrate the model so that with zero environmental preference, countries are indifferent between trading or not. We find that the *higher the environmental preference, the worse trade is compared to autarky in terms of initial utility level.* Under cooperation, *a positive environmental preference is enough for a lower initial utility level as a result of trade. Welfare level unambiguously decreases with trade then. When the countries do not coordinate their environmental policies, provided that abatement is efficient enough compared to pollution, trade yields a higher initial utility level than autarky when the environmental preference is small enough. The impact of trade on welfare level then becomes a subject of empirical studies.*

Therefore our model has identified cases when an opening to trade lowers welfare. We speculate that the increase in the size of the basket of goods available under trade is partially responsible for the result, combined with the fact that environmental quality is the sole factor of production; the combined effect of these two features is that trade indirectly results in a lowering of the environmental quality hence of the productive capacity of the environment in the long run.

Appendix A1

$$\dot{\varphi} = -\frac{\alpha}{E} - \varphi(n-2AB+AD-\rho) \qquad \text{(2.2b)} \qquad \text{or} \qquad \text{(A1.1)}$$

$$\dot{\lambda} = -\frac{\beta}{E} - \lambda(n-2AB+AD-\rho) \qquad \text{(2.4)} \qquad \text{or} \qquad \text{(A1.2)}$$

$$\dot{E} = E(n-2AB+2AD) - \frac{1}{\lambda} - \frac{1}{\varphi} \qquad \text{(2.6)} \qquad \text{or} \qquad \text{(A1.3)}$$

Try

$$E(t)=E_0\exp(\gamma_1 t) \qquad \text{(A1.4)}$$

$$\varphi(t) = \varphi_0 \exp(-\gamma_1 t) \qquad \text{(A1.5)}$$

$$\lambda(t) = \lambda_0 \exp(-\gamma_1 t) \qquad \text{(A1.6)}$$

Substitute (A1.5) and (A1.6) to (A1.1)

$$\varphi_0(-\gamma)e^{-\gamma_1 t} = -\frac{\alpha}{E_0}e^{-\gamma t} - \varphi_0 e^{-\gamma_1 t}(n-AB+AD-\rho) \Rightarrow \varphi_0 E_0 = \frac{-\alpha}{n-AB+AD-\gamma_1-\rho}$$

Similarly, $\lambda_0 E_0 = \dfrac{-\beta}{n-AB+AD-\gamma_1-\rho}$ (A1.8)

Substitute (A1.4)(A1.5)(A1.6) to (A1.3):

$$E_0\gamma_1 e^{\gamma_1 t} = E_0 e^{\gamma_1 t}(n-2AB+2AD) - \frac{e^{\gamma_1 t}}{\lambda_0} - \frac{e^{\gamma_1 t}}{\varphi_0}$$

$$E_0(n-2AB+2AD-\gamma_1) = \frac{1}{\lambda_0} + \frac{1}{\varphi_0}$$

Substitute (A1.7)(A1.8) into the above

$$E_0(n-2AB+2AD-\gamma_1) = -\frac{E_0(n-AB+AD-\rho-\gamma_1)}{\alpha} - \frac{E_0(n-AB+AD-\rho-\gamma_1)}{\beta}$$

$$\Rightarrow \boxed{\gamma_1 = n-2AB+2AD - \frac{(AD-AB+\rho)(\alpha+\beta)}{\alpha+\beta+\alpha\beta}} \qquad \text{(A1.9)}$$

Substitute (A1.9) into (A1.7) and (A1.8):

$$\varphi_0 E_0 = \frac{\alpha}{\gamma_1+\rho-n+AB-AD} = \frac{\alpha+\beta+\alpha\beta}{\beta(\rho+AD-AB)} \qquad \text{(A1.10)}$$

$$\lambda_0 E_0 = \frac{\beta}{\gamma_1+\rho-n+AB-AD} = \frac{\alpha+\beta+\alpha\beta}{\alpha(\rho+AD-AB)} \qquad \text{(A1.11)}$$

Note that (A1.10) and (A1.11) imply the transversality condition is satisfied.

Appendix A2

$$\dot{\varphi} = -\frac{\alpha+\beta}{E} - \varphi(n - 2AB + 2AD - \rho) \qquad \text{(2.9) or(A2.1)}$$

$$\dot{E} = (n - 2AB + 2AD)E - \frac{2}{\varphi} \qquad \text{(2.10) or} \qquad \text{(A2.2)}$$

Denote $G \equiv n - 2AB + 2AD$, rewrite the system

$$\dot{\varphi} = -\frac{\alpha+\beta}{E} - \varphi(G - \rho) \qquad \text{(A2.1')}$$

$$\dot{E} = EG - \frac{2}{\varphi} \qquad \text{(A2.2')}$$

$\Leftrightarrow$

$$\dot{\varphi} E = -(\alpha+\beta) - \varphi E(G - \rho) \qquad \text{(A2.3)}$$

$$\dot{E}\varphi = \varphi EG - 2 \qquad \text{(A2.4)}$$

(A2.3)+(A2.4)

$$\dot{\varphi} E + \dot{E}\varphi = -(\alpha+\beta+2) + \varphi E\rho$$

or $\quad \int(\dot{\varphi} E + \dot{E}\varphi)dt = -(\alpha+\beta+2)t + \rho\int\varphi E dt$

or $\quad E\varphi = -(\alpha+\beta+2)t + \rho\int\varphi E dt \qquad$ (A2.5)

If we let $\int\varphi E dt$ =u(t) then $E\varphi = u^{'}(t)$

(A2.5) $\quad u^{'}(t) - \rho u(t) = -(\alpha+\beta+2)t$

The solution for this differential equation is $u(t) = \frac{\alpha+\beta+2}{\rho^2}\times(\rho t + 1)$

$$\varphi E = u^{'}(t) = \frac{\alpha+\beta+2}{\rho} \qquad \text{(A2.6)}$$

Note that (A2.6) implies the transversality condition is satisfied.

Substituting (A2.6) into (A2.2'):

$$\dot{E} = EG - \frac{2}{\varphi} = EG - \frac{2E\rho}{\alpha+\beta+2} = E(G - \frac{2\rho}{\alpha+\beta+2})$$

then $E = E_0 \exp\left[G - \frac{2\rho}{\alpha+\beta+2}\right] = E_0 \exp\left[n - 2AB + 2AD - \frac{2\rho}{\alpha+\beta+2}\right]$

Appendix A3

$$\dot{\varphi} = -\frac{\alpha}{E} - \varphi(n - AB + (1-\tau)AD - \rho) \qquad \text{(A3.1)}$$

$$\dot{\lambda} = -\frac{\beta}{E} - \lambda(n - AB + \frac{AD}{1-s} - \rho) \qquad \text{(A3.2)}$$

$$\dot{E} = E\left[n - 2AB + AD(1 - \tau + \frac{1}{1-s})\right] - \frac{1}{\varphi} - \frac{1}{\lambda} \qquad \text{(A3.3)}$$

Try

$E(t)=E_0\exp(\gamma_3 t)$ (A3.4)

$\varphi(t) = \varphi_0 \exp(-\gamma_3 t)$ (A3.5)

$\lambda(t) = \lambda_0 \exp(-\gamma_3 t)$ (A3.6)

Substituting (A3.4)(A3.5) into (A3.1), we obtain:

$$\varphi_0(-\gamma_3) = -\frac{\alpha}{E_0} - \varphi_0(n - AB + (1-\tau)AD - \rho)$$

or $$\Rightarrow \varphi_0 E_0 = \frac{\alpha}{\gamma_3 + \rho - n + AB - (1-\tau)AD} \qquad \text{(A3.7)}$$

Similarly, $$\lambda_0 E_0 = \frac{\beta}{\gamma_3 + \rho - n + AB - \frac{AD}{1-s}} \qquad \text{(A3.8)}$$

Note that (A3.7) and (A3.8) implies the transversality condition is satisfied.

Substitute (A3.4)(A3.5)(A3.6) to (A3.3):

$$E_0\gamma_3 = E_0(n - 2AB + (1-\tau)AD + \frac{AD}{1-s}) - \frac{1}{\lambda_0} - \frac{1}{\varphi_0}$$

Substitute (A3.7)(A3.8) into the above

$$n - 2AB + (1-\tau)AD + \frac{AD}{1-s} - \gamma_3 = \frac{AB - (1-\tau)AD + \rho + \gamma_3 - n}{\alpha} + \frac{AB - \frac{AD}{1-s} + \rho + \gamma_3 - n}{\beta}$$

$$\Rightarrow \gamma_3 = n - 2AB + (1-\tau)AD + \frac{AD}{1-s} + \frac{(AB-\rho)(\alpha+\beta)}{\alpha+\beta+\alpha\beta} - \left[\frac{(1-\tau)}{\beta} + \frac{1}{(1-s)\alpha}\right] \times \frac{AD}{\alpha+\beta+\alpha\beta}$$

(A3.9)

Substitute (A3.9) into (A3.7) and (A3.8):

$$\varphi_0 E_0 = \frac{\alpha}{\gamma_3 + \rho - n + AB - (1-\tau)AD}$$

$$\frac{1}{\varphi_0} = E_0 \times \left((AB - \rho)\left(\frac{\alpha + \beta - \alpha\beta}{\alpha^2 \beta}\right) - \left[\frac{1-\tau}{\beta} + \frac{1}{(1-s)\alpha}\right] \times \frac{AD\beta}{\alpha + \beta + \alpha\beta} + \frac{AD}{\alpha(1-s)} \right)$$

$$\lambda_0 E_0 = \frac{\beta}{\gamma_3 + \rho - n + AB - \frac{AD}{1-s}}$$

$$\frac{1}{\lambda_0} = E_0 \times \left((AB - \rho)\left(\frac{\alpha + \beta - \alpha\beta}{\alpha\beta^2}\right) - \left[\frac{1-\tau}{\beta} + \frac{1}{(1-s)\alpha}\right] \times \frac{AD\alpha}{\alpha + \beta + \alpha\beta} + \frac{AD(1-\tau)}{\beta} \right)$$

Appendix A4

$$\overset{\bullet}{E} = E\big(n - AB(1+z) + AD(z+1)\big) - \frac{2}{\varphi} - \frac{2}{\lambda} \qquad (3.4.1b)$$

$$\dot{\varphi} = -\frac{\alpha}{E} - \varphi[n - AB + AD - \rho] \qquad (3.4.4)$$

$$\dot{\lambda} = -\frac{\alpha}{E} - \lambda[n - zAB + zAD - \rho] \qquad (3.4.7)$$

Try

$E(t)=E_0\exp(\gamma_2 t)$ (A4.1)

$\varphi(t) = \varphi_0 \exp(-\gamma_2 t)$ (A4.2)

$\lambda(t) = \lambda_0 \exp(-\gamma_2 t)$ (A4.3)

Substitute (A4.2) and (A4.3) to (3.4.4)

$$\varphi_0(-\gamma_2)e^{-\gamma_2 t} = -\frac{\alpha}{E_0}e^{-\gamma_2 t} - \varphi_0 e^{-\gamma_2 t}(n - AB + AD - \rho)$$

$$\Rightarrow \varphi_0 E_0 = \frac{-\alpha}{n - AB + AD - \gamma_2 - \rho} \qquad (A4.4)$$

Similarly, $\lambda_0 E_0 = \dfrac{-\alpha}{n - zAB + zAD - \gamma_2 - \rho}$ (A4.5)

Substitute (A4.4)(A4.5)(A4.1) to (3.4.1b):

$$E_0\gamma_2 e^{\gamma_2 t} = E_0 e^{\gamma_{21} t}(n - AB(1+z) + AD(1+z)) - \frac{e^{\gamma_2 t}}{\lambda_0} - \frac{e^{\gamma_2 t}}{\varphi_0}$$

$$E_0(n - AB(1+z) + AD(1+z) - \gamma_2) = \frac{1}{\lambda_0} + \frac{1}{\varphi_0}$$

Substitute (A4.4)(A4.5) into the above

$$E_0(n - AB(1+z) + AD(1+z) - \gamma_2) = -\frac{E_0(2n - AB(z+1) + AD(z+1) - 2\rho - 2\gamma_2)}{\alpha}$$

$$\Rightarrow \boxed{\gamma_2 = n - AB(z+1) + AD(z+1) - \frac{(AD - AB)(z+1)}{\alpha+2} - \frac{2\rho}{\alpha+2}} \qquad (A4.6)$$

Substitute (A4.6) into (A4.4):

$$\varphi_0 E_0 = \frac{\alpha}{\gamma_2 + \rho - n + AB - AD} = \frac{\alpha}{-zAB + zAD + \rho - \frac{(AD - AB)(z+1)}{\alpha+2} - \frac{2\rho}{\alpha+2}}$$

hence

$$\frac{1}{\varphi_0} = \frac{E_0\left[-zAB + zAD + \rho - \frac{(AD-AB)(z+1)}{\alpha+2} - \frac{2\rho}{\alpha+2}\right]}{\alpha}$$

$$\frac{1}{\varphi_0} = \frac{E_0(AD-AB)\left[z - \frac{z+1}{\alpha+2}\right]}{\alpha} + \frac{E_0\rho}{\alpha+2}$$

$$\frac{1}{c_1} = \varphi D \text{ hence } c_1 = \frac{1}{\varphi D} = \frac{1}{D\varphi_0 \exp(-\gamma_2 t)} = \frac{E_0}{D}\left[\frac{(AD-AB)\left(z - \frac{z+1}{\alpha+2}\right)}{\alpha} + \frac{\rho}{\alpha+2}\right]\exp(\gamma_2 t)$$

Substitute (A4.6) into (A4.5):

$$\lambda_0 E_0 = \frac{\alpha}{\gamma_2 + \rho - n + zAB - zAD} = \frac{\alpha}{-AB + AD + \rho - \frac{(AD - AB)(z+1)}{\alpha+2} - \frac{2\rho}{\alpha+2}}$$

hence

$$\frac{1}{\lambda_0} = \frac{E_0\left[-AB + AD + \rho - \frac{(AD-AB)(z+1)}{\alpha+2} + \frac{2\rho}{\alpha+2}\right]}{\alpha}$$

$$\frac{1}{\lambda_0} = \frac{E_0(AD-AB)\left[1 - \frac{z+1}{\alpha+2}\right]}{\alpha} + \frac{E_0\rho}{\alpha+2}$$

$$\frac{1}{c_2} = \lambda D \text{ hence } c_2 = \frac{1}{\lambda D} = \frac{1}{D\lambda_0 \exp(-\gamma_2 t)} = \frac{E_0}{D}\left[\frac{(AD-AB)\left(1 - \frac{z+1}{\alpha+2}\right)}{\alpha} + \frac{\rho}{\alpha+2}\right]\exp(\gamma_2 t)$$

Appendix A5

$$\dot{E} = E\left(n - AB(1+z) + AD(z+1)\right) - \frac{1}{\varphi} - \frac{1}{\lambda} \qquad (3.6.15)$$

$$\dot{\varphi} = -\frac{\alpha}{E} - \varphi\left[n - AB + AD - \rho\right] \qquad (3.6.5)$$

$$\dot{\lambda} = -\frac{\alpha}{E} - \lambda\left[n - zAB + zAD - \rho\right] \qquad (3.6.9)$$

Try

$E(t)=E_0\exp(\gamma_4 t)$ (A5.1)

$\varphi(t) = \varphi_0 \exp(-\gamma_4 t)$ (A5.2)

$\lambda(t) = \lambda_0 \exp(-\gamma_4 t)$ (A5.3)

Substitute (A5.2) and (A5.3) to (3.6.5)

$$\varphi_0(-\gamma_4)e^{-\gamma_4 t} = -\frac{\alpha}{E_0}e^{-\gamma_4 t} - \varphi_0 e^{-\gamma_4 t}(n - AB + AD - \rho)$$

$$\Rightarrow \varphi_0 E_0 = \frac{-\alpha}{n - AB + AD - \gamma_4 - \rho} \qquad (A5.4)$$

Similarly, $\lambda_0 E_0 = \dfrac{-\alpha}{n - zAB + zAD - \gamma_4 - \rho}$ (A5.5)

Substitute (A5.4)(A5.5)(A5.1) to (3.6.15):

$$E_0\gamma_2 e^{\gamma_4 t} = E_0 e^{\gamma_4 t}(n - AB(1+z) + AD(1+z)) - \frac{2e^{\gamma_4 t}}{\lambda_0} - \frac{2e^{\gamma_4 t}}{\varphi_0}$$

$$E_0(n - AB(1+z) + AD(1+z) - \gamma_4) = \frac{2}{\lambda_0} + \frac{2}{\varphi_0}$$

Substitute (A5.4)(A5.5) into the above

$$E_0(n - AB(1+z) + AD(1+z) - \gamma_4) = -\frac{2E_0(2n - AB(z+1) + AD(z+1) - 2\rho - 2\gamma_4)}{\alpha}$$

$$\Rightarrow \boxed{\gamma_4 = n - AB(z+1) + AD(z+1) - \frac{2(AD - AB)(z+1)}{\alpha + 4} - \frac{4\rho}{\alpha + 4}} \qquad (A5.6)$$

Substitute (A5.6) into (A5.4):

$$\varphi_0 E_0 = \frac{\alpha}{\gamma_4 + \rho - n + AB - AD} = \frac{\alpha}{-zAB + zAD + \rho - \frac{2(AD - AB)(z+1)}{\alpha + 4} - \frac{4\rho}{\alpha + 4}}$$

hence

$$\frac{1}{\varphi_0} = \frac{E_0(AD - AB)\left[z - \frac{2(z+1)}{\alpha + 4}\right]}{\alpha} + \frac{E_0 \rho}{\alpha + 4}$$

hence $c_1 = \dfrac{1}{D\varphi} = \dfrac{E_0}{D}\left[\dfrac{(AD - AB)\left[z - \frac{2(z+1)}{\alpha + 4}\right]}{\alpha} + \dfrac{\rho}{\alpha + 4}\right]\exp(\gamma_4 t)$

Substitute (A5.6) into (A5.5):

$$\lambda_0 E_0 = \frac{\alpha}{\gamma_2 + \rho - n + zAB - zAD} = \frac{\alpha}{-AB + AD + \rho - \frac{2(AD - AB)(z+1)}{\alpha + 4} - \frac{4\rho}{\alpha + 4}}$$

hence

$$\frac{1}{\lambda_0} = \frac{E_0(AD - AB)\left[1 - \frac{2(z+1)}{\alpha + 4}\right]}{\alpha} + \frac{E_0 \rho}{\alpha + 4}$$

thus $c_2 = \dfrac{1}{D\lambda} = \dfrac{E_0}{D}\left[\dfrac{(AD - AB)\left[1 - \frac{2(z+1)}{\alpha + 4}\right]}{\alpha} + \dfrac{\rho}{\alpha + 4}\right]\exp(\gamma_4 t)$

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