Trade and the Environment

THEORY AND EVIDENCE

BRIAN R. COPELAND
M. SCOTT TAYLOR

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Preface

We started this project with the hope of providing an answer to the question, "Is free trade good for the environment?" We soon realized that a complete answer would require a consideration of both local and global pollution, the impact of international trade on natural resource use, and also contain empirical work estimating the impact of trade and testing competing hypotheses. In short, this was not a book-length project that we could complete, but a question requiring an entire research agenda fueled by the contributions of many. In fact over the last thirty years, many *have* contributed to answering this question, and these earlier researchers provided the intellectual foundation for much of the analysis in this book. But while the existing literature contained many useful insights, it was fragmented: authors adopted very different assumptions regarding abatement, market structure, the efficacy of policy, and the tradability of both goods and factors; and the integration of theory with empirical work was rare. This made it difficult to identify key hypotheses, to focus future research on unanswered questions, and to convince both our students and our colleagues of the benefits of future research in this area.

Most progress in our discipline occurs when research efforts coalesce around a theoretical framework, develop its many implications, and examine these predictions empirically. Accordingly, we decided that a shorter and more focused effort would be of value in providing researchers with a simple and unified framework for analysis. We hope that by demonstrating how to identify and isolate the environmental impacts of trade, growth, and pollution policy, we will stir the interest of graduate students and prospective future entrants to the literature; by adopting a simple framework, we hope to lead readers to speculate about the robustness of our results and provide them with the tools for extension and qualification; and by presenting empirical evidence, we hope we have provided a provocative but partial answer to this literature's main question, while demonstrating the usefulness of combining theory with empirical work.

We have written a research monograph and not a textbook. It contains both known results and new research contributions. Chapters from the book have been taught to both advanced undergraduates and graduate students at the University of Wisconsin and the University of British Columbia. It would be suitable as a primary text in a special topics course, or as a supplementary textbook in either graduate international or environmental economics courses. Some of the material will be difficult for all but the most advanced undergraduates, but we have had great success in communicating the main ideas of the book to undergraduates by heavy use of the book's diagrams. We have tried very hard to make the book user friendly and enlarge its potential audience. Courses in agricultural economics, in public policy schools, and in specialized environmental programs may find the book useful.

Many people have helped us during this project. We are especially grateful to our colleague, Werner Antweiler, who collaborated with us on the empirical work that forms the basis of chapter 7. Gene Grossman provided excellent and detailed comments on every chapter. His input increased the book's clarity and focus. Both Sjak Smulders and Cees Withagen provided very helpful detailed comments on the book, based on their experience using the manuscript in a course at Tilburg. Arik Levinson, Larry Karp, Carol McAusland, and Chia-hui Lu also read the entire manuscript and made a number of helpful suggestions, as did several anonymous reviewers. Our students provided wonderful feedback that affected the book in very significant ways. We have also benefited from the input of seminar and conference participants at the National Bureau of Economic Research and at too many universities to mention. Research funding was provided by the Social Sciences and Humanities Research Council of Canada (Copeland) and the National Science Foundation (Taylor).

The biggest debt we owe is to our families for their patience and support during the book's very long gestation and somewhat painful labor.

1 The Trade and Environment Debate

1.1 Globalization and the Trade versus Environment Debate

"It was the best of times, it was the worst of times." This line, written by Charles Dickens over 100 years ago, captures the present-day divide between supporters and critics of globalization. During the 1990s, North America and much of Europe enjoyed its longest peacetime expansion, unemployment rates hit historic lows, and real income growth in much of the developing world soared. To many these are the fruits of globalization. But this same decade saw little progress in addressing climate change, a decline in fish and tropical forest stocks, and by some measures, rising inequality in the world distribution of income. To many others, these are its costs.

Debates over "globalization" have been going on for some time. But nowhere has the divide between the two views of globalization been more apparent than in recent discussions concerning trade liberalization and the environment.

For the last ten years environmentalists and the trade policy community have squared off over the environmental consequences of liberalized trade.[1] This debate was fueled by negotiations over the North American Free Trade Agreement and the Uruguay round of General Agreement on Tariffs and Trade (GATT) negotiations, both of which occurred at a time when concerns over global warming, species extinction, and industrial pollution were rising. The debate intensified with the creation of the World Trade Organization (WTO) and proposals for future rounds of trade negotiations.

Trade negotiators saw the WTO as a step forward because of its improved dispute settlement procedures and because it closed loopholes

1. For a good discussion of the policy issues involved, see Esty 1994.

in previous trade agreements. Environmentalists, however, were disturbed by the intrusion of trade agreements into what many thought were purely domestic matters. Perhaps not surprisingly, then, an attempt to initiate a new round of multilateral trade negotiations in Seattle became a flashpoint for growing unrest with globalization and efforts at further trade liberalization.

The purpose of this book is to study the interaction between international trade and the environment using both economic theory and empirical analysis. Our objective is to move the discussion forward by developing useful theory and devising methods to help in the empirical estimation of key magnitudes. We hope to enlist readers in further discussion and evaluation of trade's environmental effects, and this book is designed to equip them with the tools for doing so. In the end, differences of opinion will of course remain because the effects of international trade on the environment are still not fully understood. But we hope to give researchers and policymakers a common language and framework within which to discuss, debate, and continue their investigations.

1.2 Two Questions and a Preview of Our Answers

Throughout the book, we focus on two key channels through which trade can affect the environment. The first is via its effects on the level, or *scale*, of economic activity. If trade spurs economic activity, then the pure income-generating effects of trade may be harmful to the environment. The second channel is via a *composition* effect—a change in the mix of economic activity in countries, caused by trade. Many environmentalists are concerned that trade may lead to a shifting of polluting industry from rich to poor countries, and this global composition effect may also raise world pollution.

As we will see, both of these channels are more complex than these simple arguments suggest, and this leads to the two key questions that unify the book:

1. *How does the increase in economic activity induced by international trade affect the environment?*

Many in the "deep green" environmental movement believe unfettered access to world markets is necessarily harmful to the environment. While arguments differ in the details, the primary objection is that international trade leads to a greater scale of economic activity—be it transportation services, more production of goods and services, or more consumption—and that economic activity per se harms the environment. In this view, if international trade stimulates economic activity and if this activity is inherently environmentally damaging, then so too is international trade.

This concern forces us to think about the link between economic activity and environmental quality more generally and not just with regard to international trade. It leads us to define a measure of the scale of economic activity and to then link this measure to changes in the economy brought about by trade liberalization. But since any change in the scale of economic activity also affects incomes, we must also take into account the impact of income gains on environmental regulation.

If higher real incomes generate a greater ability and willingness to implement and enforce environmental regulations, then the logical chain linking trade liberalization to environmental destruction is broken. A trade liberalization that raises the scale of economic activity will then also lower the dirtiness of production techniques, and its full environmental impact can only be resolved through careful empirical investigation.

We address this first question by using our theoretical framework to separate the impact of economic growth on the environment from that caused by trade liberalization.[2] We show that the relative strength of *scale* versus *technique* effects depends on how government policy is formed and how quickly it changes in response to new conditions. We also set out the theoretical conditions under which either the scale or the technique effect is stronger. But since theory alone cannot determine the answers to our questions, we also present empirical work undertaken using a large cross-country data set on measured sulfur dioxide concentrations in over 100 major cities in the world.

By isolating the pure scale and technique effects of trade,[3] we estimate that a trade liberalization that raises the scale of economic activity by 1% raises pollution concentrations by 0.25 to 0.5% via the scale effect, but the accompanying increase in incomes per capita drives concentrations down by 1.25–1.5% via a technique effect. These estimates imply a strong policy response to trade-inspired income gains. As we show, they also imply that economic growth created by neutral techno-

2. Economic growth is modeled as once-and-for-all changes in either technologies or endowments. For a discussion of the relationship between growth and the environment in a dynamic setting see Smulders 2000.

3. Trade also generates composition effects, which we will discuss shortly.

logical progress will both raise real incomes and improve environmental quality, but economic growth fueled by capital accumulation alone will worsen the environment.

Our estimates and analysis are important in establishing that we need to identify the source of income gains before we predict its environmental consequences. For example, neutral technological progress favors no industry, and we find that it improves environmental quality through its role in raising incomes and tightening techniques of production. And while capital accumulation raises both incomes and scale, it favors the production of dirty, capital-intensive processes. Hence capital accumulation creates an additional effect leading to a worsened environment. Trade liberalization can be environmentally friendly since it brings income gains and will lead some countries to specialize in relatively clean industries. But not all countries can specialize in the production of clean goods, and hence it is important to determine which countries are likely to specialize and export relatively dirty products. This brings us to our second question.

2. How does environmental policy affect a nation's trade pattern?

This second question arises from concerns that dirty industries will leave tightly regulated countries and migrate to countries with lax regulations. As a result, international trade could alter the composition of output across countries, leading poor countries with relatively weak environmental regulation to specialize in the production of dirty goods while rich and tightly regulated countries specialize in clean goods. Even if trade liberalization had no effect on the scale of economic activity or on the dirtiness of the techniques of production, it could create pollution havens in the developing world by altering the *composition* of their output toward dirty goods.

Dirty industry migration is a serious concern because it would imply that poor less developed countries are bearing the pollution burdens of rich developed country consumption. Despite the claims of some economists that this may well be efficient, it would be unpalatable to many. Dirty industry migration may also raise concerns about competitiveness and cause regulatory chill in the developed countries which could slow down ongoing efforts to raise environmental protection. At worst it could usher in a worldwide race to the bottom in environmental protection as nations relax standards to forestall dirty industry migration.

These are valid concerns that need to be seriously addressed. To examine dirty industry migration and the creation of pollution havens we investigate how differences across countries in both environmental regulations and other country characteristics interact to determine a country's trade pattern. We also have to isolate changes in the composition of output created by trade liberalization from those created by more mundane sources such as taste changes or ongoing growth in a nation's productive capacity. To do so we employ our theoretical framework to isolate the composition effect of trade liberalization on pollution.

Isolating changes in the composition of output created by trade is critical to examining whether lax-regulation countries are destined to become pollution havens. While this may appear obvious to some, it too is an empirical question. While developed and less developed countries differ widely in the stringency of their environmental regulations, they also differ widely in average education levels, in available infrastructure, and in capital equipment per person. If these other differences are significant determinants of production costs, then it is no longer clear that lax regulations alone create a cost advantage in dirty good production.

In fact, our empirical work indicates that greater access to international markets creates only relatively small changes in pollution via the composition effect, and that conventional determinants of production costs are more important in determining "international competitiveness" than are differences in meeting the costs of environmental regulation. We find little evidence for dirty industry migration, or the pollution haven hypothesis. Our empirical results suggest just the opposite: that relatively rich developed countries have a comparative advantage in dirty goods. As a result, freer international trade shifts dirty good production from lax-regulation countries to more stringent-regulation countries. If this is correct, then the global composition effect of trade lowers world pollution. Combining our estimates of scale, composition, and technique effects created by a trade liberalization yields a surprising conclusion: freer trade appears to be good for the environment—at least for the average country in our sample and for the pollutant we consider.

While this result will be of interest to policymakers because of the importance of sulfur dioxide pollution and its close connection to other equally noxious pollutants, the most important contribution of this book is the theoretical framework it presents, the methods it espouses, and its discussion of competing hypothesis linking international trade to environmental outcomes.

1.3 Our Method of Analysis

We do not present an exhaustive account or review of all that is known about international trade and the environment, but instead develop a simplified but cohesive framework to investigate the relationship. We show that our framework is useful for understanding the links between economic growth and the environment, useful in disentangling the many different motives for trade in environmentally damaging goods, and useful as a springboard for empirical work that estimates the environmental consequences of liberalized trade. The strength of the book lies in the consistent application of our theoretical approach to various questions and our integration of this approach with empirical work.

Some readers may prefer different methods to discuss different issues, or wish for a presentation less encumbered by formal theory. We chose to be constrained by our theoretical framework because much of the current debate is not constrained by either theory or empirical work, and this has produced an astonishingly high ratio of rhetoric to results. Strong ideologies are at play here. There are those for whom free trade is a goal in and of itself and who speak of it in reverential tones; and there are also those who scorn any exercise to evaluate trade's environmental impact because they view its costs as clearly self-evident. This is an area of public policy debate sorely in need of guidance from further theory and empirical work. Accordingly, our goal is to introduce the reader to a new set of issues and build understanding. To do so we use theory to identify the main forces at work, motivate our empirical approach, and constrain the conclusions that we can draw.

While the appeal of doing "international environmental economics" has surely been present before, various difficulties face those who attempt it. The key difficulty is in introducing public goods into a general equilibrium model rich enough to explore the implications of trade, yet tractable enough to examine policy and to serve as the basis for empirical work.

We have attempted to strike a constructive balance between model complexity and tractability. Our analysis is marked by three characteristics: we adopt general equilibrium models; we assume environmental policy can be altered in light of changed economic conditions; and we adopt relatively simple economic models where the economy is aggregated into only two sectors. Throughout we examine only local pollution, although our methods can be extended to consider transboundary or global pollution.[4]

General Equilibrium

General equilibrium methods are necessary because they allow us to consider the full implications of international trade on the environment. For example, a partial equilibrium model of a clean industry might predict that the clean industry expands as a result of trade liberalization. Since the clean industry does not pollute, the partial equilibrium model does not predict any effects on the environment. But a general equilibrium analysis recognizes that as the clean industry expands, it must draw resources from other parts of the economy. If these other parts of the economy pollute, then the expansion of a clean industry can lead to a fall in the country's pollution.

In addition, a general equilibrium analysis allows us to grapple with income effects, which have played a central role in the debate over the effects of trade and growth on the environment. If trade stimulates a dirty industry, it will tend to increase pollution. But if trade also raises real incomes via general equilibrium effects, then it will increase the demand for environmental quality, and this can have a dampening effect on the increase in pollution via an endogenous policy response.

Some of the tools we employ are commonly used in competitive general equilibrium trade theory, but will be unfamiliar to many readers.[5] In an attempt to engage those unfamiliar with general equilibrium methods, we develop special cases of our models in some chapters to

4. A serious consideration of transboundary or global pollution would require a much longer book. Interested researchers can amend our analysis along the lines of Copeland and Taylor 1995, 2000.

5. Although chapter 2 sets out a more or less self-contained exposition of the principal tools we use, some readers may want to consult the book-length treatments of trade theory by Woodland (1982) and Dixit and Norman (1980) for background and a far more general treatment.

provide explicit solutions and derivations of main results. The examples we provide have the twin purpose of clarifying and simplifying the more general analysis we present elsewhere, and on occasion demonstrating surprising counterexamples.

Endogenous Policy

Endogenous policy is necessary if we are to capture the response of pollution policy to rising incomes and changing prices brought about by free trade. Much of the literature has focused on the role of differences in environmental policy between rich and poor countries in influencing the trade pattern and in determining the effects of trade on the environment. But if policy differences are caused in part by income differences, and if trade affects incomes, then we cannot evaluate the long-run effects of trade liberalization without taking into account the effects of changes in income and relative prices on environmental policy.

To facilitate a simple analysis of endogenous policy, we assume that the government maximizes an objective function that reflects the weighed sum of preferences of agents in the economy. In many cases, we assume all agents are identical; however, we will also consider a simple political economy model where the government places different weights on "Brown" consumers who benefit from dirty good production than it places on "Green" consumers who benefit mainly from clean good production.

While endogenous and fully responsive policy is a useful benchmark, it may not always reflect real-world conditions. Environmental economics was born out of the recognition of market failure and imperfect policy. Accordingly, wherever possible we present our analysis first under the assumption that policy is rigid and imperfect, and then present the case of optimal and flexible policy. This is useful not only because it may represent a reasonable representation of short- versus long-run outcomes, but also because the rigid policy analysis is often a pedagogically useful precursor to the analysis of optimal policy.

Simple Models

Finally, throughout the book, we limit the complexity of our models. Previous work in this area has sometimes been hampered by a well-intentioned effort to use very general models. This can often lead to complicated analysis in which many of the results are ambiguous. Our goal in the book is to introduce the reader to a new set of issues and build understanding. Relatively simple economic models can do just that—they shed light on different questions, they provide insight, and they guide—but not completely determine—the direction of empirical work. There are surely more general formulations that will overturn some of our results and introduce other complications, and we encourage readers to pursue these advances. But given the severe limitations researchers face in obtaining environmental data, adding further theoretical nuances will be for naught if we lack data necessary to explore their strength or validity. At present, getting the simple logic right seems a worthy goal. We leave it to readers and future researchers to elaborate on our findings.

1.4 Plan of the Book

We begin by developing our two-sector general equilibrium pollution and trade model in chapter 2. One special case of the model is a simplified version of the pollution haven model in Copeland and Taylor (1994). Another special case gives us the canonical Heckscher-Ohlin model that links relative factor abundance to international trading patterns. Chapter 2 is a difficult one, as it develops in detail the model's theoretical structure, starting with a consideration of pollution as a joint product of output and ending with a discussion of optimal pollution policy using the constructs of pollution demand and supply. Readers may wish to skip certain sections of this chapter, safe in the knowledge they may return to clarify a derivation or definition that they find puzzling in a later chapter.

After laying out the theoretical foundation in chapter 2 we proceed in chapter 3 to investigate the *environmental Kuznets curve*. We start with an examination of growth because the environmental consequences of trade and growth share some common features and any credible analysis of the effects of trade on the environment has to disentangle changes in pollution caused by trade from those caused by growth.

This chapter demonstrates that our simple pollution demand and supply framework can be employed to discuss the most commonly cited explanations for the environmental Kuznets curve. But this chapter is more than review and exercise. We present new theoretical results detailing the conditions under which strong policy responses alone can generate an EKC, new results linking increasing returns to abatement (at the industry level) to the EKC, and new results regarding the link between the sources of economic growth and environmental quality.

Following our discussion of growth, we proceed to trade liberalization in chapter 4. We identify the scale, composition, and technique effects created when a country liberalizes its trade and find that the positive and normative effects of trade liberalization depend critically on whether a country is a dirty good importer or exporter. We consider both a reduction in transport costs and a fall in tariffs as the motivations for further trade and introduce a simple political economy model as well.

In chapters 5 and 6 we turn to a discussion of the pattern of trade. We start in chapter 5 by demonstrating that differences across countries in pollution policy alone can lead to the *pollution haven hypothesis*. But since policy differences should arise endogenously from more basic assumptions about country characteristics, we then link differences in the stringency of pollution regulation to cross-country differences in institutions, in income levels, and in the fragility of environments. In each case, we demonstrate how differences in country characteristics lead to differences in the stringency of regulation and hence trade. Although in each case free trade results in the lax-regulation countries exporting dirty products, we show that this trade need not be either welfare reducing or environmentally damaging.

In chapter 6 we broaden the potential motives for trade to demonstrate that differences across countries in other characteristics can also influence relative production costs. We focus on differences across countries in their capital stocks and labor forces because these differences are at the basis of the *factor endowments hypothesis*. We examine how differences in income levels and factor endowments interact to determine the pattern of trade. This chapter contains several new results. We demonstrate that rich but capital-abundant countries may export dirty goods, while poor and capital-scarce countries export clean goods. We show that when differences in other country characteristics lead to cost advantages that overwhelm the pollution haven motives for trade, many of the dire consequences of international trade disappear. We demonstrate that world pollution can fall with trade, that imperfectly regulated and poor developing countries must both gain from trade and see an improvement in their environment, and that pollution may fall in both rich and poor countries with trade liberalization. All of these results are in direct opposition to predictions of the pollution haven hypothesis.

In chapter 7 we present empirical work estimating the strength of scale, composition, and technique effects. We employ many of the results developed in earlier chapters to develop a simple reduced form estimating equation linking pollution concentrations to country characteristics, and measures of both openness to trade and comparative advantage. This equation is then estimated on a large panel data set containing measures of sulfur dioxide pollution concentrations drawn from cities in 44 developed and developing countries over the 1971 to 1996 period.

Chapter 8 presents a short conclusion and suggestions for future research. Some of these suggestions are topics that we had hoped to include but did not because of limited time or space. Others are suggestions for further empirical or theoretical work addressing unanswered questions regarding linkages between trade and the environment.

2 Pollution in a Small Open Economy

This chapter develops the simple general equilibrium model we employ in the all subsequent chapters and provides a foundation for our analysis of trade and environmental policy. This is a "tools" chapter, and some readers may prefer to skim it and move on to the "issue" chapters that follow. But since many of the key assumptions we use throughout the book are laid out here, it is worthwhile spending some time on this chapter before proceeding.

Because the book straddles two fields—environmental economics and international trade—we develop basic concepts from each field. At times it may seem that we are being pedantic, but our objective is to ensure that readers from either field can follow and extend our analysis.

The model we develop is deliberately simple.[1] We assume two industries (one dirty and one clean) and two primary factors of production. In addition, because the pollution level in a free market may be unacceptably high, we include in our model a government that regulates pollution. Despite its simplicity, the model contains as one special case the standard Heckscher-Ohlin model of international trade, and as another, a version of our Pollution Haven model (Copeland and Taylor

1. The model builds on previous work in trade and the environment. The structure of our model is closest to that of McGuire (1982), who developed a two-sector model with two primary factors of production and treated pollution as an input as we do. Earlier work by Pethig (1976) used a two-sector model with one primary factor. Markusen (1976) used a two-sector model with two primary factors but did not allow for variable levels of emission intensity—in his model, pollution is directly proportional to output. More recent work has sometimes used more complicated models than we use here. Copeland (1994) uses a general equilibrium model that allows for many goods, many factors, and many different pollutants. Rauscher (1997, chap. 5) uses a two-sector model with one primary factor, but allows for pollution to harm producers as well as consumers, and he allows for consumption-generated pollution. Copeland and Taylor (1994) use

1994). Both factor endowments and pollution regulations play a role in determining a country's comparative advantage. This ensures the model has sufficient richness to address the issues at hand.

While much of environmental economics makes use of partial equilibrium analysis, we need a general equilibrium approach to examine the interaction of trading economies. By the end of the chapter we will have constructed a simple general equilibrium pollution demand and supply system determining equilibrium pollution as a function of world prices, endowments, technology, preferences, and government type. Environmental economists would refer to our constructs as general equilibrium marginal abatement cost and marginal damage schedules, and this is what they are. This system will then be used to examine the environmental consequences of growth in chapter 3, trade liberalization in chapter 4, and so on.

It is easy to lose the forest for the trees in a chapter with over 80 equations. And while the chapter contains many derivations and diagrams, it is organized around the development of just four key concepts. Before we launch into the specifics it may be useful to spell them out here.

First, in much of the book we treat pollution as if it were an input into the production of goods.[2] In fact, pollution is a joint (and undesirable) output. In section 2.1, we show how the two approaches are equivalent given some restrictions on the technology. We define a joint production technology where pollution and final goods are produced from primary inputs, and show how one can derive an equivalent technology where pollution (or access to environmental services) plays the role of an input into production. This allows us to use standard tools, such as isoquants and unit cost functions, in analyzing the economy.

Second, we need a model rich enough so that both factor endowments and pollution regulations play a role in determining a country's comparative advantage, but also tractable enough so that we can do comparative statics. For factor endowments to play a role in determining comparative advantage independently of pollution regulations, we

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a model with one primary factor, but allow for a continuum of goods, all with different pollution intensities.

2. The treatment of pollution as an input has been standard in the general equilibrium literature on trade and environment. See, for example, Pethig 1976; McGuire 1982; Copeland 1994; Copeland and Taylor 1994; Rauscher 1997; and others. Siebert et al. (1980), Rauscher (1997, chap. 2), and Copeland and Taylor (1994) discuss the conditions under which this approach is equivalent to treating pollution as a joint output.

specify a model with two primary factors (capital and labor). This allows us to consider countries that differ in relative capital abundance. However, because pollution is also treated as an input, this gives us a model with three inputs. To keep the model tractable, we make two key assumptions: we assume the abatement activity employs factors in the same proportions as does production of the dirty good; and we assume a specific form for the abatement production function. With these two assumptions our three-factor model simplifies tremendously. For example, if we hold emissions per unit output in the dirty industry constant, our model inherits all the comparative static properties of the Heckscher-Ohlin model of international trade. Specifically, as we show in section 2.2, the Stolper-Samuelson theorem holds: an increase in the relative price of the dirty good raises the real return to capital and lowers the real return to labor. In addition, the Rybczinski theorem holds: an increase in the supply of capital raises the output of the capital-intensive dirty good and lowers the output of the labor-intensive clean good. This is an important feature of our model because, as we will show in later chapters, it allows us to separate the role played by factor endowments from those of pollution policy in determining trade patterns.

Third, the focus of the book is on how exogenous changes in the economy (such as trade liberalization) lead to changes in equilibrium levels of pollution. To facilitate this analysis, we develop two diagrams that illustrate how equilibrium pollution is determined. The first diagram exploits the production frontier. Given pollution policy, we show how to determine the level of goods production on the production frontier, and then project down onto a pollution frontier to determine emissions. This diagram is also useful in illustrating how changes in pollution caused by shocks to the economy can be decomposed into *scale*, *composition*, and *technique* effects. This decomposition is employed to examine the consequences of trade liberalization and growth in chapters 3 and 4; and in chapter 7, we estimate these effects empirically.

The second diagram uses a general equilibrium demand-and-supply approach to determine the equilibrium level of pollution. Once we treat pollution as an input, we can then ask how much firms would choose to emit for a given price of pollution emissions. This gives us the general-equilibrium derived demand for pollution. On the other hand, the supply of pollution reflects the willingness of the regulator to allow increased emissions and depends on the policy regime. If an aggregate pollution quota is in place, the supply curve is simply a vertical line, and its intersection with the demand curve determines the equilibrium price of emissions. If the regulator imposes a fixed pollution tax, the supply curve is horizontal and its intersection with the demand curve determines the equilibrium quantity of emissions. In much of the book, however, we need a model where pollution policy is endogenous, and since we have already argued that one can think of pollution as an input, it is natural to think of the willingness to allow pollution as similar to a problem of endogenous factor supply. We can therefore derive the pollution supply curve from optimizing behavior of the regulator. Its intersection with pollution demand determines both the equilibrium price and the quantity of emissions.

The final key concept developed in this chapter is the use of national income or GNP functions to represent the supply side of the economy. This is motivated by the central role that income plays in our analysis. One of the prominent issues in the debate on the effects of trade and the environment is the interaction between per capita income, pollution policy, and the pattern of trade. According to the pollution haven hypothesis, for example, high-income countries have relatively stringent pollution policy and this shifts dirty good production to poorer countries via international trade. We need a tool that allows us to analyze the role of income in determining the supply of pollution, but which also takes into account the endogeneity of income. To deal with these complications in a tractable manner, it is useful to employ national income or GNP functions. These are commonly used in the international trade literature, but their use in environmental economics is less common. A GNP function exploits the result that if the conditions for production efficiency hold, then profit-maximizing firms will in aggregate end up maximizing the value of national income at producer prices. We can therefore represent the value of national income at producer prices as a maximum value function. This is a very convenient tool to exploit when modeling the dependence of pollution policy on per capita income. In addition, because the GNP function is a maximum value function, it satisfies a number of useful properties that expedite our comparative statics analysis.

We complete the chapter in section 2.4 by determining the efficient level of pollution using our pollution supply and demand framework. Our pollution supply and demand can be interpreted as general equilibrium marginal damage and marginal abatement cost schedules, and so this section clearly links our approach to standard textbook treatments of pollution in environmental economics.

With these tools in hand, the reader will be well equipped to examine the relationship between pollution and growth in chapter 3, and between pollution and trade in subsequent chapters.

2.1 Technology

We start by considering a small open economy that faces fixed world prices.[3] At least two goods are needed for trade to occur, and for trade to be interesting, the two goods should differ in pollution intensity. Consequently, we assume the economy produces two goods, X and Y. Good X generates pollution during its production, and good Y does not.[4] We let good Y be the numeraire (so that $p_Y = 1$), and denote the domestic relative price of good X by p. Throughout the chapter world prices and domestic prices are identical, but at some points we distinguish between the two for clarity.

There are two primary factors, capital and labor (K and L), with market returns r and w. Both factors are inelastically supplied.[5] X is capital intensive and Y is labor intensive. This means that for any w and r, the capital/labor ratio in X is higher than in Y:

$$\frac{K_x}{L_x} > \frac{K_y}{L_y}. \tag{2.1}$$

We assume the capital-intensive sector is also the polluting sector. For industrial pollution, this is consistent with the evidence.[6]

To keep things simple, we assume that pollution from any given firm harms consumers but does not affect productivity in other firms.[7] In addition, we rule out pollution generated during consumption.

3. We consider endogenous world prices starting in chapter 5.
4. It is straightforward to generalize the model to allow both goods to pollute, but for most of our purposes, this would just add unneeded complexity. For an example of a model with more than one polluting good, see Copeland and Taylor 1994, where we consider a model with a continuum of goods, each with a different pollution intensity.
5. Recently, one branch of the environmental literature (the double dividend literature—see Fullerton and Metcalf 1998 for a review) has focused on models with endogenous labor supply in order to analyze the interaction between pollution taxes and distortionary labor taxes. As our focus is on trade, we follow the standard international trade literature and treat labor supply as exogenous.
6. See chapter 7.
7. See Baumol and Bradford 1972 and Copeland and Taylor 1999 for an analysis of some of the complexities that arise when there are cross-sectoral production externalities.

Both goods are produced with a constant returns to scale technology. The production function for good Y is

$$y = H(K_y, L_y). \tag{2.2}$$

We assume that H is increasing and strictly concave in inputs.

The X industry jointly produces two outputs—good X and emissions Z. However, abatement is possible, and so emission intensity is a choice variable. To capture the possibility of abatement very simply, suppose that a firm can allocate an endogenous fraction θ of its inputs to abatement activity. Increases in θ reduce pollution, but at the cost of diverting primary factors from X production. The joint production technology is given by

$$x = (1 - \theta)\, F(K_X, L_X), \tag{2.3}$$

$$z = \varphi(\theta)\, F(K_X, L_X), \tag{2.4}$$

where F is increasing, concave, and linearly homogeneous, $0 \leq \theta \leq 1$, $\varphi(0) = 1$, $\varphi(1) = 0$, and $d\varphi/d\theta < 0$. We discuss the interpretation of φ in detail below.

If $\theta = 0$, there is no abatement, and by choice of units, each unit of output generates one unit of pollution. We can think of $F(K_X, L_X)$ as potential output; this is the output of X that would be generated if there were no pollution abatement. That is, without abatement activity, we have

$$x = F(K_x, L_x), \tag{2.5}$$

$$z = x. \tag{2.6}$$

If firms choose $\theta > 0$, then some resources are allocated toward abatement. If a vector (K_x, L_x) of inputs is allocated to the X sector, then θK_x units of capital and θL_x units of labor are allocated to abatement.[8] Equivalently, we can think of the firm as producing a gross or *potential output* of $F(K_x, L_x)$, and using a fraction θ of this as an input for abatement. This leaves the firm with a *net output* $(1 - \theta)\, F(K_x, L_x)$, which is available for consumption and export.

It is convenient for expository purposes to put a little more structure on (2.4); hence we adopt the following functional form for abatement:

$$\varphi(\theta) = (1 - \theta)^{1/\alpha}, \tag{2.7}$$

8. We are assuming the abatement technology uses the same factor intensity as the production of the final good X. This is a simple way to capture the notion that abatement is

where $0 < \alpha < 1$. Using (2.3), (2.4), and (2.7), we can eliminate θ and invert the joint production technology to obtain

$$x = z^{\alpha} [F(K_x, L_x)]^{1-\alpha}, \tag{2.8}$$

which is valid for $z \leq F$, because $\theta \geq 0$. That is, although pollution is a joint output, we can equivalently treat it as an input.[9] This allows us to make use of familiar tools, such as isoquants and unit cost functions. One can think of pollution Z as the use of "environmental services," as the firm must dispose of its emissions in the environment. Alternatively, if we treat Z explicitly as pollution emissions, then we can think of the firm as requiring Z pollution permits in order to produce.

To help understand the technology in our model and its relation to others in the literature, it is useful to consider the abatement technology that lies behind (2.4). Many authors begin by specifying an abatement function, and then obtain pollution emissions as the difference between pollution potentially produced and the amount of abatement.[10] Our model can be interpreted in this way as well.

Abatement is like any other activity the firm undertakes in the X industry. The quantity abated depends on the amount of resources allocated to abatement, which we denote x^A, and the amount of pollution potentially produced, z^P. Define the abatement technology as $A(z^P, x^A)$, where A exhibits constant returns to scale. Pollution emissions are the difference between potential pollution and abatement:

$$z = z^P - A(z^P, x^A). \tag{2.9}$$

Because abatement is a constant returns activity, we can rewrite (2.9) as

$$z = z^P [1 - A(1, x^A / z^P)]. \tag{2.10}$$

costly, but avoids the complexity of modeling three activities (each with different factor intensities) in a general equilibrium model.

9. More generally, if we do not impose the added structure on the abatement technology, we have: $x = [1 - \varphi^{-1}(z/F)] F$, which is increasing and homogeneous of degree 1 in z and F. The specific functional form adopted in the text generalizes the model in Copeland and Taylor 1994 to allow for two primary factors. Separability ensures that the marginal rate of substitution between capital and labor is not affected by pollution taxes or quotas. This will allow us to use simple diagrams to illustrate much of our analysis, and later on to generate simple clean results on trade patterns. The unitary elasticity of substitution assumption implicit in (2.8) simplifies the algebra. Much of our work will generalize to the case where $x = \Phi[z, F(K_x, L_x)]$, with both F and Φ being linearly homogeneous. But we have opted for the simpler (albeit more restrictive) specification for clarity.

10. For an example of the explicit modeling of abatement in the trade and environment literature, see Barrett 1994 in a partial equilibrium context, and Siebert et al. 1980 for a general equilibrium approach.

Recall from (2.6) that potential pollution is equal to potential output (hence $z^P = F$) and that θ is the fraction of resources devoted to abatement (hence $\theta = x^A/F = x^A/z^P$). Hence we can write (2.10) as

$$z = [1 - A\,(1, \theta)]\,F\,(K_x, L_x) = \varphi\,(\theta)\,F\,(K_x, L_x), \tag{2.11}$$

where we have defined $\varphi\,(\theta) \equiv 1 - A\,(1, \theta)$. Thus our specification in (2.4) can alternatively be interpreted as being supported by an explicit abatement technology. This interpretation will be useful later on when we want to think about generalizing the model to allow for technological change or increasing returns to scale in abatement.

The particular form we adopted for φ in (2.7) corresponds to a particular abatement production function, A. Our choice in (2.7) has two benefits. First, it ensures we obtain the neat expression (2.8). This in turn requires the share of pollution taxes in the value of net output be constant. This aids in calculations as it did in Copeland and Taylor 1994. Second, it ensures the first unit of abatement has a bounded marginal product. This feature makes zero abatement optimal for firms when pollution taxes are low. This seems sensible, and in fact we show in the next chapter how this feature was exploited by Stokey (1998) in explaining the environmental Kuznets curve.

The relationship between net output, potential output, and the resources allocated to abatement can be illustrated using isoquants. In figure 2.1 we have drawn isoquants for two different levels of net output in the X sector. The higher isoquant (labeled X_1) corresponds to higher output. An isoquant illustrates the trade-off between "inputs" of potential output, denoted by F, and pollution emissions, denoted by Z, for a constant amount of net output. The constant returns to scale assumption implies all isoquants have the same shape: higher isoquants are radial blowups of lower isoquants.

At point A on the isoquant for X_1, no abatement is undertaken and pollution is proportional to output.[11] This corresponds to $\theta = 0$ in (2.3) and (2.4). Similarly, other points along the dashed ray through the origin correspond to the no-abatement points on other isoquants.

As we move down along an isoquant, pollution falls because firms allocate resources to abatement. To maintain a constant level of net output, the inputs into production as measured by F must increase as the pollution level falls.

11. Recall that we have chosen units to make the factor of proportionality equal to 1.

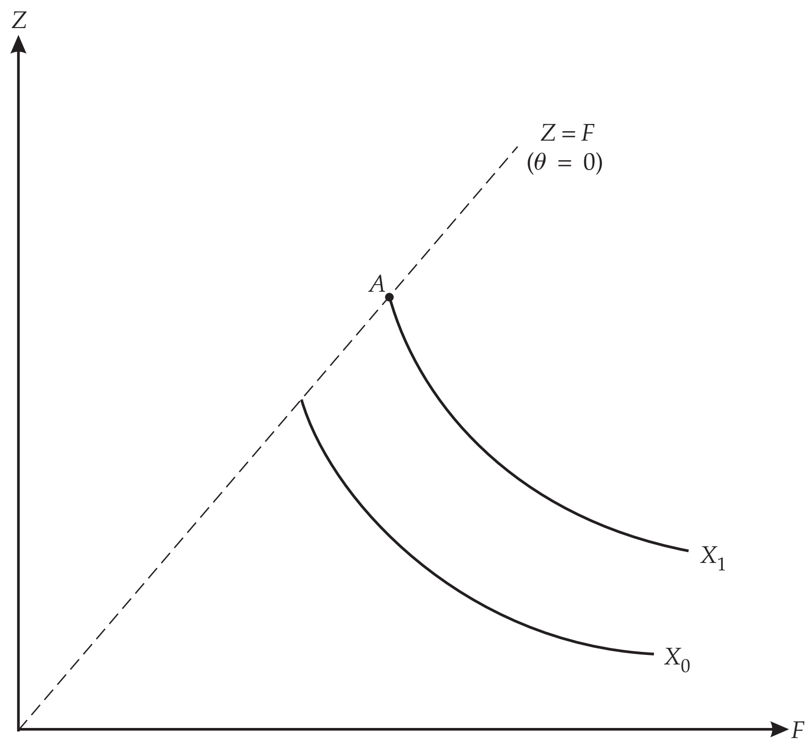

Fig. 2.1. Isoquants for the X Industry

Cost Minimization

In a competitive market, firms choose production techniques to minimize their cost of production. Because there is pollution, production costs depend on the regulatory regime. If there is no regulation, then there is no incentive to abate, and firms choose a point like A in figure 2.1. If there is regulation, the firm's problem is more complex: it must satisfy constraints imposed by the regulator as well as those coming from the market.

Our model can incorporate a variety of regulatory approaches. For example, in some jurisdictions, governments impose emission intensity restrictions. We could capture this regulation as a constraint that emissions per unit output not exceed some target. In other cases, governments charge an emission tax, which is a fee per unit of emissions released into the environment. And in other cases, firms must purchase emission permits if they want to pollute.

In much of the book, we assume that firms have to pay a fee for each unit of emissions they generate. The fee can either be an emissions tax, or it can be the market price for a pollution permit. We make this assumption in part because of its simplicity, but also because it ensures that the government's pollution target is implemented efficiently.[12]

Our focus is on the larger issue of how trade liberalization affects the environment, and we want to ensure that our results are not confused with side issues arising from the inefficient implementation of a pollution target. Notice we are not requiring the pollution target itself be efficient—we will spend considerable time on the implications of pollution policy that is too lax or too rigid.

Let us suppose then that firms face a price τ for each unit of emissions they generate. Given the price of emissions τ, and the prices of capital and labor (r and w), firms are now faced with a standard cost minimization problem. Moreover, because of the separability of our production function, we can break the firm's problem into two steps: first minimizing the cost of producing potential output F; and then finding the most efficient way to combine F with environmental services to produce net output X.

First, the firm can find the minimum cost of producing a unit of F (potential output). Because of constant returns to scale, a unit cost function for F exists, which we denote by c^F. That is, the firm has only to determine the most efficient techniques to produce one unit of F, because by constant returns to scale, multiple units are produced by simply scaling up production. The unit cost function for F can be found by solving the following problem:

$$c^F(w, r) = \min_{\{k, l\}} \{rk + wl : F(k, l) = 1\}. \tag{2.12}$$

The firm chooses the combination of capital and labor that allows it

12. A restriction on emissions per unit of output is not an efficient way to implement a pollution target—it can be shown to be equivalent to an emissions tax combined with an output subsidy. The output subsidy component of the policy leads to inefficiently high output. The problem is that if a firm is told to satisfy a restriction on emissions per unit of output, it can satisfy the regulation by either reducing emissions or by increasing output. In fact, in some cases, such a policy can lead to an increase in overall pollution. The policy can be rendered efficient if it is accompanied by an output tax, in which case it becomes equivalent to an emissions tax. In some strategic trade policy contexts, a government may actually want to subsidize output, and if production subsidies are illegal under trade rules, a devious choice of seemingly inefficient pollution instruments can actually be to a country's advantage. See Bruneau 2000. But these issues do not arise in a small open economy with perfectly competitive markets.

to produce a unit of potential output at lowest cost. The total cost of producing more that one unit of F is just $c^F(w, r)F$.

Next, the firm can determine how much abatement activity to undertake, by finding the unit cost function for net output, which we denote by c^x. Again, by constant returns to scale, it suffices to find the efficient production techniques for one unit. The firm weighs emissions charges against the cost of foregone potential output to determine the most cost-effective techniques of production. Formally, the firm solves the following cost minimization problem:

$$c^x(w, r, \tau) = \min_{\{z, F\}} \{\tau z + c^F(w, r) F : z^\alpha F^{1-\alpha} = 1\}. \tag{2.13}$$

The solution is illustrated in figure 2.2. The unit isoquant for net output of X is illustrated. The isocost line has slope $-c^F/\tau$, which is the relative cost of the two inputs (potential output and environmental services) used to produce net output X. The cost-minimizing choice of emissions and primary factor inputs (F_0, Z_0) is at point B.

To solve for the optimal level of emissions per unit of net output at a point like B, we can solve the problem (2.13), and rearrange the first-order conditions to obtain

$$\frac{z}{F}\,\frac{(1-\alpha)}{\alpha} = \frac{c^F}{\tau}. \tag{2.14}$$

Because (2.8) is linearly homogenous, we must also have

$$px = c^F F + \tau z. \tag{2.15}$$

Therefore, using (2.15) and (2.14), we can solve for pollution emissions per unit of net output, which we denote by e:[13]

$$e \equiv \frac{z}{x} = \frac{\alpha p}{\tau} \leq 1. \tag{2.16}$$

The emission intensity falls as pollution taxes rise because emissions become more expensive. The emission intensity rises when the price of the polluting good rises because the resources used in abatement have become more valuable.

13. Those familiar with the properties of Cobb-Douglas production functions can obtain (2.16) more quickly by noting from (2.8) that at an interior solution, the share of emission charges in the total cost of production of X must be α; that is, $\tau z/px = \alpha$. Rearranging yields (2.16).