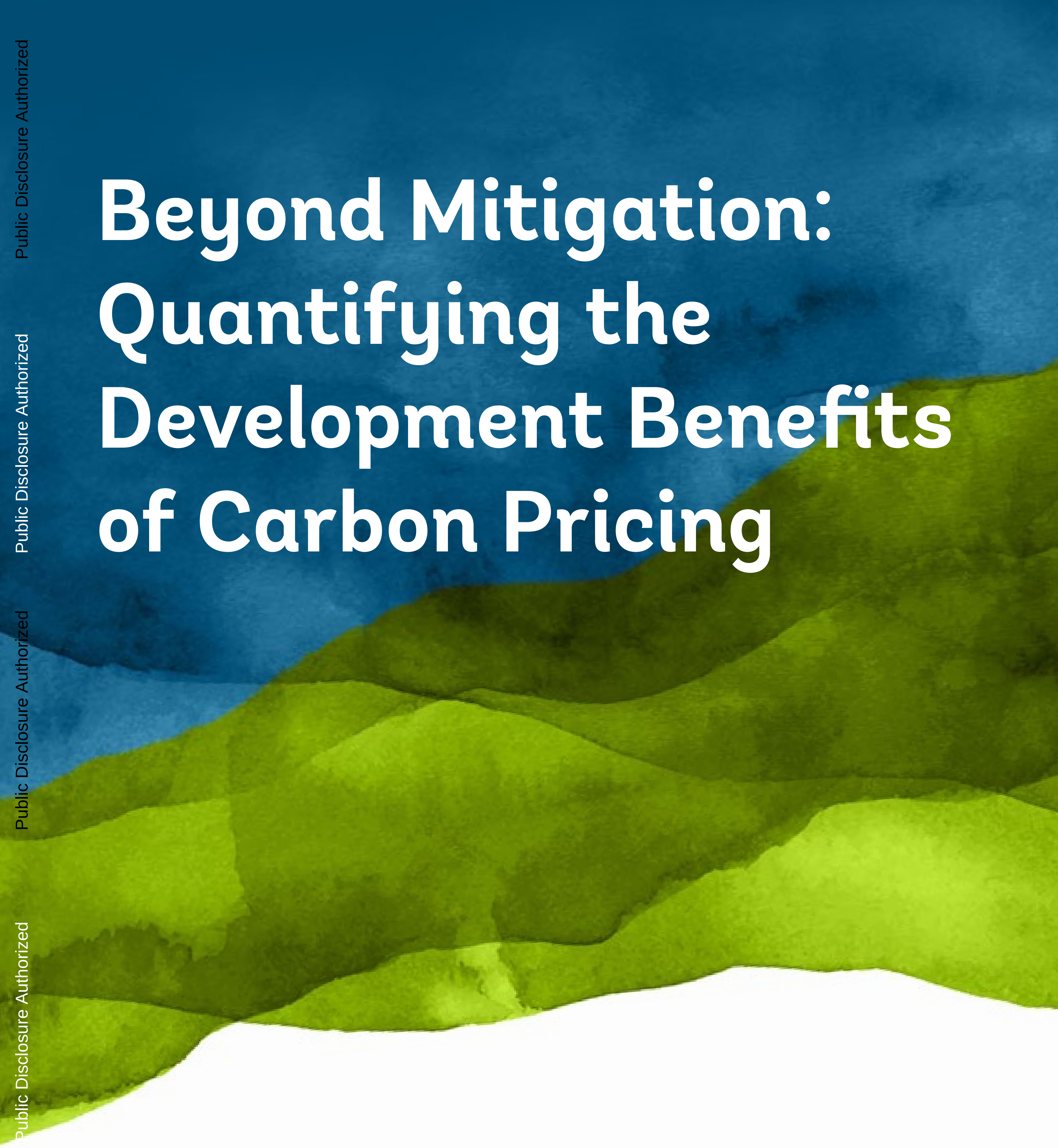

Beyond Mitigation: Quantifying the Development Benefits of Carbon Pricing

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MARKET READINESS

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1818 H Street NW
Washington DC 20433
Telephone: 202-473-1000
Internet: www.worldbank.org

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Design: Simpelplus

Acknowledgments

This report was prepared for the Partnership for Market Readiness by Berkeley Economic Advising and Research. The team was led by David Roland-Holst with support from Drew Behnke, Samuel Heft-Neal, and Ryan Triolo. Research assistance was provided by Charles Fondecave, Liam Frölund, Joslyn Fu, Sydney Schoonover, and Anna Wang.

The World Bank oversaw the development of the guide, including providing substantive inputs and managing the project. The World Bank team consisted of Daniel Besley and Marissa Santikarn. Technical input and expertise were provided by Carlo Alberto Amadei, Simon Black, Ira Dorband, Hasan Dudu, Erick Fernandes, Harikumar Gadde, Dirk Heine, Charl Jooste, Sean Nelson, and Gregor Schwerhoff. Technical inputs were also provided by Cyril Cassisa, Luca Lo Re, and Insa Handschuch from the International Energy Agency.

Contents

Figures

Tables

Boxes

Abbreviations

AFOLU	agriculture, forestry, and other land use
BOP	balance of payments
CGE	computable general equilibrium
CO_2	carbon dioxide
CPAT	Carbon Pricing Assessment Tool
CTM	chemical transport models
DALY	disability-adjusted life years
DSGE	dynamic stochastic general equilibrium
EPA	Environmental Protection Agency (US)
ETS	emissions trading system
EU	European Union
EU ETS	European Union Emission Trading System
FASST	Fast Scenario Screening Tool
GAINS	Greenhouse Gas and Air Pollution Interactions and Synergies
GBD	Global Burden of Disease
GDP	gross domestic product
GHG	greenhouse gas
GNP	gross national product
Gt	gigatonnes
GTAP	Global Trade Analysis Project
ha	hectare
ITC	induced technological change
kg	kilogram
kgN	kilogram of nitrogen
LCT	low-carbon technology
LPG	liquified petroleum gas
m^3	cubic meters
MAR	mean annual runoff
MJ	megajoule
MMBtu	million BTUs
$MMTCO_2e$	million metric tons of CO_2 equivalent
OECD	Organisation for Economic Co-operation and Development
PMR	Partnership for Market Readiness
POLES	Prospective Outlook for the Long-term Energy System
R&D	research and development
SAM	social accounting matrix
SDG	Sustainable Development Goal
SIMPLE-G	SIMPLE-on-a-Grid
VAT	value added tax
VMT	vehicle miles traveled
VOT	value of travel time
VSL	value of statistical life
WBM	Water Balance Model
$\mu g/m^3$	micrograms per cubic meter

All dollar amounts are US dollars unless otherwise indicated.

1.

Synthesis: Benefits of Carbon Pricing in Brief

1. Synthesis: Benefits of Carbon Pricing in Brief

This guide is a handbook for public decision makers, researchers, and private stakeholders who want to understand the broader economic benefits of carbon-pricing measures. These are measures that explicitly price the carbon content of goods, such as carbon taxes, emissions trading systems, and crediting mechanisms.[1] The world's current reliance on carbon-based energy has pervasive implications for economic activity, so it is no surprise that a carbon price can have extensive spillover effects. These effects or linkages offer a roadmap for policy makers seeking to combine carbon mitigation with strategies that advance other public policy and development objectives. The guide identifies seven major areas of carbon-pricing benefits: air quality, water, soil health, transport, fiscal policy, balance of payments, and technological changes.

Because climate goals often compete with other public priorities, it is important to recognize that carbon prices can yield numerous benefits to society beyond climate mitigation. These include, but are not limited to, cleaner air and water, improvements in human health, safer and less congested roads, increased energy and food security, induced adoption and diffusion of technological innovation, and enhanced macroeconomic stability through stronger fiscal and international payments balances. Carefully designed carbon price reforms can also improve the efficiency of existing tax systems, driving more effective coverage of the informal sector in domestic resource mobilization, improved fiscal neutrality for value-added taxation, reduced distortionary impacts from exemptions in preexisting tax schemes, taxation of economic rents rather than profits, reduced risks of tax evasion, and reduced costs of tax compliance and administration (see figure 1.1).

These benefits can be substantial[2] and can help governments secure a more sustainable and inclusive basis for livelihood improvement. Many of these benefits are more direct, localized, and immediate than climate benefits, and in some cases they are even larger (Parry, Veung, and Heine 2014). By factoring in these potential benefits at the start of their mitigation policy process, policy makers can design their carbon price and other climate strategies to deliver benefits beyond emissions reductions, ensuring growing human needs are met in parallel with environmental goals. Importantly, quantifying and communicating these benefits can also build broader support for the adoption of carbon pricing.

It should be acknowledged at the outset that all policies will have distributional effects, and carbon pricing is no exception. Carbon pricing can create benefits but also lead to costs and challenges. As a carbon price affects basic commodity prices, these costs may be more visible than in the case of alternative policies, but alternative policies will also have cost implications. For example, to the extent that the poor spend a larger proportion of income on fuel, carbon pricing might be regressive unless compensatory measures, such as targeted exemptions or clean fuel subsidies, are also implemented. Likewise, carbon pricing of marketed fuels might induce rural households to substitute biomass burning, increasing indoor air pollution unless paired with compensatory measures. While such challenges may arise, the guide identifies relevant mitigating countermeasures that allow the main benefits of carbon pricing to be realized in most circumstances.

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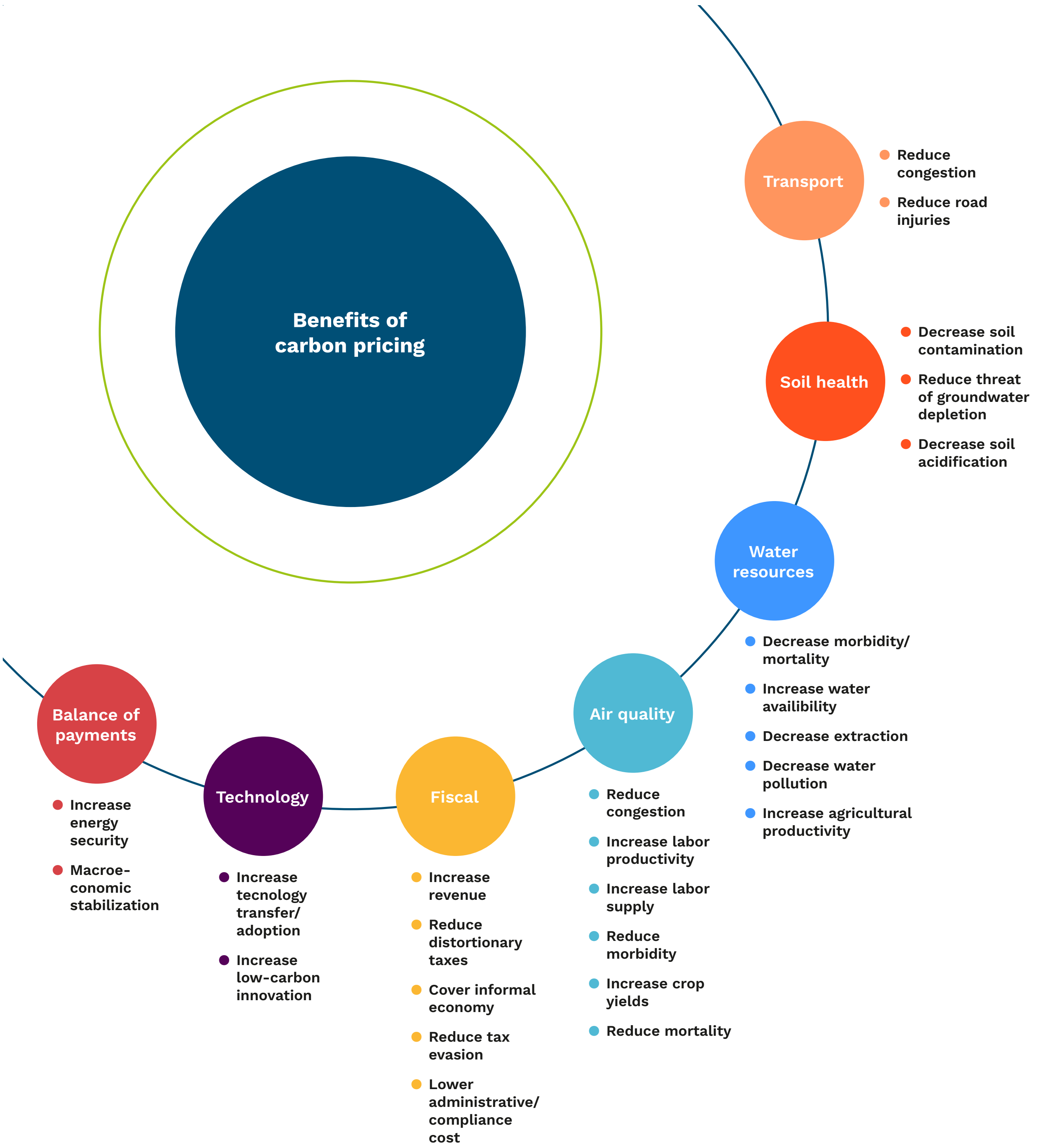
[1] It should be noted, however, that many of the benefits examined in this guide can be obtained from a wide array of climate mitigation policies.

[2] Note that these "development benefits" of climate policy (in this case carbon pricing) should not be confused with "climate benefits" (e.g., reduced greenhouse gas emissions or increased adaptation) of development policies.

Figure 1.1

Carbon Pricing Benefits beyond Mitigation



Source: World Bank.

Despite their potential importance, carbon price benefits have received quite limited attention to date from policy makers. Carbon pricing's environmental effects on issues like air and water have been studied in the scientific community, but greater effort is needed to bring these findings to the attention of policy makers. While some acknowledgment of the sustainable development benefits of carbon-pricing credits is evident in the voluntary carbon market, additional work is needed to more systematically consider how these benefits can be identified, quantified, and factored into both the technical case for carbon pricing and the shaping of communication narratives to build support for the policy.

A review of carbon price modeling reveals an historically narrow conceptualization of the costs and benefits. Technical, ex ante assessments employed by policy makers–including partial equilibrium approaches (e.g., cost-benefit analysis) and general equilibrium approaches (e.g., computable general equilibrium [CGE], macrostructural, or dynamic stochastic general equilibrium [DSGE] models)–tend to focus on the effects on regulated sector emissions, adjustment costs, employment, and output. In doing so, they are likely to miss a substantial portion of the benefits of carbon pricing for achieving government objectives. Worse, governments may not even know that these benefits exist, a problem compounded by pervasive gaps in the economic literature on benefits.

Existing studies focus on specific benefits while ignoring others, examine effects globally or in developed countries rather than in developing country contexts, and rely heavily on science or engineering as opposed to economic or social science methods (Deng et al. 2017). Such sample and methodological biases tend to concentrate the evidence on specific technical issues and direct impacts; they largely omit the complexities and constraints of policy design and implementation in developing countries, as well as extensive indirect effects across heterogeneous stakeholder groups.

Table 1.1 summarizes the key benefits explored in this guide, alongside some initial recommendations on how these benefits can be quantified and modeled.

Table 1.1

Policy Benefits of Carbon Pricing

Benefits	Significance for the economy and society	Quantification of benefits
Air quality	• Carbon pricing disincentivizes carbon-heavy fuel use and can reduce local pollution levels. • Potential benefits from improved air quality are significant and likely the largest benefits of carbon pricing. • Benefits include improved human health, increased agricultural productivity, and reduction of pollution-related drags on economic growth such as worker absenteeism.	• Emissions changes due to carbon pricing can be translated into pollution changes and applied to existing dose-response functions to model direct benefits from improved air quality. • Health benefits from improved air quality can be incorporated into CGE modeling frameworks through dynamic modeling of labor supply and allocation.
Water resources	• Many regions of the world are affected by water scarcity and by threats to water quality and water resource sustainability. • Carbon pricing benefits include improvements in both the quantity and quality of water resources. • Key pathways for water sector benefits include reduced overexploitation of groundwater resources, changes in water end-use demands, and reduced water contamination.	• Long-term rainfall, draining of soils, atmospheric deposition, ammonium-based fertilizers, land use changes.
Soil health	• Key threats to soil health include soil contamination, soil acidification, and altered soil nutrient balance. • Primary pathways by which carbon pricing leads to soil benefits include changes in agrochemical application (fertilizer and pesticides), air pollutant deposition, land use, and deforestation. • Benefits may be realized in improved human health outcomes, improved crop yields, reduced deforestation, and reduced biodiversity loss.	• CGE modeling may be used to quantify the indirect benefits related to soil health due to complex intersectoral linkages.
Transportation	• Carbon pricing can reduce the prevalence of both road injuries and congestion through a gasoline tax based on carbon content. • Empirical evidence shows higher gasoline prices lead to reduced accidents and congestion.	• Benefits can be quantified through a variety of metrics. For accidents these include fatalities, nonfatal injuries, medical costs, property damage, and forgone wages and expenditures. For congestion these include negative health outcomes, travel delays, reduced benefits of urban agglomeration, additional fuel use, and travel time variability. • Direct benefits can be used as inputs into CGE models, and the related linkages and overall benefit to the macroeconomy can be measured.

Benefits	Significance for the economy and society	Quantification of benefits
Fiscal policy	• Carbon pricing offers a unique opportunity for revenue generation with limited distortionary impacts on the economy. • Replacing conventional taxes with carbon taxes incentivizes expansion of the formal sector. • Carbon taxes help limit tax evasion and reduce tax administration costs. • While carbon taxes are often assumed to be regressive, existing evidence suggests they are generally progressive.	• Most benefits associated with fiscal policy are indirect and are thus best assessed through a CGE modeling framework.
Balance of payments	• Carbon pricing can increase energy independence and reduce the risk of uncertain external imbalances for importing countries. • For fossil fuel exporters, carbon pricing promotes energy efficiency at home, freeing more resources to earn foreign exchange. • For the same exporters, pricing also reduces the risk of Dutch disease, improving competitiveness and investment in other tradable goods and services.	• Using historical trade data, a variety of standard macroeconometric models can estimate and leverage relevant trade elasticities to develop uncertainty bounds on expected balance of payment variation subject to historical price volatility.
Technological change	• Carbon pricing can provide a dynamic incentive to induce technological change that leads to low-carbon technology innovations. • Empirical evidence finds that environmental regulations typically lead to innovations, although the costs do not always offset the gains from innovation.	• Benefits of technological change can be measured by the following metrics: business performance, innovation, productivity, and export competitiveness. • To fully reflect the benefits from technological change, CGE models must consider technology as an exogenous parameter.

Source: World Bank.

2.

Introduction

2. Introduction

Carbon pricing can reduce emissions cost-effectively, and it can also generate a number of other benefits. This guide provides an overview of these benefits to help policy makers advance a variety of sustainable development objectives in their own countries and around the world. Carbon prices are broadly recognized as necessary for correcting market failures that arise from pollution externalities, because the prices paid for using fossil fuels do not come close to compensating society for the costs that greenhouse gas (GHG) emissions impose on society. Where there is a divergence between (externality-based) social costs and private values, carbon pricing is an essential environmental policy tool.

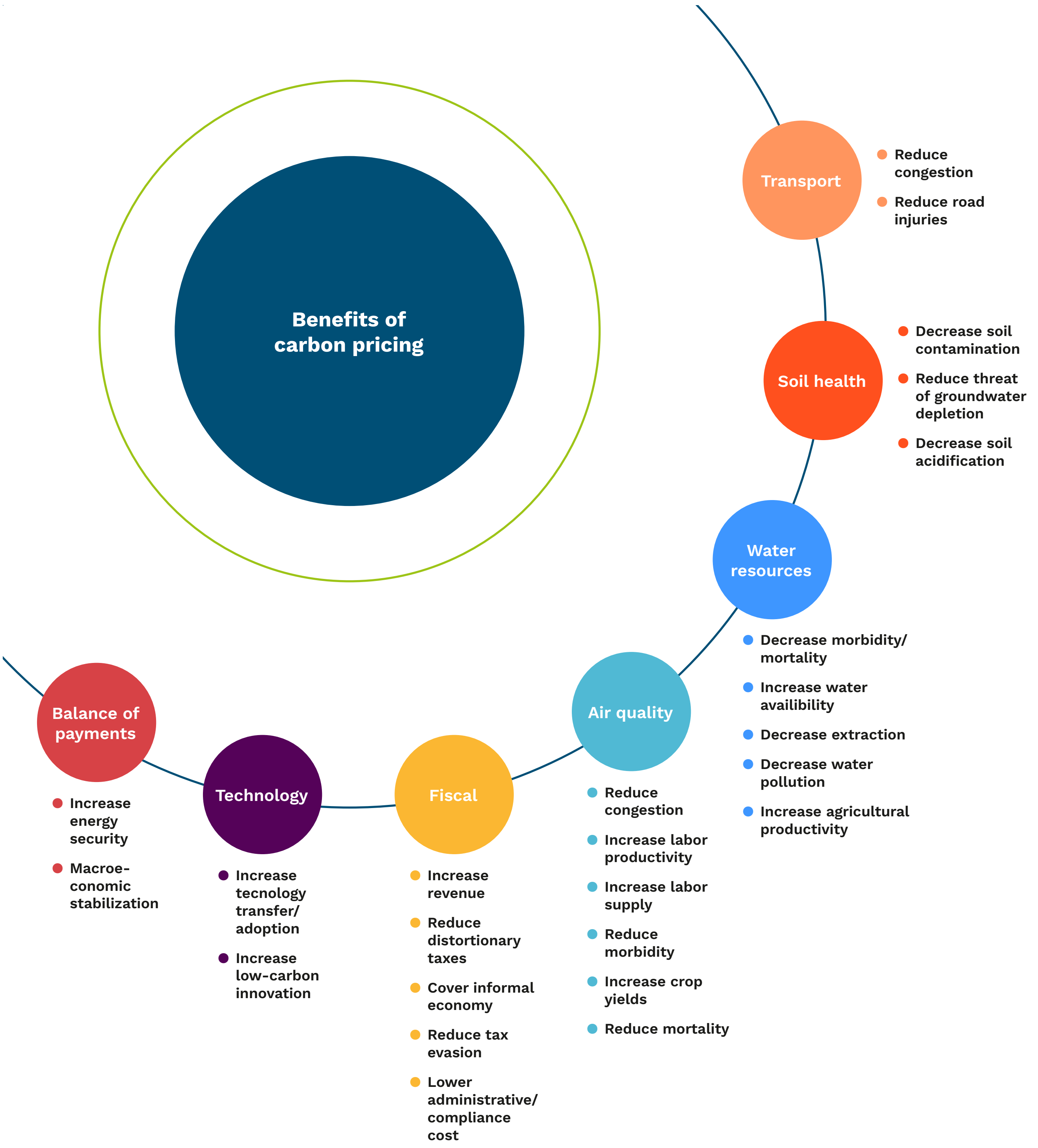
This guide uses the term “carbon pricing” to refer to policies that explicitly price the carbon content of goods–carbon taxes, emissions trading systems, and crediting mechanisms. However, many of the benefits examined in this guide can be derived from a wide array of climate mitigation policies. Where a benefit is exclusive to carbon pricing, this is highlighted in the text.

This guide is designed to meet the need for more timely and reliable evidence on benefits to help policy makers in developing countries make decisions–and communicate–about carbon-pricing instruments, and to help policy researchers choose and implement models that yield reliable evidence on benefits and other relevant policy impacts. To support these efforts, this guide identifies a broad range of carbon price benefits beyond mitigation, which include improvements in seven areas: air quality, water resources, soil health, transport, fiscal policy, balance of payments, and technological change (see figure 2.1). The guide also analyzes case studies of benefit estimation in a diverse array of countries and contexts.

By incentivizing low-carbon changes in consumption and production, a carbon price offers benefits that may go well beyond the benefits for global climate change mitigation. This broader conceptualization gives policy makers a more nuanced understanding of the pervasive impact a carbon price can have and how it can support other development goals. Of course, a carbon price will not solve the issue of air pollution or excessive groundwater use, for instance, but if designed properly it can support positive changes in the seven categories outlined in this guide.

Figure 2.1

Carbon-Pricing Benefits beyond Mitigation



Source: World Bank.

2.1 Purpose, Structure, and Scope of the Guide

The purpose of this guide is to help policy makers identify and measure carbon-pricing benefits. In particular, it provides insights into how to incorporate benefits into CGE modeling. While there are many different types of economic models used to assess mitigation policy, the CGE framework is one of the most common, particularly for assessing indirect effects. Developed within the Technical Work Program of the Partnership for Market Readiness (PMR), this guide draws on the experience of PMR participants, other countries, and subnational jurisdictions that have designed and implemented carbon-pricing strategies, offering insights on the implications, benefits, and drawbacks of different approaches.

The guide is targeted to high-level policy and legislative decision makers, technical experts in the public and private sector, nongovernmental organizations, and international organizations directly or indirectly involved in the design and implementation of carbon-pricing instruments.

The guide has been designed as a handbook of carbon-pricing benefits, and it is organized thematically by type of benefit. Because of the pervasiveness of carbon fuels in today's economies, the effects (benefit or cost) of carbon pricing will be far more numerous than can be discussed in detail here. For this reason, the guide focuses on the seven most prominent benefits (see figure 2.1).

As with any policy, there will be costs and benefits to imposing a carbon price. Because a carbon price affects basic commodity prices, its costs may be more visible than those of other policies. However, alternative climate policies–or inaction–will also have distributional effects. When considering a carbon price, policy makers will need to assess the consequences of changing the cost of fossil fuels relative to cleaner sources. It will create winners and losers across different metrics (e.g., income group, sector, race, region, etc.). These distributional effects are beyond the scope of this guide, as are methods to mitigate any potentially negative effects. However, a deeper understanding of the linkages among carbon prices, environmental quality, the fiscal space, and health benefits can help policy makers design a policy package that minimizes any potentially negative consequences.

The guide is structured as follows. The next subsection provides an overview of the modeling approaches policy makers can use to quantify the benefits of carbon pricing. It also provides information to help policy makers in cases where data may be limited or resources constrained, so that reliable estimates of the scale and direction of these benefits can be estimated. Following this, each of the seven benefits is discussed in turn. These chapters follow the same three-part structure: after a high-level introduction to the benefit, the second section breaks down the components of the benefit. The benefits to transport, for instance, stem from reductions not only in road injuries but also in road traffic. The causal chain linking carbon pricing to the benefit or group of benefits is also delineated. Each chapter concludes with a review of estimation methods, including recommended techniques and examples from real-world applications.

This guide offers a starting point for understanding and strengthening the evidence about the benefits of carbon pricing, with the goal of broadening support for adopting carbon prices. How policy makers can communicate about carbon pricing is already well covered in the *Guide to Communicating Carbon Pricing* (PMR and CPLC 2018) and is therefore not canvased in this guide. Every individual policy context will need its own justification and design for carbon pricing, but it is hoped that the diversity of potential benefits, and evidence for these from very diverse applications, will help policy makers make more proactive and fully informed choices.

2.2 Overview of Modeling Approaches

When designing a carbon-pricing instrument, it is important to understand both its potential benefits and its costs. Policy makers considering a carbon price need to answer two key questions: why should we implement a carbon price, and what are the impacts of a carbon price for my jurisdiction? Existing international experience and empirical case studies can provide some insight into the performance and effects of a carbon-pricing instrument. However, specific instruments operate in very different contexts, and a jurisdiction's own situation must be considered when drawing on international experience.

Most policy makers will also undertake both quantitative and qualitative impact assessments when considering and designing a carbon price. Modeling can be an important tool for these purposes and can shed light on the potential outcomes, costs, and benefits of a carbon price. Estimating the benefits from a carbon price remains an incredibly difficult exercise that draws on a number of sources, each with its own inherent assumptions and data limitations. For these reasons, any modeling results will provide only an overly simplified forecast–and not a prediction–of the possible impacts of a carbon price.

While there are many approaches to estimating benefits, most are either partial or general equilibrium approaches. Both types of approaches have strengths and weaknesses, and when used correctly the two can be complementary. Partial equilibrium models can evaluate the effects of a carbon price on a section of the economy with granular detail, though they do not give an indication of potential indirect effects. Conversely, general equilibrium models are well suited to assess macroeconomic and wider impacts of a carbon price.

This guide is not intended to teach CGE or even partial equilibrium modeling (further details on both these approaches are included in appendix A). Its goal is to illustrate relevant contexts and real-world applications of these approaches, thus promoting their application to assess the benefits that would follow from carbon pricing. Understanding these benefits beyond emissions reduction is critical. When these benefits are not factored into carbon-pricing models, the result is a narrower conceptualization of costs and benefits and the omission of some potentially substantial benefits, such as to air quality and congestion reduction. Ultimately, evidence of these benefits beyond emissions reduction can make an important contribution to building support for carbon-pricing policies.

3.

Air Quality

At a Glance

Air quality benefits

- Air pollution is a leading cause of death worldwide and is a significant issue for developing countries.
- Carbon pricing disincentivizes fossil fuel consumption and production, which can also help reduce local air pollution levels.
- The potential benefits from improved air quality are large and more than outweigh the potential costs of a carbon price.
- Air quality improvements provide positive health benefits by reducing mortality and morbidity rates, in turn increasing labor productivity and agricultural productivity.

Quantifying air quality benefits

- Distinct dose-response curves that relate health, agricultural, or labor outcomes to different pollution concentrations can be used to estimate the direct benefits of air quality improvements from a carbon price. However, indirect benefits also need to be estimated to capture secondary and spatial effects.
- The health benefits of improved air quality can be incorporated into CGE modeling frameworks by restructuring social accounting matrixes to account for pollution health effects and through dynamic modeling of labor supply and allocation.
- Air quality benefits on agricultural production can similarly be incorporated by linking total output in the agricultural sector to pollution levels in CGE models.
- Estimates of air quality benefits should be considered a lower bound on total direct benefits, as many improvements are more difficult to quantify and are likely omitted.

3. Air Quality

3.1 Introduction

Air quality is determined by the levels of pollution emitted from a variety of activities, including power generation, industrial processes, transportation, household activities, fuel combustion, and non-energy activities. Conversely, improving air quality is one of the most consequential benefits of carbon pricing. The most up-to-date global research indicates that, in 2018 alone, almost one in five deaths was caused by fossil fuel pollution–amounting to more than 8 million people. This is about twice the number of people suggested by previous research (Vohra et al. 2021). The impacts of poor air quality depend on both the type and the amount of pollutants present. Particulate matter can have significant impacts on things like health and labor productivity, while ozone, which is formed by secondary chemical reactions involving hydrocarbons and NOx, is harmful to health as well as agricultural productivity. Moreover, many pollutants (NOx, SO_2, VOC, and NH_3) are particulate matter precursors, so reductions of these pollutants will also result in lower concentrations of particulate matter.

A carbon-pricing instrument disincentivizes carbon-heavy fuel use and can thus reduce emissions by spurring some combination of reduced fuel use and switching to cleaner fuels. Carbon fuel use generates many types of pollution. Here we focus on highlighting the benefits of reducing particulate matter and ozone, the two pollutants with the most evidence for impacts on health, labor, and agriculture. In most cases fewer emissions leads to lower pollutant concentrations and overall improved local air quality. We also discuss the important case of household air pollution, which, if not considered in the policy design, may increase in response to a carbon price (a potential "harm").

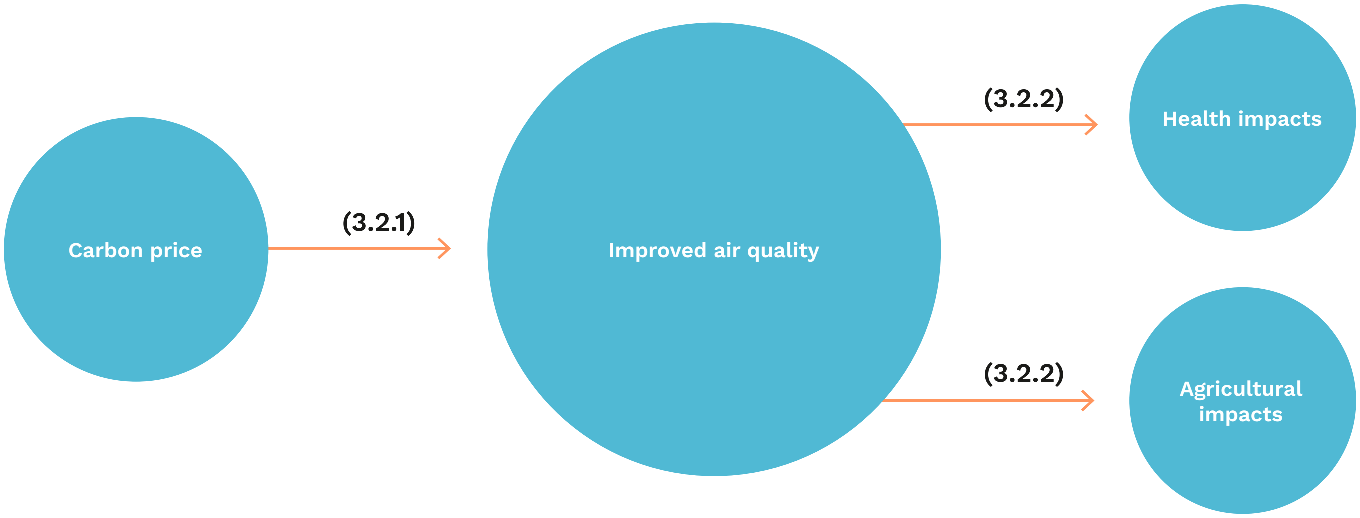
Section 3.2 identifies and discusses the benefits that come from improved local air quality and examines how the range of impacts is linked to changes in the price of carbon. Section 3.3 discusses methods for estimating the magnitude of the direct benefits described in the first section. Finally, section 3.4 provides guidance on incorporating air quality benefits into a CGE modeling framework in order to capture the indirect impacts (i.e., secondary and tertiary effects) of these benefits throughout the economy.

3.2 Identifying Air Quality Benefits and Linkages

Air quality is closely linked to local carbon fuel usage intensity. In this section we discuss settings where carbon pricing does and does not lead to improved air quality. We then proceed to identify and discuss benefits of air quality improvements, focusing on economic impacts through health and agriculture channels (see figure 3.1). The significant mortality and morbidity issues that occur as a result of exposure to fossil fuel pollution have been well documented. A carbon price can help reduce pollution levels by disincentivizing fossil fuel production and consumption, and the scale of these health benefits alone is likely quite sizable. A reduction in pollution can also improve crop yields, generating economic benefits for the agricultural sector.

Figure 3.1

Overview of Benefits from Improved Air Quality



Source: World Bank.
Note: The numbers in parentheses refer to the section of the chapter in which the subject is discussed.

In addition to the health and agriculture benefits quantified in this report, there are many other potential benefits from improved air quality. For example, improved air quality has been linked to increased happiness,[3] improved biodiversity,[4] improved water quality, and increased tourism, among other benefits. Therefore, while health and agriculture are two of the most important benefits, they should be viewed as lower bounds on total benefits associated with a given improvement in air quality.

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[3] *See Zheng et al. (2019); Levinson (2012), and Welsch (2006), among others.*
[4] *See for example Liang et al. (2020); Lee, Davies, and Struebig (2017).*

3.2.1 Changes in Air Quality

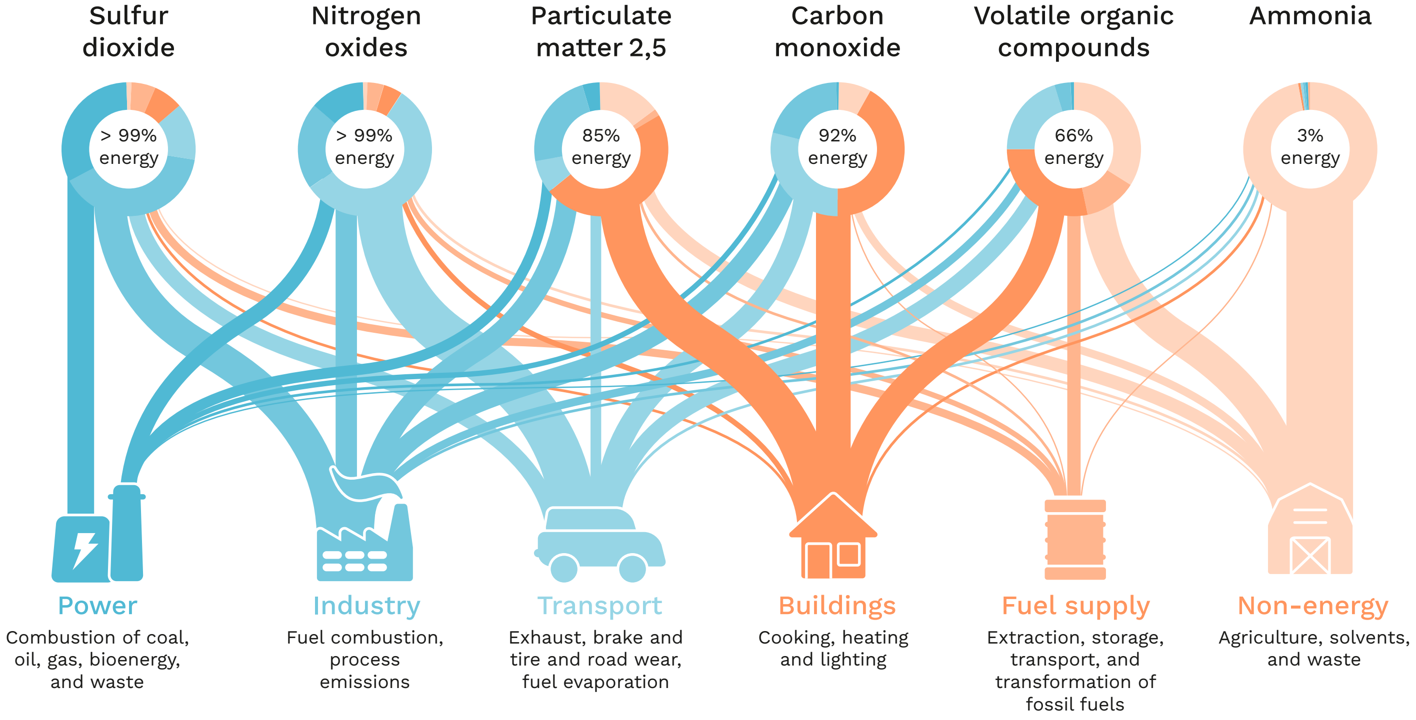
A carbon price has the potential to improve air quality by incentivizing emissions reductions through higher prices of emissions-intensive fuels. When costs increase for these fuels, there is a financial incentive to reduce fossil fuel usage and consumption. The consumption of fossil fuels also contributes to local air pollution, and this too can be reduced by well-designed carbon-pricing instruments.

Increasing the price of carbon can lead to a reduction of emissions in those regulated sectors when the price increase is sufficiently large given the price elasticity of demand in the sector.[5] In sectors with inelastic demand, larger carbon price increases are required to induce behavioral changes. Power generation from fossil fuel-based technologies, like thermal power plants, is a major contributor to poor air quality in many countries. However, countries may have alternative fuel options that lead to some fuel switching and improvements in air quality even with relatively lower carbon prices.

Different processes are responsible for producing different types of emissions and consequently different pollutants. For example, SO_2 and NO_X emissions are largely created through power generation and consumption (e.g., through coal combustion). Figure 3.2 outlines the sources of selected air pollutants.

Figure 3.2

Primary Air Pollutants and Their Sources



Source: International Energy Agency (2016) as modified by CPLC (2019a).

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[5] *This issue is discussed in more detail in section 3.3.1.*

When considering air quality, policy makers have to consider both household air pollution and ambient air pollution. Household air pollution is generated from household fuel combustion; for instance, from stoves and lamps. Conversely, ambient air pollution is outdoor pollution; for instance, from vehicles or fossil fuel–based power generation.

The linkage of carbon pricing with household air pollution is fundamentally different from the linkage with ambient air pollution. In fact, there is some concern that carbon-pricing policies designed without considering the effects on fuel use by low-income households could increase household air pollution; this would occur as households substitute informal solid fuels with higher emissions for formal carbon-based fuels (see box 3.1). However, there is little empirical evidence on whether carbon prices increase household air pollution or not. While there are theoretical reasons to believe they might, complementary policies are available to combat intensified use of solid fuels in settings where this is a concern.

Box 3.1

The Interaction between a Carbon Price and Household Air Pollution

Household air pollution is an important source of pollution exposure in many parts of the world. Nearly a third of the world's population uses solid fuels like coal, wood, and agricultural residues for cooking, heating, or lighting indoors (Gordon et al. 2014); when burned indoors these fuels represent a major health risk. Household air pollution is the leading source of pollution deaths in Sub-Saharan Africa and a major contributor to premature mortality from pollution in other regions. The impact is particularly heightened in rural and/or low-income areas in developing countries, where these populations tend to lack access to alternative fuel sources. Women and children tend to bear a disproportionately large share of the negative health costs of household air pollution (World Health Organization [WHO] 2020). There can also be substantial economic costs alongside the health risks and loss of life; studies in Latin America estimate the cost at 1–2 percent of gross domestic product (GDP) (Larsen and Skjelvik 2013, 2014; Larsen 2015, 2017).

In light of household air pollution's contribution to pollution exposure, it is important to consider how this form of pollution is impacted by a carbon price (see figure B3.1.1 below). Solid fuels are often collected or purchased through informal channels that are not subject to a formal carbon price. Thus, while carbon pricing increases the price of formal fuels, it may make the relative price of solid and other informal fuels cheaper and therefore incentivize more use of solid fuels. This is called a "leakage" effect and has the potential to contribute to increased burning of solid fuels indoors, which increases both household and ambient air pollution (as smoke is filtered outside from its indoor source), offsetting some of the gains from the carbon price.

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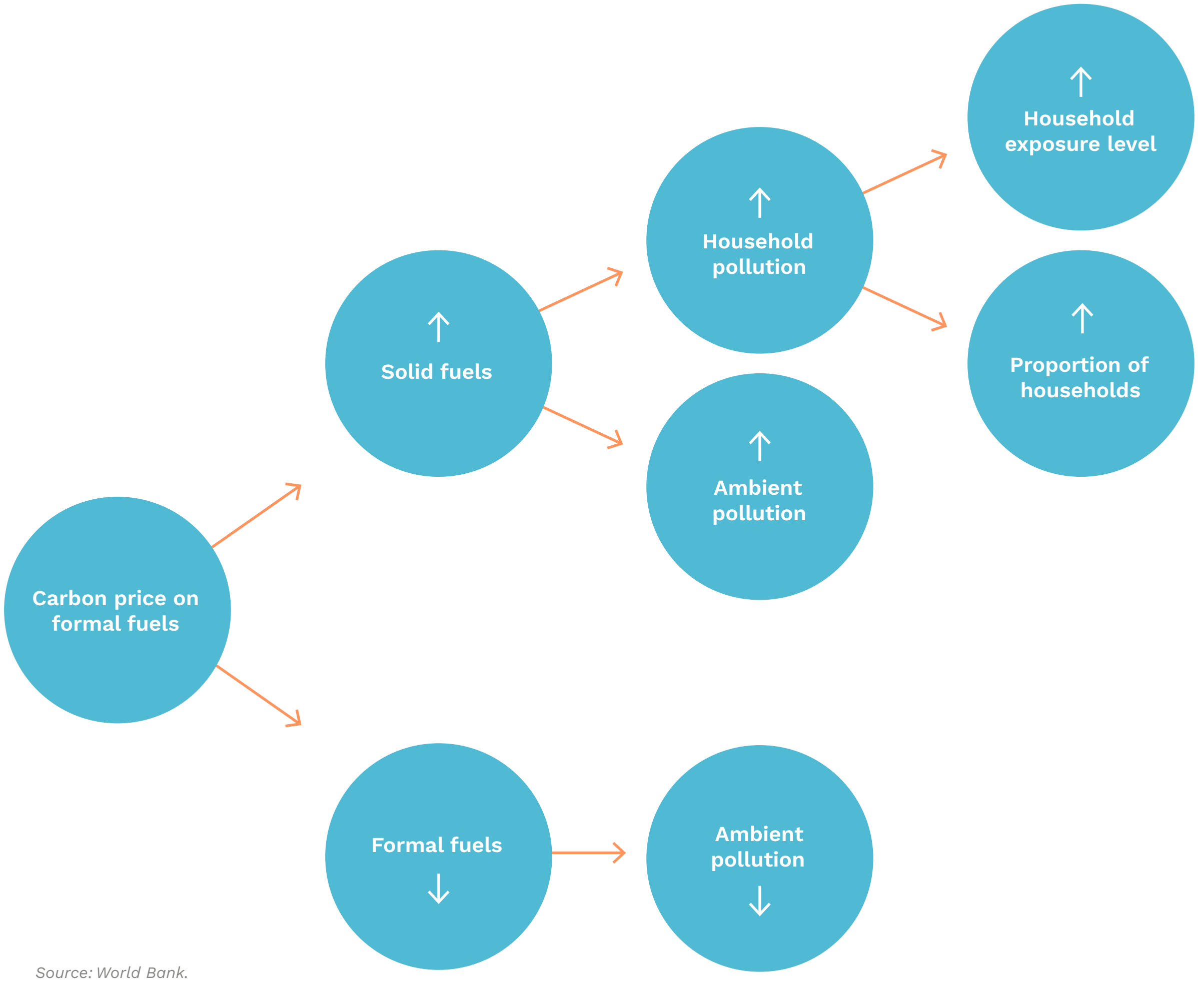
Figure B3.1.1

How a Carbon Price Affects Household Air Pollution



Source: World Bank.

As figure B3.1.1. illustrates, both the proportion of households using solid fuel and the volume of use among households using it may increase with carbon pricing. The magnitude of these impacts depends on the relative price difference between solid (informal) and formal fuels, as well as the extent of solid fuel use within the jurisdiction. Given that household air pollution is a serious health risk, many policy makers are concerned about a carbon price's negative impact on household air pollution. However, to date there is little empirical evidence of carbon leakage actually increasing household air pollution in practice. Moreover, if leakage does become a serious issue, then complementary policies like subsidization of clean cooking fuels can be used to counteract these effects.

Regulators have utilized a number of policy instruments to disincentivize solid fuel use in homes. One common approach to reducing household air pollution is designing complementary policies to reduce the price for cleaner fuel substitutes rather than solely relying on policies to increase the price of the dirty fuel (as a carbon price would do). For example, India actively promotes liquified petroleum gas (LPG) in part by targeting provision to poor and rural households, providing an LPG connection through the Pradhan Mantri Ujjwala Yojana program. Because of this policy, the implicit price of carbon is raised for the majority of the population, but it is kept low for the section of the population with a high cross-price elasticity that would otherwise be incentivized to switch to solid fuels. If designed and implemented effectively, policies like these can be used to offset potential increases in household air pollution associated with the introduction of a carbon-pricing instrument. In India, estimates suggest that as a result of the policy of LPG promotion, within the next few years 90 percent of households will have access to clean cooking fuels (Goldemberg et al. 2018).

3.2.2 Health Benefits

Policies that improve air quality have the potential to generate large health benefits. Moreover, evidence is accumulating that the morbidity burden of pollution is also extremely costly due to its effects on exacerbated respiratory issues, cognitive decline, and other pathways. A carbon-pricing instrument that improves air quality therefore has the potential to generate substantial economic benefits through avoided health costs from pollution.

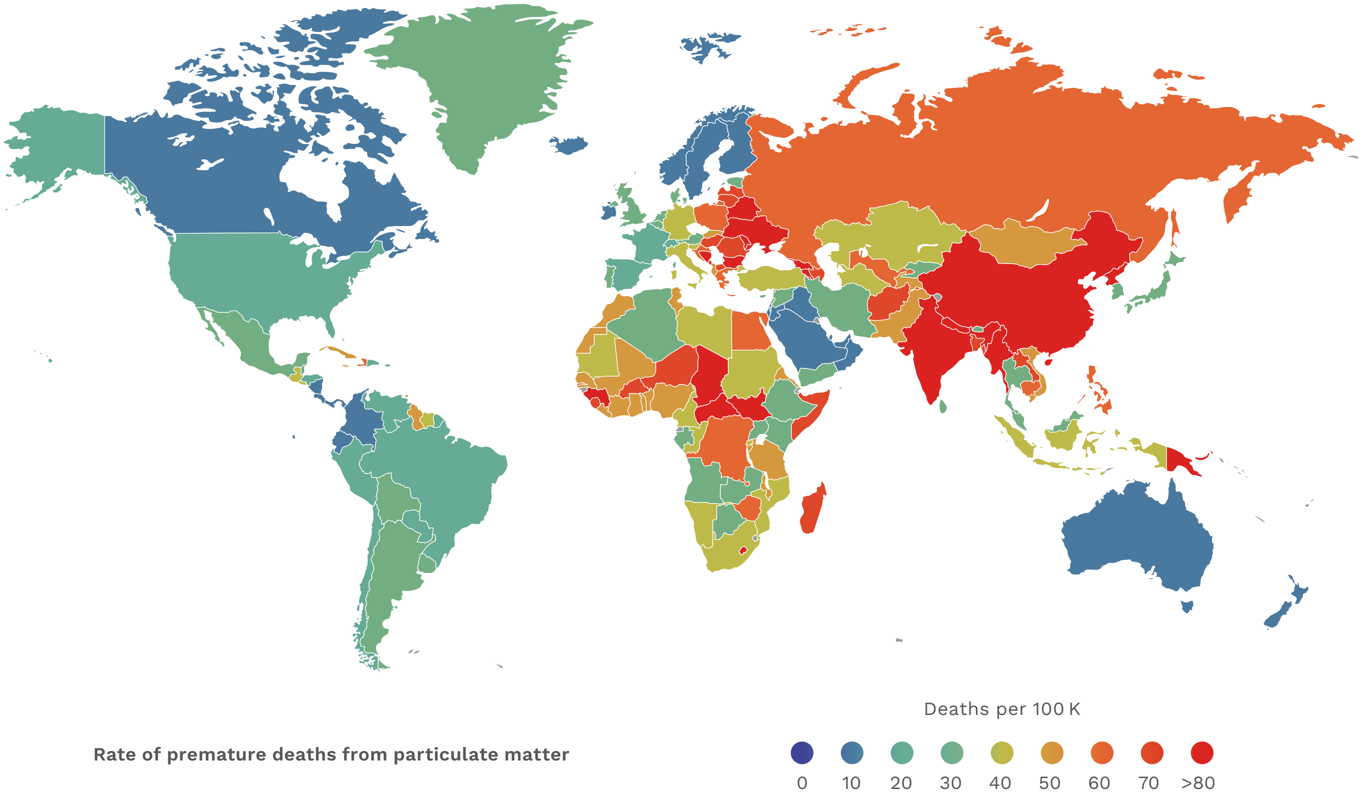
The discussion of health benefits is divided into two parts. The next section discusses the current mortality burden from air pollution and the extent to which carbon pricing can help reduce it. The following section highlights the wide range of morbidity benefits such as reduction in medical costs and worker absenteeism.

3.2.2.1. Premature Mortality

There is a long-established link between air quality and premature mortality, progressing with fossil fuel–based industrialization around the world and most recently demonstrated by the startling results of Vohra et al. (2021), which showed air pollution from fossil fuels were responsible for one in five deaths in 2018. Figure 3.3 shows estimated rates of premature deaths from particulate matter by country. Many countries experience rates of 75 or more pollution deaths per 100,000 people. To put this into context, malaria is responsible for just 41 deaths per 100,000 in Africa, and 10 deaths per 100,000 globally (WHO 2019). Avoiding even a portion of these deaths is an important potential benefit of improved air quality.

Figure 3.3

Global Distribution of Pollution Mortality Rates



Source: Calculated using estimates from IHME, Global Burden of Disease (2017) data, http://ghdx.healthdata.org/gbd-2017.

All individuals are susceptible to negative health impacts if exposed to high pollution levels for an extended period. However, pollution exposure poses a greater risk for people with certain health conditions, like asthma or heart disease, and for those in particular age brackets, like the elderly and infants.[6] These risks arise not only from particulate matter exposure but also as a result of exposure to other pollution types (see Figure 3.4). Reducing these types of pollution would most likely prevent early deaths from pollution.

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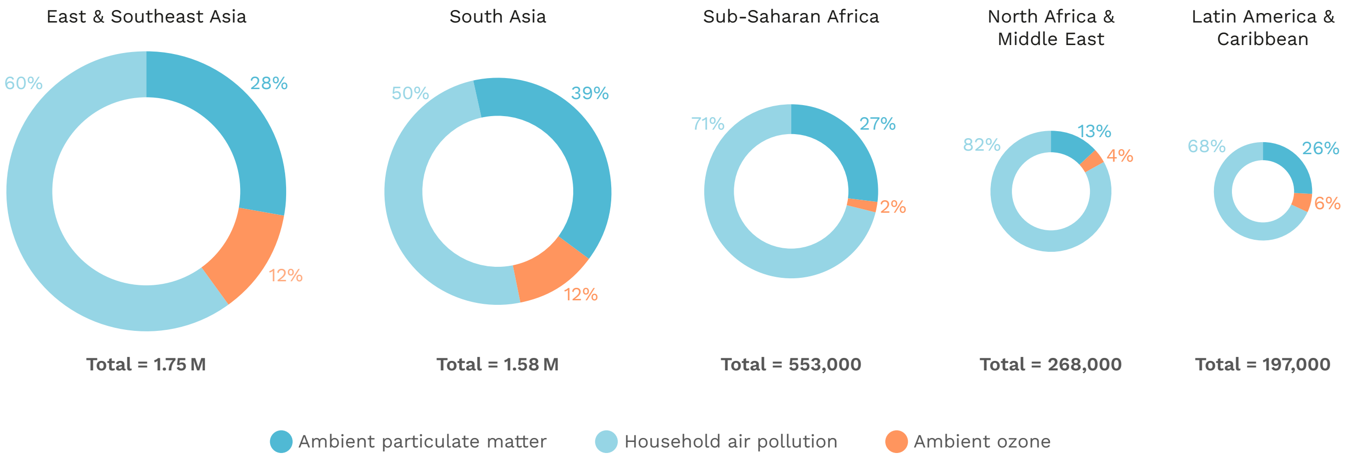
[6] *An increase in particulate matter 2.5 (PM2.5) of 10 micrograms (μg) per cubic meter (m^3) is estimated to increase infant mortality by 10–35 percent, depending on the study location and design. To put 10 μg/m^3 into perspective, a reduction of that magnitude would represent a 43 percent reduction in South Africa, a 23 percent reduction in China, and a 16 percent reduction in India. Moreover, there is a precedent for achieving large reductions. For example, between 2013 and 2017, environmental policies in China were estimated to reduce PM2.5 concentrations by 20 ug/m^3 (Zhang et al. 2019).*

Figure 3.4

Pollution Deaths by Pollution Type



Source: Calculated using data from IHME, Global Burden of Disease (2017), http://ghdx.healthdata.org/gbd-2017.

3.2.2.2. Morbidity

As data availability improves around the world, more and more studies are linking pollution exposure to a diverse collection of afflictions (table 3.1).

Table 3.1

Morbidity Impacts and Costs of Pollution Exposure

Health end point (impact)	Cost
• Asthma (Delfino et al. 2008, 2014; Zhang et al. 2016) • Lower respiratory infections (Glick et al. 2019; Asta et al. 2019; Luong et al. 2020) • Ischemic heart disease (Xie et al. 2015) • Chronic pulmonary disease (Hansel et al. 2013; Hansel, McCormack, and Kim 2016) • Stroke (Leiva et al. 2013) • Diabetes (Bowe et al. 2018) • Preterm birth (Bekkar et al. 2020) • Low birth weight (Bekkar et al. 2020) • Depression (Braithwaite et al. 2019) • Dementia (Peters et al. 2019)	• Cost of hospitalization • Cost of medicine • Cost of transportation to medical care • Lost wages of affected individual • Lost wages of family members caring for affected individual • Decline in productivity associated with injury

Source: World Bank.

There is also more general evidence that exposure to pollution increases health care costs. For example, Carugno et al. (2018) in Italy and Phung et al. (2016) in Vietnam both find that hospitalizations increase with higher exposures to particulate matter and ozone. The cost of hospitalization and medical care arising from the health problems outlined in table 3.1 can be significant, in addition to the costs for social and household care, losses in well-being, and loss of productivity.

Morbidity effects from poor air quality can also have a significant impact on the labor supply and labor productivity in both the short and long runs. Air quality can negatively affect labor in the short run in two main ways: absenteeism and decreased productivity. There is evidence that absenteeism increases during periods of poor air quality due to pollution-related illnesses (see for example Hanna and Oliva 2015). This may occur because conditions such as asthma are exacerbated or people overall feel less well and are more inclined to take time off. Globally, pollution is currently estimated to result in 1.2 billion lost working days per year, and projected increases in pollution concentrations could lead this figure to triple to 3.7 billion work days per year by 2060 (Organisation for Economic Co-operation and Development [OECD] 2016). When the labor supply is reduced, even temporarily, output and ultimately GDP go down. There is also evidence that working in high-pollution conditions negatively affects how productively employees perform their duties; empirical studies have found pollutants decrease worker productivity in a wide range of settings by as much as 5 percent.[7]

The long-run impacts of pollution exposure on productivity are potentially even more harmful than the short-run impacts.[8] There is evidence that exposure to air pollution in utero and early in life affects a child's cognitive development, which can lead to a lifetime of lost human capital (see for example Sanders [2011]; Bharadwaj et al. [2017]). Even more worrisome, in utero pollution exposure can affect lifetime earnings. Bharadwaj et al. (2017) estimate that the observed 50 percent reduction in carbon monoxide in Santiago between 1990 and 2005 increased lifetime earnings by approximately $100 million per birth cohort. This suggests the air quality benefits of protecting pregnant women from pollution are vast. In light of the extensive harms from pollution exposure, air quality improvements have the potential to generate large and lasting benefits through a reduction in labor productivity losses.

Ambient air pollution is one of the leading causes of premature death globally, and a reduction in premature deaths associated with lower pollution levels is the single most valuable potential benefit of a carbon tax. Ambient PM2.5 and ambient ozone account for a majority of pollution deaths and diseases in most regions;[9] by incentivizing reductions in carbon fuel use, a carbon price could reduce both these pollutants. Policy makers will therefore need to account for these factors and consider the current burden of pollution-related mortality in their jurisdictions when evaluating potential mortality benefits from a carbon price. Just factoring in some of the health benefits identified and quantified in this chapter will more than outweigh the total costs of a carbon price (Markandya et al. 2018)—even though this will likely yield a lower, conservative estimate of the morbidity benefits. Particularly for developing countries, where air pollution presents such a visible and pressing issue to citizens, mitigation policies that reduce air pollution and deliver health benefits may be able to achieve broad-based support. These net benefits will only become larger once morbidity effects have been accounted for.

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[7] *For those interested in more information on the impact of pollution exposure on worker productivity, see Graff Zivin and Neidell (2012) on agricultural workers in the United States; Adhvaryu, Kala, and Nyshadham (2014) on garment factory workers in India; Hanna and Oliva (2015) on labor market outcomes in Mexico; Li et al. (2015) on manufacturing workers in China; Chang et al. (2015) on pear packers in the United States; Chang et al. (2019b) on call center workers in China; and He, Liu, and Salvo (2019) on textile workers in China.*

[8] *It should be noted that capital-intensive industries are mostly unaffected by changes in health. Additionally, in the long run it may be easier for pollution-affected workers to be replaced when healthy workers are underemployed.*

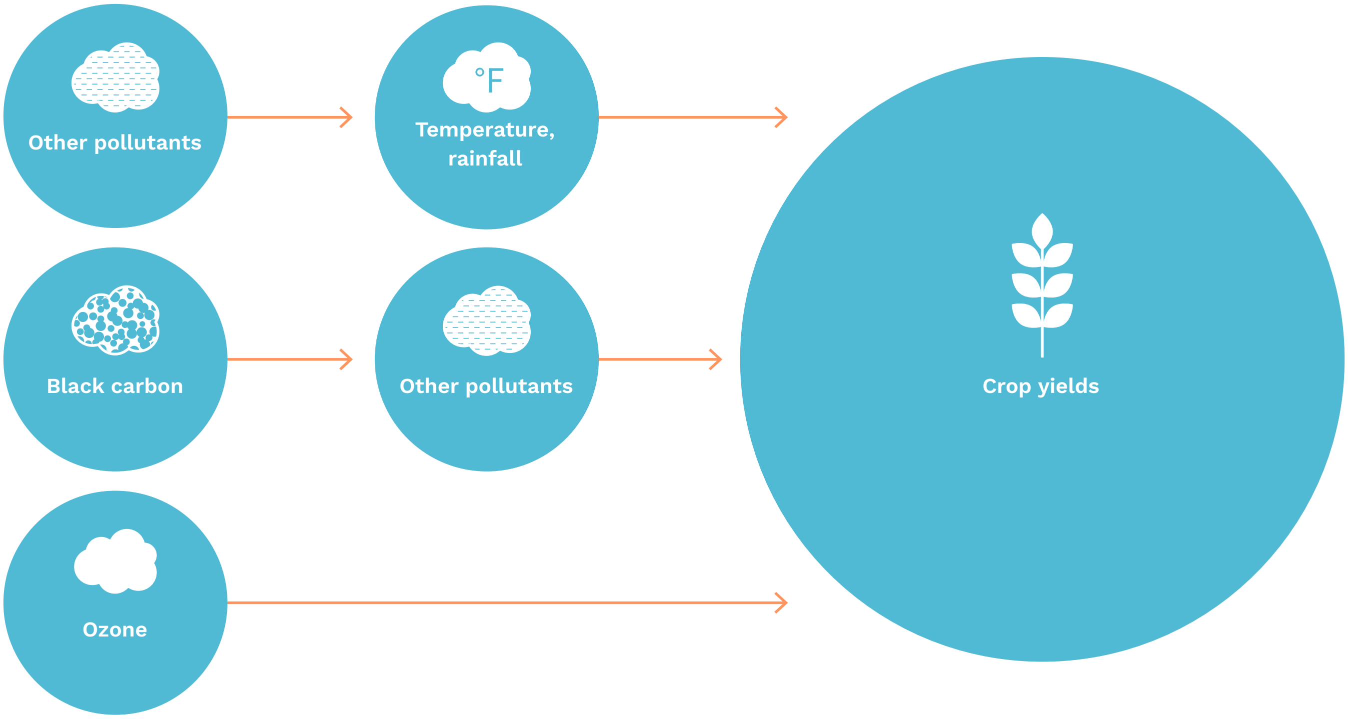
[9] *Sub-Saharan Africa, where household air pollution accounts for a majority of pollution deaths, is the exception.*

3.2.3 Agriculture

Air pollution has an impact on agriculture, as it can reduce crop yields. There are three main channels that relate air pollution to yields (figure 3.5). First, pollutants such as ozone are directly toxic to plants (Ainsworth et al. 2012). Second, pollutant concentrations can influence temperature and rainfall patterns, key inputs to crop growth. Third, black carbon aerosols alter the nature of solar radiation reaching the surface both locally and at larger spatial scales (Ramanathan and Carmichael 2008), reducing both the quantity and quality of sunlight available to plants and negatively affecting crop growth.

Figure 3.5

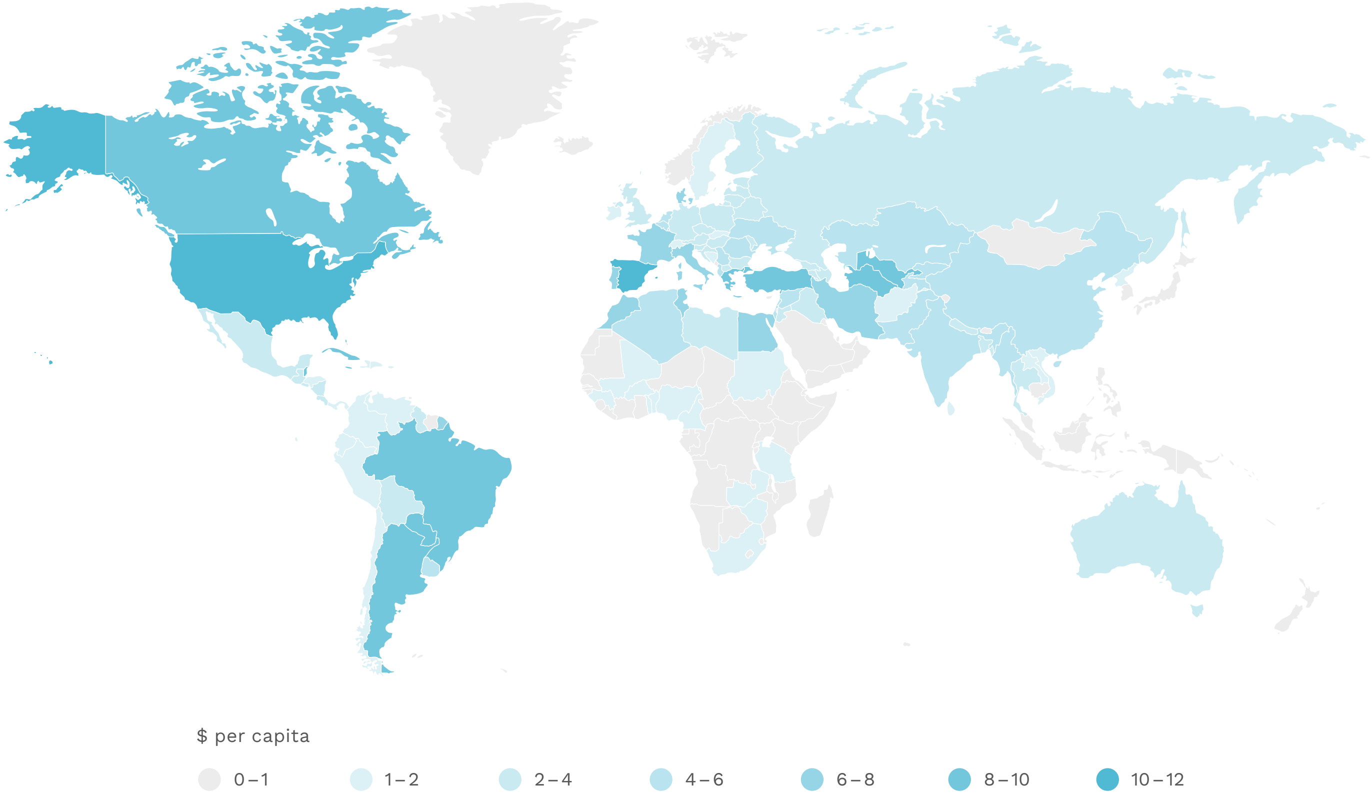
Linkages between Pollution and Crop Yields



Source: World Bank.

Figure 3.6

Projected Ozone-Related Crop Yield Benefits of Emissions Reductions, 2050



Source: Vandyck et al. (2018).

There is ample global evidence connecting air pollution with negative agricultural outcomes. For example, estimates in India suggest yields over the past 30 years would have been 30 percent higher absent the observed rising levels of ozone and black carbon (Burney and Ramanathan 2014). Globally, substantial yield losses from pollution have also been estimated for maize and soybeans (Avnery et al. 2011). Vandyck et al. (2018) estimate that ambitious emissions controls could raise global maize yields by 1 percent, rice yields by 0.5 percent, soy yields by 2.2 percent, and wheat yields by 1.3 percent, generating sizable benefits, particularly in Asia and South America (figure 3.6).

Absent stricter emissions controls, negative pollution impacts on agriculture are expected to rise substantially in the coming decades (OECD 2016). Given that many developing countries' economies depend on agriculture, raising crop yields (or avoiding any lowering of crop yields) through improved air quality is an important potential benefit of a carbon price.

3.2.4 Summary

In summary, air quality benefits can broadly be characterized as relating to health or to agriculture, and each category has its own metrics. Figure 3.7 lists the metrics for air quality benefits discussed previously. The next section examines how to quantify each of the metrics.

Figure 3.7
Air Quality Benefit Metrics

Health

- Mortality costs
- Health care costs
- Labor supply
- Labor productivity
- Household income distribution
- Returns to labor and capital
- Labor intensity of production

Agriculture

- Crop yield
- Value of lost output

Source: World Bank.

3.3 Measuring and Modeling Direct Impacts

A carbon price has direct and indirect impacts on air quality. The direct effects measure the influence of a carbon price on a particular sector or area of the economy (e.g., labor productivity), while indirect effects capture the impacts of secondary linkages that result from the directly affected sector (e.g., the indirect effects of lost spending on other parts of the economy as a result of lower wages). While indirect effects require a general equilibrium modeling framework for estimation, direct effects can be measured using either partial or general equilibrium models.

The links between improved air quality and benefits can be broadly generalized as follows:

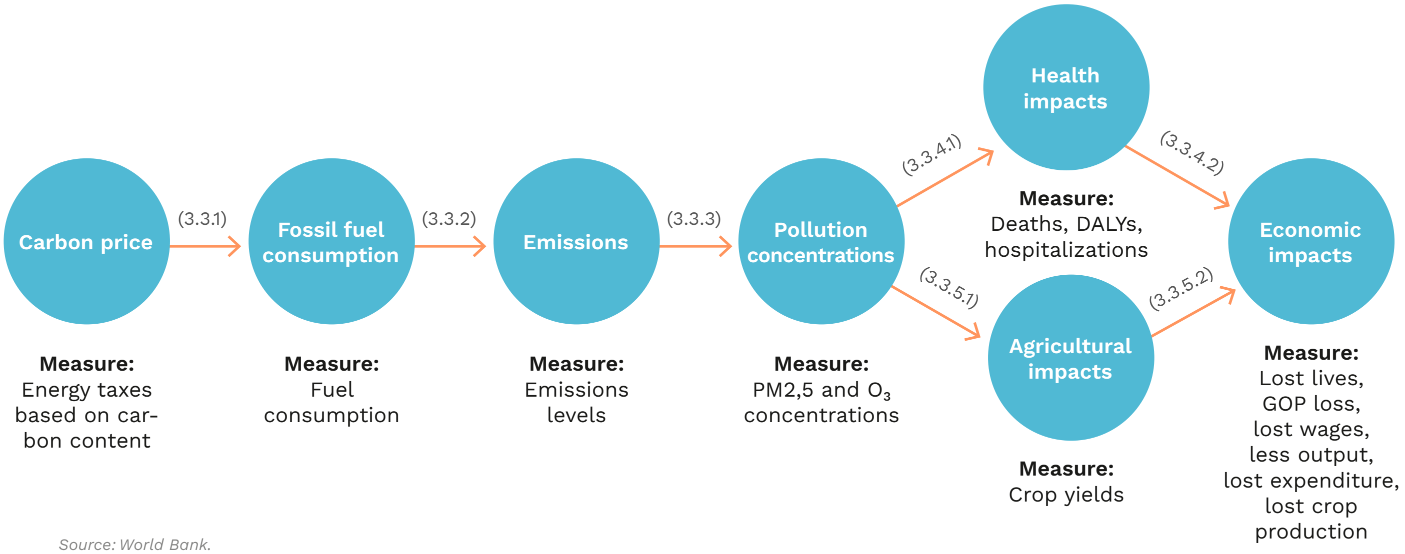
1. A carbon price disincentivizes fossil fuel consumption and production, reducing greenhouse gas emissions.
2. Lower greenhouse gas emissions can help improve local air quality.
3. Changes in levels of fine particulate matter can lead to health and agricultural effects–namely, fewer deaths, lower morbidity costs, increased human capital accumulation, higher labor productivity, and increased agricultural productivity (direct impacts).
4. Through linkages in the economy related to the items listed in (3), additional indirect benefits are accrued. For example, reducing air pollution may reduce the need for health care services in the future.

Below, we examine approaches to estimating the direct benefits of improved air quality using partial equilibrium econometric models. Then in section 3.4 we assess approaches to modeling indirect effects of improved air quality in a CGE modeling framework.

Figure 3.8 shows the pathways that link a carbon price to benefits from improved air quality. In most cases, to measure and model the economic benefits of improved air quality, policy makers need to quantify and model the relationship across all stages.

Figure 3.8

Overview of Benefits from Improved Air Quality



Source: World Bank.
Note: DALYs = disability-adjusted life years.

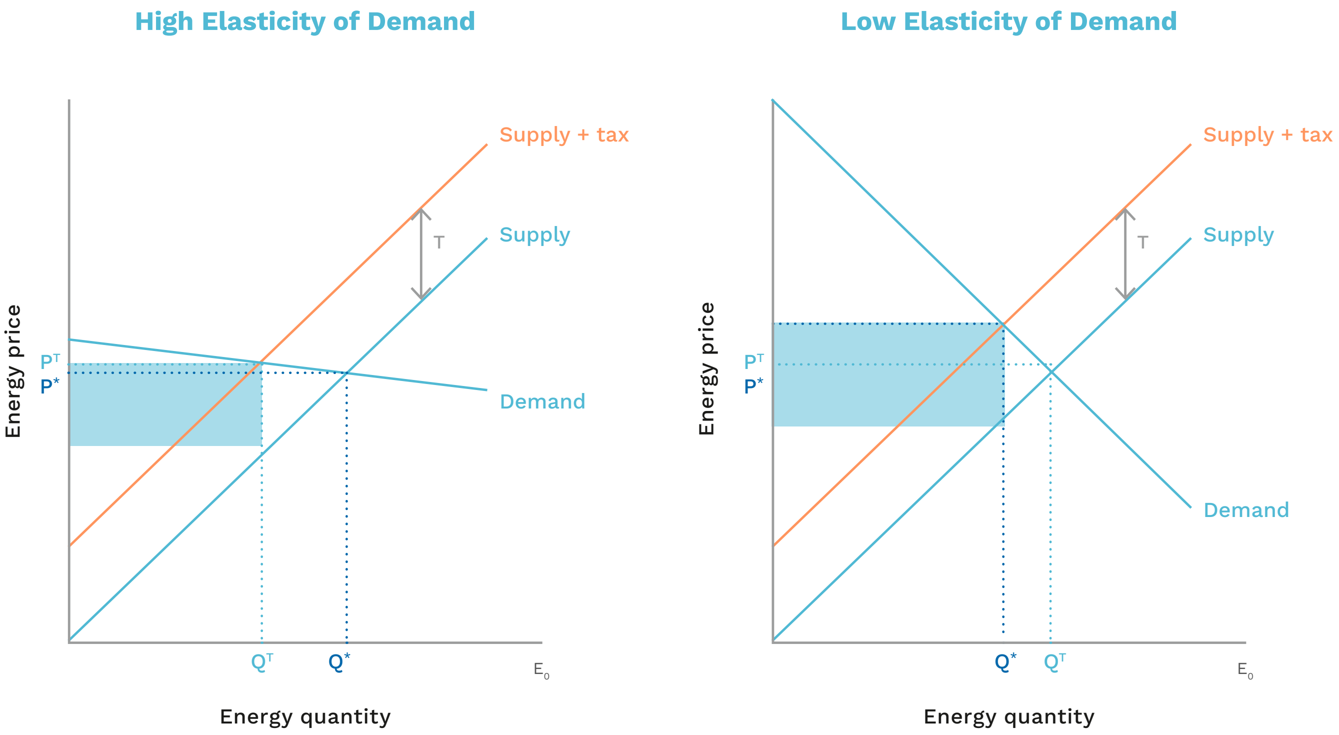
The following subsections provide an overview of available methods and important considerations for estimating the broad range of benefits arising from improved air quality at the country level.

3.3.1 Fuel Consumption

Characterizing how fuel prices respond to a carbon price is the first step in quantifying air quality benefits. Each fuel's price will change depending on the design and level of the carbon price and on the fuel's carbon content.

For each fuel, the change in the volume of fuel consumption depends on the price elasticity of demand. The more elastic the demand, the greater the change in fuel use—assuming alternative energy sources are readily available to all consumers (figure 3.9). In addition, fuel elasticities will be larger in the longer term, as it becomes more feasible to respond to prices with investments in different energy use patterns. Table 3.2 provides estimates of short-run and long-run elasticity estimates produced by a meta-analysis of the empirical literature.

Figure 3.9
Elasticity of Demand for Energy and Reductions in Energy Use



Source: PMR (2017).

Table 3.2

Average Energy Elasticities in the Empirical Literature

Energy	Short term	Long term
Electricity	-0.126*	-0.365*
Natural gas	-0.180***	-0.684*
Gasoline	-0.293***	-0.773***
Diesel	-0.153**	-0.443***
Heating oil	-0.002	-0.185

Source: Labandeira et al. (2017), table 6.
*Note: Significance level: * = 10 percent, ** = 5 percent, *** = 1 percent.*

Gasoline has the highest short-run and long-run elasticities because it is relatively straightforward to substitute through ride-sharing, public transportation, and other travel choices. If countries do not have alternative low-carbon options, such as a robust public transport system, price elasticity will be lower.[10] Heating oil, on the other hand, is generally less elastic because buildings that use furnaces or boilers for heating cannot easily switch to other heating methods. Where demand–or demand for a specific fuel–is less elastic, complementary policies, like public investments, may be required to encourage substitution.

For governments with limited resources or capacity, identifying key sectors and/or fuels that are the primary cause of air pollution can help narrow the focus of the quantification work. For instance, governments may choose to focus on power and heating, transport, and industry as they make up a significant share of global fossil fuel consumption.

To estimate the change in fuel consumption from a carbon price, price elasticities of demand for each fuel are multiplied by the percentage change in price for that fuel. Where available, locally estimated elasticities should be used to provide a more accurate picture. Where these are unavailable, estimates can be drawn from meta-analyses of estimates across a range of countries (e.g., Labandeira et al. 2017).

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[10] *For example, Fay et al. (2015) find that the price elasticity of demand for motor fuels is four times higher in countries that have good public transportation systems than in countries that do not.*

3.3.2 Emissions Reductions

Emissions reductions from carbon pricing can be modeled using "emissions factors," which measure the mass or weight of emissions for a given quantity of fuel use. These factors vary by fuel and emissions type and are used in the measuring, reporting, and verifying (MRV) system that monitors compliance with a carbon pricing instrument. For a given volume of fuel consumption estimated in the previous section, emissions factors can be multiplied to estimate the volume of associated emissions. The impact on emissions can be mapped using monitoring data or satellite estimates according to population density and exposure to give policy makers an indication of how emissions reductions would be distributed across the jurisdiction.

3.3.3 Changes in Pollution Concentrations

The next step in estimating benefits from improved air quality involves translating emissions to ambient concentrations of pollutants. Two distinct processes affect air quality. First, pollutants such as particulate matter and NO_X can be emitted as primary pollutants directly into the environment. Second, as a result of chemical reactions involving primary pollutants, secondary pollutants can form in the atmosphere. Particulate matter can be emitted as a primary pollutant or form as a secondary pollutant, while ozone forms only in secondary reactions.

There is more than one approach to quantifying pollutant concentrations associated with emissions. In most cases, policy makers will need to trade off between ease of implementation and model sophistication.[11] Two common approaches that illustrate this trade-off are source-receptor modeling and chemical transport modeling.

Source-receptor models are reduced form statistical models that use historical relationships between GHG emissions and ambient pollution to translate average emissions to average ambient pollution. A source-receptor model like the Fast Scenario Screening Tool (FASST) (Van Dingenen et al. 2018) multiplies changes in emissions by the set of coefficients in a source-receptor matrix in order to estimate changes in pollutant concentrations.

Source-receptor models do not take into account determinants of local air quality such as meteorology and chemical transformation mechanisms (e.g., how gases react in the atmosphere); however, they offer several advantages: they provide reasonable approximations for how changes in emissions will relate to changes in air quality, they require limited expertise to apply, and they are more easily extrapolated to new settings than the reduced form models concerned with the relationship between a carbon price and pollution (discussed at the start of section 3.3). For these reasons they are increasingly being used to estimate pollution from emissions for cost-benefit analyses (Amann et al. 2011).

Chemical transport models (CTMs), on the other hand, are state-of-the-art modeling tools that can be used to estimate changes in air pollutant concentrations from changes in emissions. These computational models combine extensive emissions inventories with principles from atmospheric chemistry and meteorological factors to simulate how air pollution concentrations vary with emissions. The benefit of this approach is that it explicitly models the chemical reactions that create secondary pollutants and allows for a detailed simulation of pollutant concentrations over space and time; this is as opposed to source-receptor models, which offer static estimates. However, it can be difficult to validate CTM predictions;

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[11] *For a detailed examination of estimation approaches, see the World Bank and IMF's Carbon Pricing Assessment Tool (forthcoming).*

the models are sensitive to inputs, and running them may not be feasible for non-experts. Fortunately, in response to the last point, a number of transport modeling groups have developed user-friendly interfaces. Examples of CTMs include TM5-CTM, which is the full model that the FASST source-receptor model discussed above is based on.

In summary, source-receptor models offer easy-to-implement preliminary approximations for how changes in emissions will affect air quality. However, when more robust estimates of air quality changes are required, and the technical capacity is available, chemical transport models can be used to offer detailed estimates.

3.3.4 Estimating Responses to Changes in Air Quality

Once changes in pollution exposure have been estimated, the next step is to characterize how they impact health, agriculture, and labor. The overall approach is similar for all three categories. Distinct “dose-response curves” (also referred to as “dose-response functions”) that relate the outcomes of interest (i.e., health, agriculture, or labor output) to different pollution concentrations can be identified in the epidemiology literature. Combined with the pollution concentration changes estimated in the previous step, these provide estimates for the impacts of air quality improvements from a carbon price. The following sections describe how to quantify each of the three categories.

3.3.4.1. Health

Scientific understanding of air quality impacts on health has grown immensely in recent decades, and numerous estimated health response functions now exist for different health outcomes. These health dose-response functions relate health outcomes to different pollution exposures and are often measured in terms of relative risk. For each pollution concentration, relative risk (“RR” in the equation) dose-response functions indicate how much higher the risk of a health end point is for someone exposed to that pollution concentration compared to “low” levels of pollution.[12] Multiplying changes in risk by the baseline rate of the health outcome gives the change in rate, and multiplying the change in rate by the relevant population provides an estimate of the number of additional cases associated with the change in pollution:

$$\Delta\ cases = [change\ in\ risk] * baseline\ risk * population$$
$$= [RR(PM_{2.5}^{NEW}) - RR(PM_{2.5}^{OLD})] * base\ rate_{cases} * population$$

Replicating these steps with the relevant response curves and baseline data for different mortality and morbidity causes and for both particulate matter and ozone gives estimates of total avoided deaths and adverse health outcomes. The Global Burden of Disease (GBD) study provides a comprehensive estimate of mortality and disease rates for 195 countries and may be a useful starting point for policy makers undertaking this analysis (see box 3.2).

To do this analysis, policy makers need the following:

5. A relative risk curve that relates the health outcome of interest to the pollutant of interest across different pollution concentrations.
6. Data on the baseline risk for each health outcome of interest.
7. Data on the population for the relevant group (e.g., total population or a specific risk group, like the population over 65).

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[12] *The definition of “low” pollution is specified by the modeler.*

Box 3.2

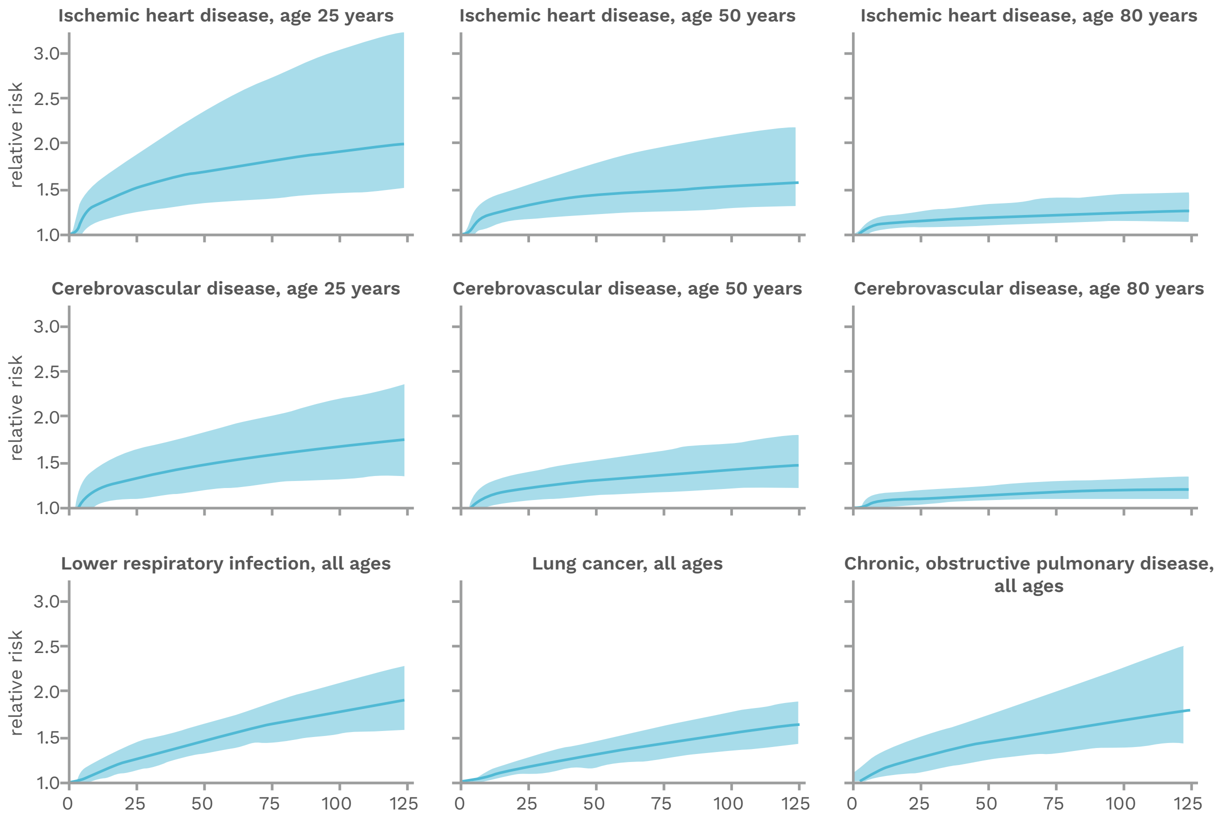
Data Sources for Estimating Premature Deaths from Pollution

The GBD study is the most comprehensive scientific effort to characterize health conditions and risks around the world. The most recent version, GBD 2019, uses a systematic methodology to estimate population, mortality, and disease rates for populations in 195 countries and territories. The project characterizes more than 250 diseases and injuries and more than 85 risk factors for 23 age groups.

Results for the most recent GBD study are available for download through a searchable database on their website (the GBD Results Tool, http://ghdx.healthdata.org/gbd-results-tool). All three data components (risk response curves, baseline health risk, and population data for relevant risk groups) are available for download at the GBD website for all 195 countries; see figure B3.2.1 for an example.

Figure B3.2.1

Sample Relative Risk Curves for Different Health End Points and Age Groups Generated from GBD Website



Source: GBD Results Tool, http://ghdx.healthdata.org/gbd-results-tool.

The risk of premature death from particulate matter is determined in part by the shape of these response curves, as well as the initial pollution levels and baseline rates of health. Pollution-health response curves are often found to flatten out at higher particulate matter concentrations, suggesting that after a certain point, the incremental harm of an additional unit of pollution is decreasing. This is intuitive. A person who goes from smoking 45 cigarettes per day to 41 per day is likely to experience less benefit from a four-cigarette reduction than someone who goes from smoking five cigarettes to smoking one. For constant baseline health conditions, a reduction in PM2.5 from lower initial concentrations may have a larger beneficial effect on health than the same reduction from a higher starting PM2.5 concentration. In the context of carbon pricing, this suggests that for a given change in pollution, countries with very high pollution levels may initially see smaller health gains than countries with moderately high pollution levels (if baseline health rates are similar).

A special case of morbidity costs that directly affects economic output is labor losses due to absenteeism and decreased productivity. These labor impacts can have far-reaching consequences in the economy. Reductions in these negative effects can be directly incorporated into CGE modeling by adjusting the labor supply in CGE models. Ostro (1987) provides a pollution-workday response function that can be used to estimate the number of missed workdays. The value of lost days can then be calculated by multiplying missed workdays by average wages. To assess losses in labor productivity, similar steps can be taken using the effect estimates from any of the studies highlighted in table 3.1. Lost hours worked can be valued by multiplying lost hours by the average wage rate.

3.3.4.2. Valuing Direct Health Benefits

The value for mortality risk per life is a concept that outlines the price people are willing to pay for a small reduction in mortality risk, scaled up to 100 percent risk (i.e., death). Because incomes vary across countries, the amount people are willing to pay to reduce mortality risk also varies. Therefore, values for mortality risk per life are often thought to vary with income. A common approach to estimating these values for different countries is to take the value in the United States (or an average across developed countries), and scale it by a function of the ratio of the country's incomes. Using World Bank income data, it is possible to use this approach to estimate values for other countries.[13] Once a value has been established, the number of avoided deaths times the value for mortality risk per life provides an estimate for the value of avoided deaths. Box 3.3 illustrates a sample calculation for Guatemala.

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[13] *For detailed explanation of value of statistical life calculations, see Narain and Sall (2016) and Robinson, Hammitt, and O'Keeffe (2019).*

Box 3.3

Calculating Income-Adjusted Value for Mortality Risk per Life for Individual Countries

The value for mortality risk per life for individual countries ($V_{country}$) can be estimated as a function of the value in OECD countries and the ratio of incomes raised to ε.

$$V_{country} = V_{OECD}\left(\frac{I_{country}}{I_{OECD}}\right)^{\varepsilon}$$

The term ε measures the percentage change in mortality value per 1 percent change in real per capita income, and the exact value is uncertain. Following Parry et al. (2014), we use a value of 0.8 for this example calculation. Taking the example of Guatemala, which has income at approximately 1/15 the level of the average OECD country (i.e., $4.4 million), we estimate the following equation to derive the value for mortality risk per individual at $504,000.

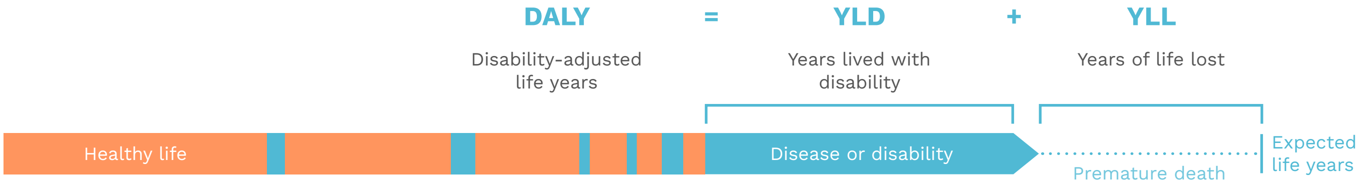
$$V_{Guatemala} = 4.4M\left(\frac{1}{15}\right) = \$504{,}000$$

Source: World Bank calculations based on Parry et al. (2014).

One of the challenges of incorporating quantitative estimates of morbidity burdens is that morbidity, unlike mortality, does not represent a one-time cost. Morbidity costs can be ongoing for many years until the person is either cured or passes away. In order to account for this dynamic, the concept of DALYs jointly characterizes the number of years a person lives with a disability or disease and the number of years lost to premature death (figure 3.10).

Figure 3.10

Characterization of Morbidity Measures



Source: World Bank.

DALYs provide a more comprehensive measure of health damages than number of premature deaths because they also capture morbidity effects, and have thus become a commonly applied metric. DALY-specific response curves can be used to estimate the number of avoided DALYs associated with a given change in pollution, and DALYs can be valued at a fraction of the value of mortality risk per life.

3.3.4.3. Agricultural Impacts

In order to estimate agricultural impacts for a given change in pollution, crop-yield response curves can be applied to pollution concentrations in a manner analogous to the health approach described previously. As with health, there are multiple estimate yield response curves that could be used to estimate agricultural benefits. For example, Burney and Ramanathan (2014) estimated a response curve for wheat and rice using Indian data. In addition, Avnery et al. (2011) estimated pollution-yields response curves for maize and soybeans using global data. These or similar studies can be applied to observed changes in pollution to estimate the crop yield change associated with a change in pollution. Yield changes can be converted to value by multiplying implied production by average crop prices.

3.3.5 Summarizing Direct Impacts

The total direct benefit of improved air quality is the sum of the values of avoided losses related to mortality, morbidities (including labor productivity), and crop yields. This calculation does not fully capture the extent of all the direct benefits, as these metrics omit potentially large impacts from other benefits mentioned in this chapter that are more difficult to quantify, most notably long-run loss of human capital due to inhibited cognitive development. The subset of benefits quantified here should therefore be considered a lower bound on total direct benefits. Nonetheless, due to the sheer magnitude of these impacts, even a lower-bound estimate of direct air quality benefits will more than outweigh the total costs incurred from a carbon price (Markyanda et al. 2018).

3.4 Indirect Impacts

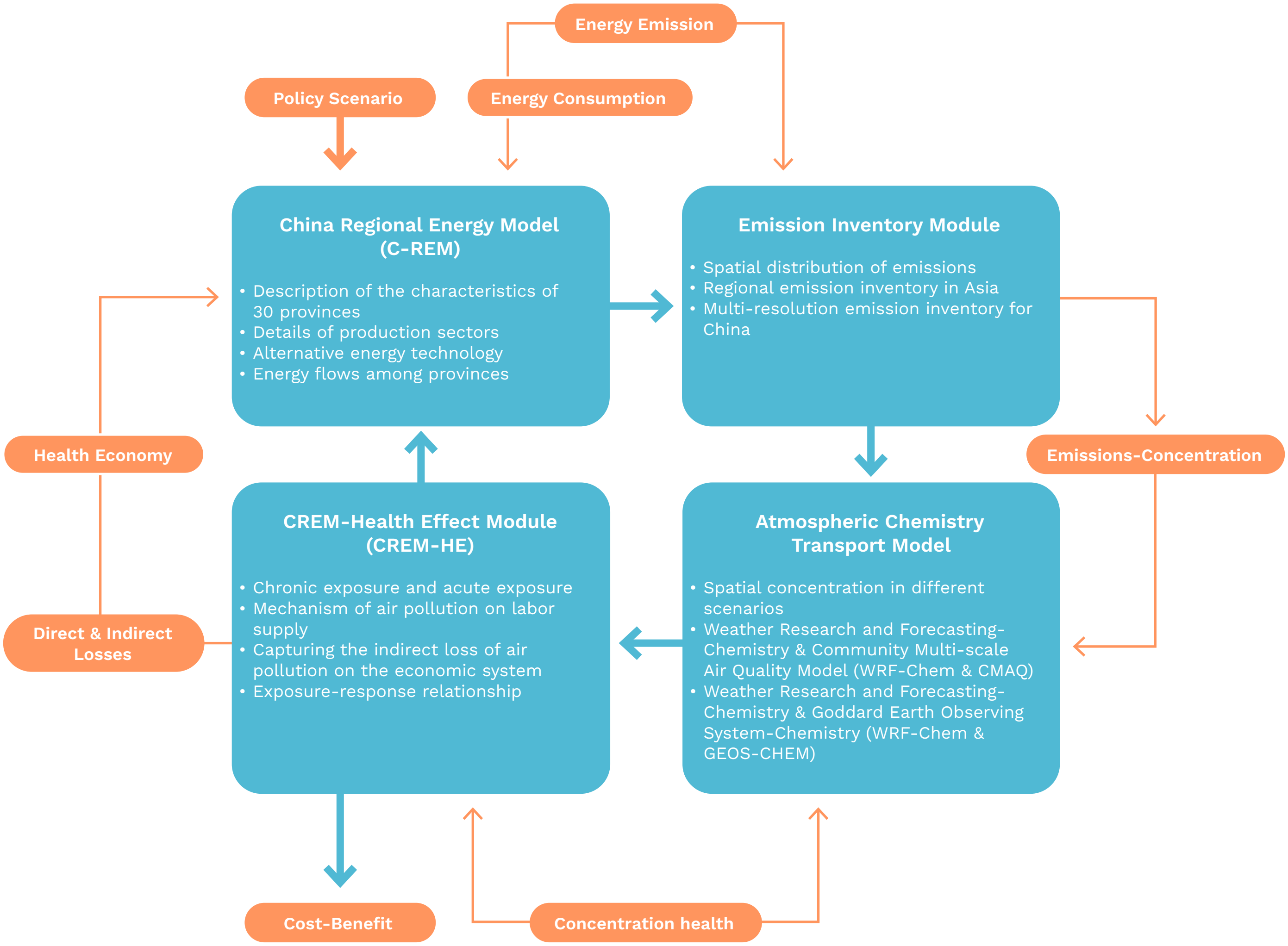
Air quality improvements from a carbon price will have indirect impacts across the economy. Estimation of direct benefits from improved air quality discussed in section 3.3 reflects a static approach that negates cumulative dimensions of economic damage. For example, wages lost to pollution in one period may reduce capital inputs available in future periods. Improved air quality may also reduce demand for health care services in future periods. In order to capture these dynamic effects, CGE models can be integrated into the estimation framework by feeding the direct effects into a dynamic modeling framework.

Early work in this area (Beghin et al. 2002a, 2002b) used national average health data on respiratory conditions without reference to individual pollutants, estimating “elasticities” with respect to historical criteria pollutant emissions. This approach yielded useful indicative estimates of the potential economic benefits from carbon pricing and other emission mitigation strategies, but at the time, alternative technologies were relatively expensive and health/mortality costs relatively low.

More recently, CGE models have been combined with health response estimation procedures, analogous to those described in section 3.2.2, to create a single unified framework for modeling indirect health benefits from improved air quality (Zhang et al. 2017). Hoekstra and Chapagain (2007) show an example of how a combined framework can function by modeling dynamic feedbacks between energy policy, emissions, pollution, health, and the economy. This type of framework has been used, for example, to incorporate health benefits into estimation of the costs and benefits of different designs for China’s emissions trading system scheme (Chang et al. 2020).

Figure 3.11

Incorporating Health Benefits into a CGE Modeling Framework



Source: Adapted from Zhang et al. (2017).

The framework developed by Zhang et al. (2017) utilizes four separate modeling components: (1) emissions inventories, (2) atmospheric chemistry transport modeling, (3) health effect evaluation, and (4) a CGE model of the economy (including the energy system). The first modeling steps, from policy to changes in air quality, are closely aligned with the steps of estimating direct benefits described in section 3.14. However, instead of simply using response functions to estimate direct health benefits, this approach incorporates changes in air quality and corresponding health responses into the dynamic modeling framework.

In order to incorporate pollution health effects into the CGE modeling component of their framework, Zhang et al. (2017) build on earlier work by

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14 For details on exactly how these estimations are carried out for China, see Zhang et al. (2016) and Zhang et al. (2013), in addition to Zhang et al. (2017).

Nam et al. (2010) and restructure the conventional social accounting matrix (SAM) to include a household service sector dedicated to mitigating pollution-health effects.[15] Figure 3.12 shows this restructured SAM with nonstandard components highlighted in italics. As household services draw on more labor and service inputs from other sectors, increased output of the household services sector comes at the expense of reduced output in other sectors. In addition to direct losses (i.e., medical expenditures and lost wages), these distortions in resource allocation cause inefficiencies in the economy. Labor losses from mortalities are subtracted from the available pool of labor, while labor losses from morbidities are modeled as increasing demand for household services. Morbidities and mortalities also cause loss of leisure, which does not directly enter production functions. Instead, leisure is treated as a potential labor input valued equal to wages. Within this framework, changes in air quality can be modeled as economic shocks while capturing both direct costs from pollution to the economy (i.e., labor and leisure loss and medical expenditures) and indirect costs (i.e., efficiency loss from distorted resource allocation).

Figure 3.12

Social Accounting Matrix Extended to Include Health Effects from Pollution

		INTERMEDIATE USE						HOUSEHOLD SERVICES		FINAL USE				OUTPUT
		1	2	…	f	…	n	Mitigation of Pollution Health Effects	Labor Leisure Choice	Consumption	Investment	Government Purchase	Net Export	
DOMESTIC PRODUCTION	1													
	2													
	…													
	f													
	…													
	Medical Services for Health Pollution							Medical Services		Health Services				
	n													
IMPORTS	1													
	2													
	…													
	f													
	…													
	n													
LEISURE									Leisure	Leisure				
VALUE ADDED	Labor							Labor	Labor					
	Capital													
	Indirect Taxes													
	Resources													
INPUT														

Source: *Nam et al. (2010).*
Note: *Nonstandard components are labeled in italics.*

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[15] *See Nam et al. (2010) and Zhang et al. (2017) for more details on how SAMs can be adapted to account for health effects from pollution through the inclusion of a household service sector.*

This type of framework is well suited to estimate total health benefits associated with short- to medium-run pollution exposures. As currently designed, this framework does not capture the types of long-run impacts on human capital accumulation (discussed above) that can result from children being exposed to pollution in utero or at young ages and the resulting drag on future labor market outcomes. Nonetheless it provides a relatively comprehensive approach to characterizing health benefits from air quality. The Zhang et al. (2017) framework also does not capture agricultural benefits. In order to model air quality effects on agricultural production, total output in the agricultural sector can be linked to pollution levels in the way that health is linked to pollution in the Zhang et al. framework. This relationship can be parameterized according to the estimation framework and existing literature discussed in section 3.3.4.3 so that as pollution levels change, output (and in turn prices) in the agricultural sector change too.

Incorporating air quality benefits into CGE models is still a relatively new area of research. Recent work illustrating frameworks that can be used to capture these dynamics provides a useful path forward as methodological innovations continue to improve our understanding of the full range of benefits from improved air quality.

Table 3.3 provides an overview of the key steps in quantifying the direct and indirect benefits of a carbon price for air quality.

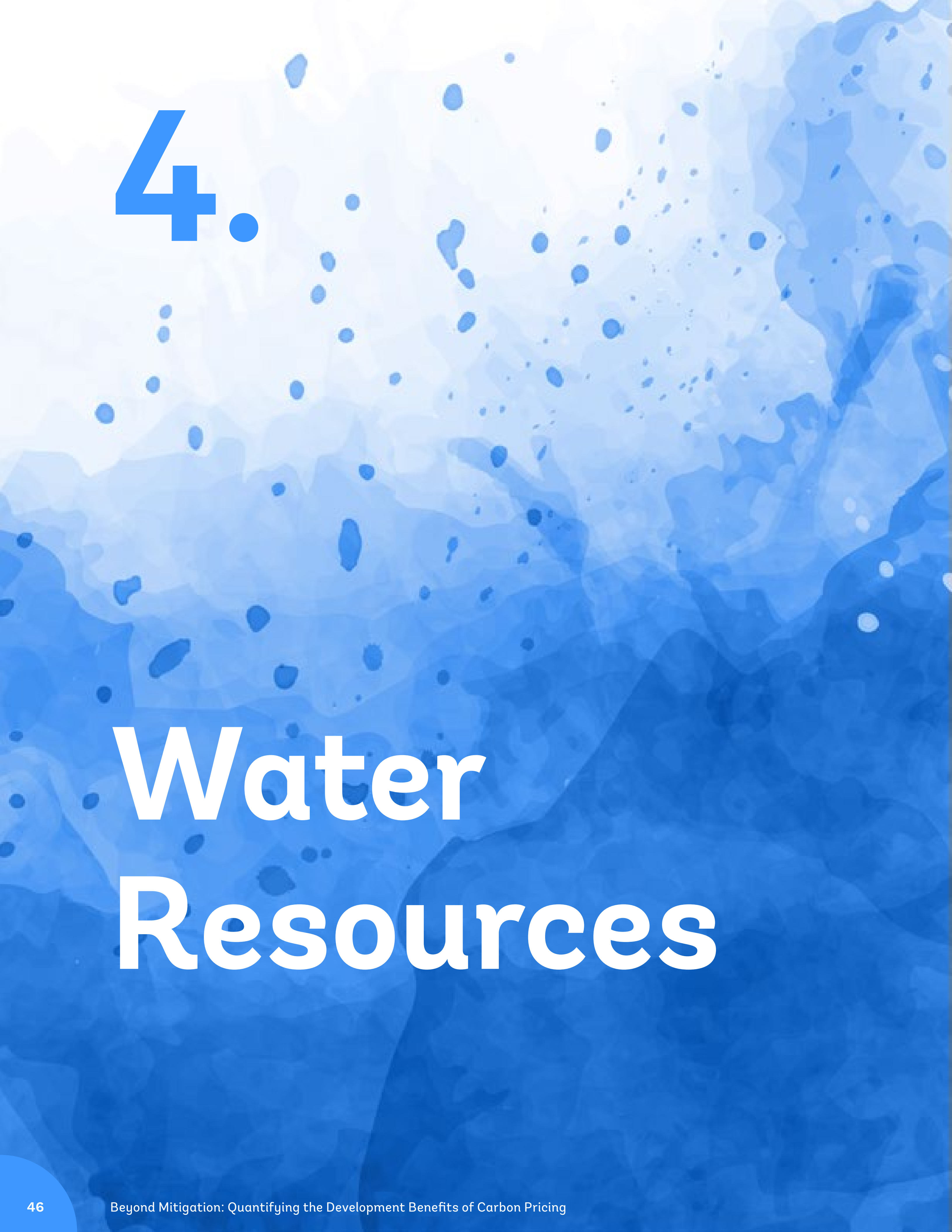
Table 3.3

Quantifying the Effects of a Carbon Price on Air Quality (Health and Agricultural Impacts)

	Step	Notes
1	Estimate the impact of a carbon price on fuel consumption	• Short- and long-run fuel-specific elasticities of demand (ideally, local estimates) should be applied for each fuel subject to analysis. • The change in fuel consumption from a carbon price = price elasticity of demand for each fuel x percentage change in price for that fuel. • Where available: power sector and district heating models can give an indication of which fuels are used for power and heating respectively. • Where available: country-specific urban-transport-environment models can offer a more nuanced approach to the air pollution from vehicles.
2	Estimate impact on greenhouse gas emissions	• Reductions can be modeled using emissions factors, which vary by fuel and emissions type. • Emissions reduction volume = volume of fuel consumption x emissions factor.
3	Estimate change in air pollution concentrations	• Prevailing air pollution concentration should be established. • Source-receptor modeling or chemical transport modeling can translate GHG emissions to average air pollution levels. Source-receptor models offer easy preliminary approximations of air quality changes, but chemical transport modeling offers more robust, detailed, and dynamic estimates.

	Step	Notes
4	Estimate direct health effects	• Relative risk dose-response functions should be applied to identified mortality and morbidity causes. • Changes in number of specific mortality or morbidity cases = (change in risk as a result of lower air pollution levels) x baseline risk x population. • The GBD study provides comprehensive mortality and disease rates for 195 countries. • Population can be divided into relevant groups (e.g., a specific risk group, like the population under 10 or over 65).
5	Estimate direct agricultural effects	• Crop-yield response curves can be applied to pollution concentrations (similar to steps 1–4).
6	Estimate the economic value of health and agricultural effects	A financial value should be established for each unit of health effect. For instance: • Value of a statistical life (premature mortality): value in the United States (or average across developed countries) and scaled by a function of the ratio of the specific country's income • Disability-adjusted life years: a more comprehensive measure of health damages that captures morbidity effects • Reductions in the negative effects on economic output due to reduced absenteeism or increased productivity with better air quality (can be directly incorporated into CGE modeling by adjusting the labor supply in CGE models) • Lost hours worked = lost hours x average wage rate • Agricultural yield value = implied production x average crop price(s) • Note: The sum of these benefits should be considered a lower bound on total benefits due to difficulties in characterizing other benefits.
7	Estimate indirect effects	• CGE models can be combined with health response estimation procedures to model indirect health benefits. • Pollution health effects can be incorporated by restructuring the social accounting matrix to include a household service sector dedicated to mitigating pollution-health effects. • Changes in air quality can be modeled as economic shocks to capture both direct costs (e.g., changes in labor, leisure, and medical expenses) and indirect costs (e.g., changes in resource allocation).

Source: World Bank.



4.

Water Resources

At a Glance

Water resource benefits

- Many regions of the world are affected by water scarcity and by threats to water quality and water resource sustainability.
- Water resources are deeply intertwined with energy systems, particularly in energy extraction, transport, and generation. Equally, energy is needed to treat and deliver water. Thus, a carbon price, in shifting away from fossil fuel–based energy use, can have a pervasive impact on water resources.
- Water sector benefits of carbon pricing include improvements in both the quantity and quality of water resources.
- A carbon price can improve water resources by reducing the overexploitation of groundwater resources, changing water end-use demands, and reducing water contamination.
- Improving water quality can promote positive health outcomes, improve agricultural productivity, and improve water availability.

Quantifying water resource benefits

- Modeling strategies for estimating the magnitude of benefits include partial equilibrium approaches and CGE modeling for capturing indirect effects of intersectoral linkages.

4. Water Resources

4.1 Introduction

Water resources are fundamental to human well-being and economic productivity. Access to clean water is essential for basic human needs, such as a secure food supply and living environments free from disease. Water problems generally fall into one of three areas: water scarcity, water quality, and excessive water (e.g., flooding). In addition, water is a key input to a wide variety of modes of production and is a critical factor in economic development. Agricultural production, industrial activity, energy systems, and other sectors are highly dependent on the availability of water resources. Healthy water systems are also central to healthy ecosystems, supporting biodiversity and enabling ecosystem services.[16] Many regions of the world are affected by water resource scarcity and threats to water quality, and these threats will only increase with growing populations (especially in urban areas), higher standards of living, and a changing climate.

Water scarcity can hinder economic growth, lead to adverse health outcomes, and potentially be a causal factor in migration and civil conflict (World Bank 2016). Contamination of water resources resulting from human activity can also have adverse effects on human health through direct consumption and other exposure. In addition, poor water quality adversely affects soil health through irrigation, adversely impacts biodiversity, and may reduce freshwater availability. Excessive water, or flooding events, can be exacerbated by climate change; and to the extent that a carbon price can help mitigate climate change, the risk of floods may also be reduced. However, given its somewhat peripheral connection to a carbon price, this link is not examined in this chapter.

Water resources are deeply interconnected with energy systems, with a significant amount of water used for energy extraction, transport, and generation. In fact, end uses in the energy sector account for approximately 10 percent of freshwater resource withdrawals globally (United Nations Educational, Scientific and Cultural Organization [2020]). In addition, energy is a key input to the extraction, transportation, and treatment of water resources. The complex linkages that exist between water and energy resources, known as the "water-energy nexus," have been the subject of considerable research in recent years (see Water in the West [2013] for details). This nexus means that climate policy will have pervasive impacts on the water sector, including both direct impacts, such as altered water use, and indirect impacts, such as changes in sectoral competitiveness.[17]

In this chapter we discuss the primary challenges presented by water scarcity, water quality, and the water-energy nexus, as well as the potential benefits of carbon pricing to help address these issues. We then present key considerations for quantifying and modeling water sector benefits of carbon pricing.

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[16] *Daily (1997) defines "ecosystem services" as "the conditions and processes through which natural ecosystems, and the species that make them up, sustain and fulfill human life... In addition to the production of goods, ecosystem services are the actual life-support functions, such as cleansing, recycling, and renewal, and ... intangible aesthetic and cultural benefits."*

[17] *For instance, water-intensive industries, where water usage is also energy-intensive, will experience greater increase in costs of production than industries that are less water- and energy-intensive, thereby altering the relative competitiveness of the industries.*

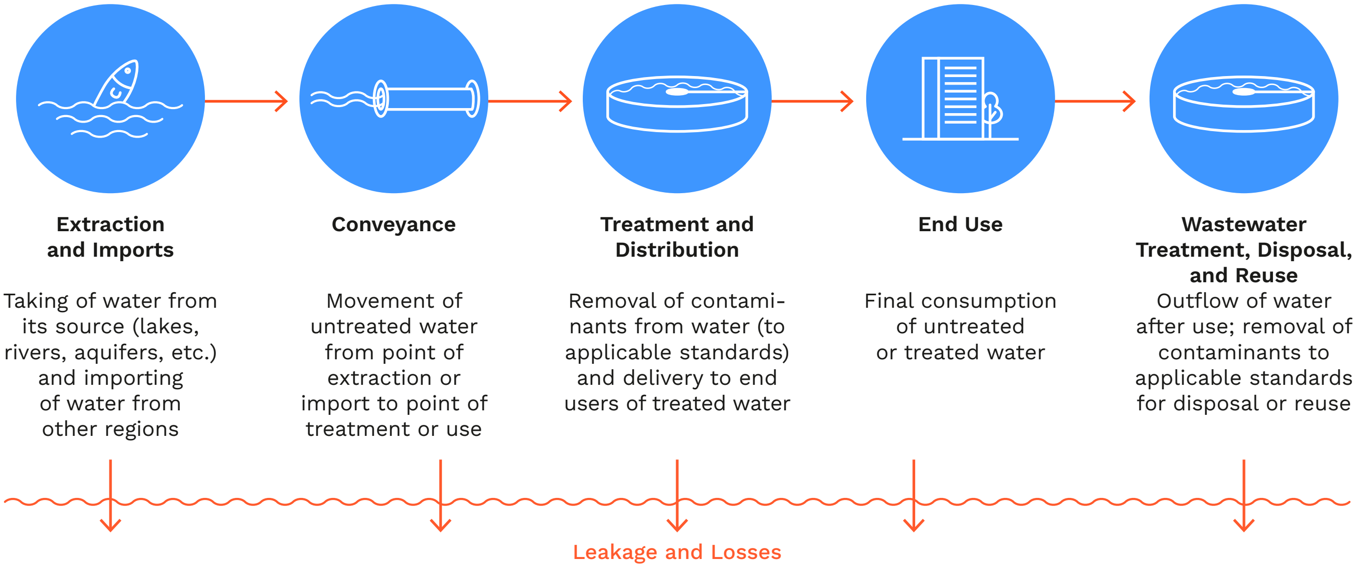
4.2 Identifying Benefits and Linkage to Carbon Prices

Implementing national climate policy can have a substantial impact on both the availability of water and its quality. Due to the macrostructural changes induced by carbon pricing, demand for water and water use patterns may change throughout the economy. In addition, certain processes that pose risks to water quality are also likely to be impacted, in many cases resulting in water quality improvements. A country (or other region under consideration) may achieve a net water benefit through reduced stress on water resources and improved water quality. In this section, we examine the linkages between water resources and climate policy. We present a systematic view of national water resources, discuss specific benefit linkage mechanisms in terms of water quantity and water quality, and finally provide notes on measuring and modeling these benefits.

4.2.1 A Systematic Approach to Water Resource Assessment

The first step is to have a clear view of national water resources, which can be broken down into five primary components (listed below) plus a category for leakages and other losses. Based on these, policy makers then need to identify how these resources and their use will interact with the carbon pricing policy under consideration, and finally estimate impacts relative to a business-as-usual case. A comprehensive assessment of impacts will include both direct and indirect effects. The five components of a national or regional water system are (1) extraction and imports; (2) conveyance; (3) treatment and distribution; (4) end use; and (5) wastewater treatment, disposal, and reuse (Roland-Holst and Sancho 1995). Decomposing the water sector is important for benefit modeling, as each component may be affected differently by carbon pricing. Components may also interact with one another, and those relationships should also be considered.

Figure 4.1
National Water System Components



Source: World Bank.
Note: Though presented linearly, these components are interrelated, with end use also connected to extraction, for instance.

Available water resources are fundamental to the understanding of water scarcity in a given region. Natural mean annual runoff (MAR), measured in million cubic meters per year, is a measure of total national or regional water resources. Of this amount, only some proportion will be available as reliable yield. Finally, due to evaporation and geographic variation of rainfall and water demand, some fraction of this amount will be available as economic development potential.[18] Box 4.1 describes national water resources in South Africa as an example.

Box 4.1

Water Resources in South Africa

In South Africa, the MAR is about 49,000 million m^3 per year; of this total, 27 percent is considered reliable yield, or stable water supply across years. Evaporation, variability in geography, and other factors result in only 11 percent remaining as economic development potential. Thus, per capita water MAR is approximately 1,060 m^3 per year, with 300 m^3 per capita as reliable yield on an annual basis (UNESCO 2006). The per capita MAR of South Africa is relatively low compared to global averages; globally, estimated average potential water availability is 7,600 m^3 (Shiklomanov 2000).

Of the available water resources in the country, 77 percent is surface water, 9 percent is groundwater, and 14 percent is secondary use of return flows. Due to low levels of seasonal rainfall, South Africa is dependent upon neighboring Lesotho for imports that amount to 25 percent of its total water supply. In South Africa, irrigation accounts for less than 30 percent of water used in agriculture, while rainfall accounts for more than 70 percent. Agriculture is the primary demand sector for water in the country (8.4 billion m^3), followed by the urban sector (6.0 billion m^3), and industrial sector (3.3 billion m^3) (McKinsey 2010; UNESCO 2006).

With demand for water increasing in the country, a disequilibrium between water demand and supply, resulting in water scarcity, is expected in the future. Demand is forecasted to increase to more than 17 billion m^3 by 2030, but the water supply will be only approximately 15 billion m^3 (McKinsey 2010).

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[18] The AQUASTAT core database of the Food and Agriculture Organization of the United Nations (http://www.fao.org/aquastat/) provides national and regional water resource availability statistics.

4.2.2 Water Quantity Benefits

The primary forces driving greater water resource demand are increasing population, rising standards of living, and increased consumption–all of which are especially at play in urban and urbanizing areas. The expansion of irrigated agriculture increases water demand as well (along with energy demand). As of 2012, irrigated agriculture was the world's largest source of water demand, accounting for 70 percent of groundwater withdrawals globally and 85 percent in developing countries (International Energy Agency 2016). Recent research has found that seasonal fluctuations in water consumption and availability exacerbate scarcity conditions. A 2016 study found that two-thirds of the global population–4 billion people–live under severe water scarcity conditions during at least one month of the year on an annual basis, with half a billion living under severe scarcity all year round (Mekonnen and Hoekstra 2016). This is almost double the estimates of previous studies,[19] and the number will only increase as climate change intensifies challenges in water-constrained regions. Extreme water events like floods and droughts are also becoming more severe and more frequent (UNESCO 2020). Overall, increasing water use can put a strain on the resilience of water systems (i.e., their ability to absorb and adapt to change), particularly in urban areas.

Limited water availability is expected to be a significant constraint on economic development in the future. A World Bank (2016) study estimated that under a business-as-usual scenario, growth rates in certain regions will fall by up to 6 percent of GDP by 2050 due to water scarcity, though the impacts of water scarcity are highly varied across different regions of the world.

Water is a critical factor of production, and it has been estimated that industry (including the energy sector) accounts for approximately 19 percent of freshwater resource withdrawal globally. In addition, the share of water use by industry is projected to increase to 24 percent by 2050 (UNESCO 2020).

A carbon pricing benefit analysis of water quantity investigates the mechanisms by which a carbon policy affects water supply and demand throughout the economy and estimates the change in water usage that can be attributed to a carbon price. There can be a wide range of water quantity benefits, though the main one is the potential to increase water availability. These benefits can be systematically categorized based on the five components previously outlined.

This guide focuses on two components likely to yield benefits: water extraction and end use. We emphasize these benefit pathways because existing research suggests that they are likely to be substantially impacted by the implementation of carbon pricing. The reader should bear in mind that the other water sector components will be affected as well; water conveyance, for instance, could see water and energy efficiency increases as a result of the carbon price. The examples in this guide should not be considered as an exhaustive set of linkages for a particular setting. Every region or country will have unique circumstances and conditions, and appropriate linkages specific to the region of interest should be defined.[20]

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[19] *Studies conducted between 2000 and 2012 estimated between 1.5 billion and 3.1 billion people; see Vörösmarty et al. (2000), Oki et al. (2001), Oki and Kanae (2006), Wada et al. (2011), and Hoekstra et al. (2012), among others.*

[20] *We refer readers to* Water in the West *(2013) as a resource that clarifies the complex linkages between energy and water in the economy and identifies additional linkages that may exist in specific settings.*

4.2.2.1. Water Quantity Benefit Linkage: Extraction

Water extraction refers to the intake of a water source into a specific water system. The composition of water resources varies greatly across countries, as does water availability. Lakes, rivers, and streams are important sources of water in many regions. Groundwater aquifers also often play an important role in national water supply, and in recent years groundwater extraction has rapidly intensified. In fact, 40 percent of all irrigated land relies on groundwater resources, and groundwater extraction is the primary form of irrigation in many countries, including India and China (Zilberman et al. 2008). This process has allowed increases in agricultural productivity and resulted in rising incomes in many rural communities; however, in many regions pumping has exceeded the aquifer recharge rate, leading to declines in water tables and eventual depletion of these water resources. This is a condition referred to as groundwater overdraft. In the Middle East, North Africa, South Asia, and western North America, this issue is particularly acute (Scott 2011). Box 4.2 provides some details on how ground water extraction is affecting future water supply in India.

Box 4.2

Groundwater Use and Scarcity in India

India accounts for 18 percent of worldwide population, but is host to only 4 percent of global water resources. Water scarcity is prevalent in many regions of the country (World Bank 2019a). India is the world's largest user of groundwater resources: it extracts approximately 230 billion m³ per year, accounting for over a quarter of the worldwide total. Groundwater resources are leveraged for over 60 percent of all irrigated agriculture in the country, while 85 percent of drinking water depends on these resources. Under current practices, an estimated 60 percent of groundwater aquifers in India may be in critical condition before 2032 (World Bank 2012).

Increase in groundwater use in India has been driven by four main factors: poor public water delivery systems leading private actors to seek their own water supply, cheaper pump technologies reducing the capital cost of pumping, flexibility of self-extraction compared to less responsive supply by official channels, and electricity subsidies that reduce the marginal cost of private pumping (World Bank 2010). The World Bank (2010) provides an extensive study on the causes and consequences of groundwater overexploitation in India.

In rural areas, electric or diesel pumps are often used to extract groundwater for irrigation and other purposes. Increasing the cost of power generation through a carbon price could lead to less groundwater extraction. In regions with groundwater overdraft challenges, lower equilibrium levels of extraction will result in a benefit of increased sustainability of groundwater resources. Note that higher prices may also lead to increased adoption of renewable-powered pumping. This would have the opposite effect; with near-zero marginal cost, solar and other renewable-powered pumping would lead to increased groundwater extraction. In the case of groundwater extraction, then, the extent to which a carbon price will lead to reductions depends on the availability of cost-comparable low-carbon pump alternatives. From a mitigation perspective, the substitution of fossil fuel–powered diesel pumps with low-carbon alternatives is desirable. But in these cases, additional policies may be required to disincentivize groundwater pumping.

The magnitude of the effect will depend on the price elasticity of demand for pumping energy, in addition to other factors like water scarcity, agricultural practices, and market structures. Reduced aquifer depletion may be an additional benefit of carbon pricing in a variety of regional settings.

4.2.2.2. Water Quantity Benefit Linkage: End Use

Water sector end use refers to the final consumption or usage of extracted and delivered raw or treated water. End-use sectors include the agricultural sector, the power generation sector, the industrial sector, the commercial sector, and the residential sector. Across these sectors, carbon pricing will have different impacts on water-consuming activities. For instance, fossil fuel–based electricity generation and certain heavy industries such as steel production have significant water input requirements. With generation becoming more expensive as a result of the carbon price and the cost of heavy industry goods increasing in turn, production might decrease, which might result in lower water demand. A carbon price might also drive energy-saving or efficiency measures, which would also reduce the demand on water supplies. A decrease in production would free up more water resources and reduce issues of water scarcity. Switching to a lower-carbon power source could increase or decrease water usage depending on the technology type. Solar and wind use considerably less water than fossil–fuel based generation; however, the case is less clear for hydropower or geothermal. The relative water use of these substitutes will have to be factored into any water resource benefit analysis to get a more accurate picture of the changes as a result of the carbon price. The International Energy Agency's (2016) World Energy Outlook provides a more thorough examination of the water use of different types of electricity generation and energy production.

A carbon price might also have a similar effect on water use in the agricultural sector, which is water-intensive and sensitive to energy input price changes. However, carbon pricing may also incentivize the shift to different crops or changes in the production process (e.g., shifts from carbon-based fertilizers to organic fertilizers). These shifts may result in lower or higher water demand, and more complicated general equilibrium modeling techniques will be required to capture these dynamic effects. We give an overview of such methods applied to the water sector later in this chapter.

In addition, relative changes in food commodity prices are likely to incentivize shifts in consumer food preferences. If energy inputs increase in price, agricultural products that are relatively energy-intensive will increase in price, while the price of less energy-intensive products such as grains would become more competitive. These changes would lead to changes in agricultural production and consumer quantity demands. Changes in crop production decisions will change agricultural water demand because different crops have different water requirements.

Various studies have examined links between upstream cost input changes and retail food commodity prices and the response of consumers and farmers to these changes (Abbott and Battisti 2011; Food and Agriculture Organization of the United Nations [FAO] 2009). Alexander et al. (2016) find that the Indian diet requires approximately half the agricultural land of the world average, while a US diet requires nearly double. This difference is largely due to the US diet's much higher proportion of animal products–and ruminant species in particular–relative to the Indian diet. However, the authors note that food waste and overconsumption in the US are also contributing factors. The study estimates that if the entire world were to adopt the equivalent of an Indian diet, 55 percent less agricultural land would be required to meet food demand. Shifts in agriculture production have the potential for large impacts on water, energy, and land use.

4.2.3 Water Quality Benefits

Diminished water quality is associated with a variety of risks. The main risks relate to adverse health outcomes (from consumption or other uses of water) and adverse soil health and agricultural productivity. Damania et al. (2019) found that poor water quality may eliminate as much as one-third of economic growth potential in the most polluted regions. Carbon pricing and water quality are not directly linked, but a variety of indirect channels allow the carbon price policies to promote more sustainable, higher-quality supplies of fresh water. Because most water supply and use require energy inputs (extraction and conveyance), carbon pricing will promote use efficiency. By reducing water inputs to activities and processes that contaminate water (sewage, agrochemicals, industrial effluent), carbon prices protect this essential renewable resource. For instance, as discussed in the chapter on soil health, a carbon price can disincentivize fossil fuel–based fertilizers, which could have broader implications for the use of chemicals and contaminants in water resources. However, carbon prices also increase the cost of water treatment, though if treatment services price this cost accurately, carbon prices could further discourage water-intensive use technologies.

The United Nations Environment Programme (UNEP 2018) has developed guidelines for measuring and monitoring key threats to water quality in rivers, lakes, and groundwater, based on the following categories:

- **Oxygen:** The dissolved oxygen present in a body of water is measured by biological oxygen demand and chemical oxygen demand. Dissolved oxygen is naturally occurring and important for aquatic organisms. Very low concentrations are associated with the presence of foreign organic matter such as sewage.

- **Salinity:** The salinity of a water body can be characterized by electrical conductivity, a measure of dissolved substances. Measures that deviate from normal ranges can imply the presence of pollution.

- **Nitrogen:** Nitrogen is often measured by total oxidized nitrogen, a composite measure of nitrate and nitrite. Although essential for aquatic organisms, higher levels can have adverse effects on water resources.

- **Phosphorous:** Orthophosphate (OP) concentrations are an indicator of phosphorus levels in water. OP is a dissolved inorganic form of phosphorous that is naturally occurring, but at higher than normal levels it can be detrimental to aquatic ecosystems.

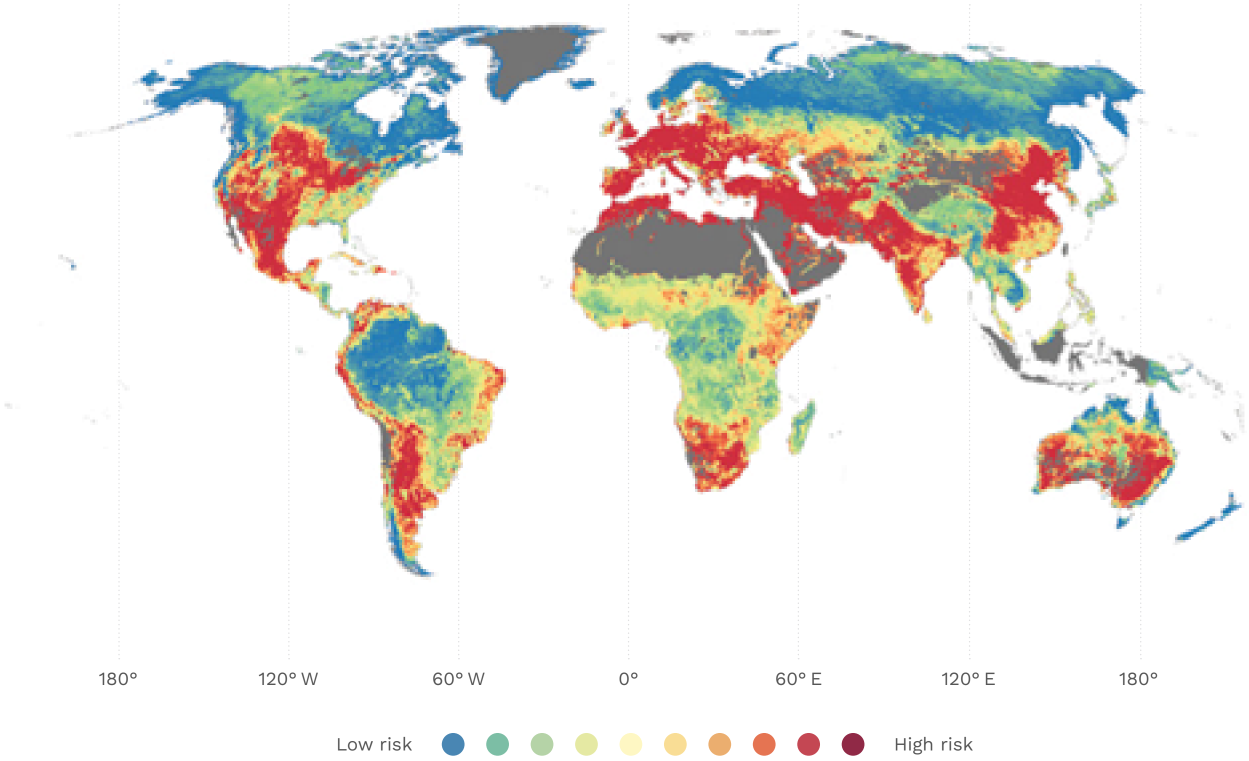
- **Acidification:** Measured by pH level, acidity is an important and widely used measure of water quality. The pH level is a measure of hydrogen ion activity in water, which can fluctuate outside of normal ranges due to certain sources of pollution.

The relative importance of the above parameters will vary based on national circumstances. Biological oxygen demand, nitrogen, and salinity are primary factors affecting river and lake health, while nitrogen and electrical conductivity are of key importance for groundwater. Other factors may also be considered. For instance, if water is used for human consumption, the presence of heavy metals would be a metric of concern. Equally, the risk of contamination as a result of runoff, such as from pesticides or mining activities, may also be factored in when assessing water quality. As a carbon price is likely to affect energy-intensive activities like heavy industry and agriculture, such concerns could also be taken into account. The UNEP (2018) provides more details on establishing a national indicator of water quality.

Figure 4.2 below displays a water quality index indicating risk levels associated with water quality. The threats to water quality are highly differentiated around the world, and each country faces unique challenges in addressing its risks.

Figure 4.2

Water Quality Risk for Biological Oxygen Demand, Nitrogen, and Electrical Conductivity



Source: Damania et al. (2019).

To assess the water quality benefits of carbon policy, linkages must be defined that connect the policy to water quality in the country. Water quality metrics may include the level of contamination of lakes, rivers, aquifers, and other sources of water for the water system. This contamination in turn degrades the quality of water being supplied to on-site or off-site users of raw water, or water being treated and supplied to users of treated water. Degraded water quality can also increase the cost of water treatment. Contamination can occur as a result of agrochemical runoff in the agricultural sector (see section 5.2.3 in the next chapter) or as a result of mining and other energy-intensive activities. For instance, effluent containing high levels of fertilizers and pesticides could run on from agriculture or soil erosion and degrade the quality of waterways. Mining not only has the same runoff risks but also poses the risk of spills near water sources, as well as the risk of groundwater or surface water contamination from mine tailings. Because agriculture, mining, and other energy-intensive activities are heavy users of fossil fuel inputs, carbon pricing may lead to lower outputs, thereby improving water quality outcomes. Depending on the substitute, there could also be further water quality improvements.

In summary, the water quality benefits of carbon pricing discussed in this guide include (1) reduced negative human health externalities arising from contaminated water, (2) improved agricultural productivity arising from reduced water resource contamination and resulting soil contamination, and (3) improved water availability with reduced freshwater resource contamination. Although these are expected to be primary water quality benefits of carbon pricing, this list is not exhaustive. Improved water quality may also lead to benefits related to improved biodiversity, improved human recreation possibilities, and other positive effects. Researchers must decide which benefits should be included for a particular region under study, and for which benefits reliable metrics can be constructed.

4.2.4 Water Valuation Methods

In order to quantify the benefits of carbon pricing due to water quantity for cost-benefit analysis, it is necessary to attach monetary value to changes in water quality and quantity across scenarios, and UNESCO (2006) provides guidance on water valuation based on different agents. In general, water valuation in the policy-making context focuses on incremental gains and losses and assignment of the appropriate value, taking into account the complexities of benefits accrued, opportunity cost, and externalities. The value of water quantity benefits will also vary across countries and regions depending on the risk factors. Reig, Shiao, and Gassert (2013) list various dimensions across which water quantity risk may be assessed, such as seasonal variability.

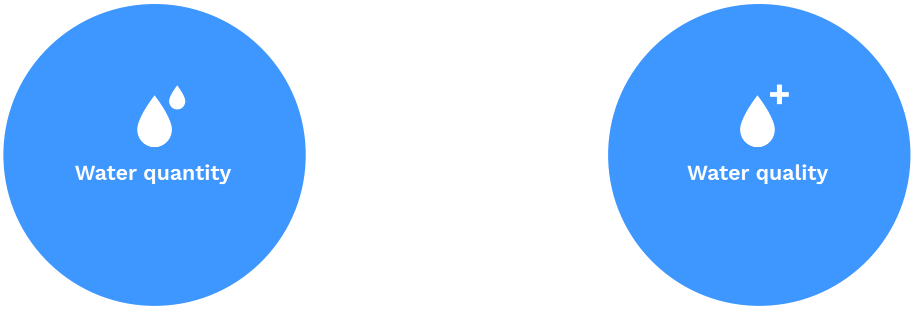
Young (2005) provides an authoritative overview of water valuation methods that are used in the policy-making context. A complete overview and description of potential water valuation methods is outside the scope of this guide, and we refer readers to this and other resources on the topic (for example, Birol, Karousakis, and Koundouri 2006; Kremer et al. 2011; Van Houtven, Powers, and Pattanayak 2007) so they can assess the benefits and weaknesses of differing water valuation methods in specific national contexts.

4.2.5 Water Quantity and Quality Benefit Metrics

In order to quantify the benefits of carbon pricing in the water sector, metrics should be defined to measure the magnitude of benefits accrued. Some key metrics by which water quantity and quality benefits may be measured are outlined in figure 4.3.

Figure 4.3

Metrics for Assessment of Water Sector Benefits



- Water scarcity risk
- Water resource depletion
- Agricultural output changes
- Producer surplus changes
- Consumer surplus changes
- Net costs of water provision
- Other indirect effects

- Water resource degradation
- Loss of water resources
- Human health impacts
- Agricultural output changes
- Producer surplus changes
- Consumer surplus changes
- Other indirect effects

Source: World Bank.

4.3 Measuring and Modeling Impacts

Approaches to modeling and quantifying water resource benefits of climate policy are varied and will depend on technical resources, data availability, and country-specific conditions. As in other sectors, carbon pricing in the water sector will result in both direct and indirect impacts. Direct impacts are often modeled using econometric approaches and bottom-up technology-based models, or hybrid approaches. Indirect effects are generally much more complex, and computable general equilibrium models are often used for quantifying them. For more information on these types of models, and their advantages and disadvantages, see PMR (2017).

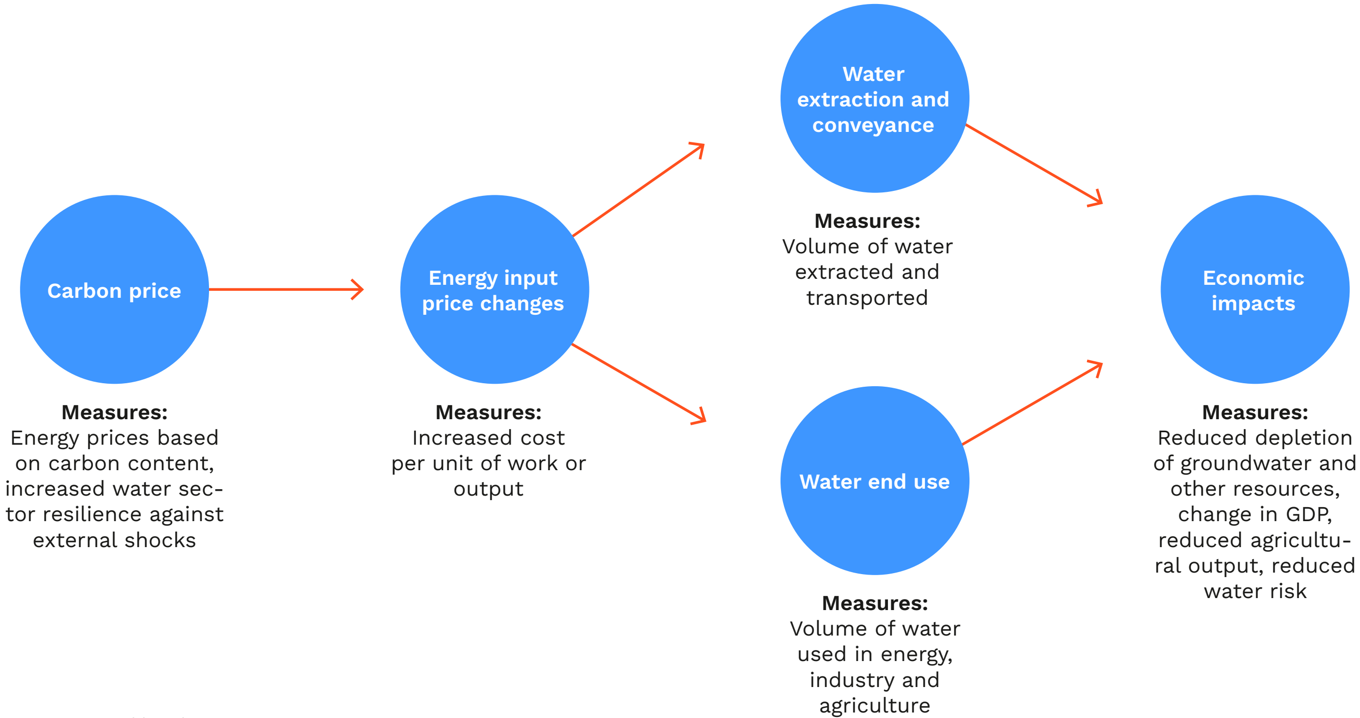
In this section, we address modeling benefits of carbon pricing for water quantity and water quality. We begin with strategies for modeling water quantity and quality benefits through direct impact channels. We then discuss including these expected impacts in economy-wide CGE models to capture indirect effects.

4.3.1 Direct Impacts: Water Quantity

Figure 4.4 displays pathways linking carbon pricing to economic impacts as a result of increased water resources. A carbon price will impact the price of energy inputs to production processes based on the carbon content of the associated fuels. Here the water system is affected in two distinct ways. First, excessive water extraction and conveyance are disincentivized because the increase in costs of energy inputs increases the marginal cost of energy extraction and conveyance (treatment, distribution, wastewater treatment, and recycling may also be considered in this pathway). Second, energy-intensive industries for which water is a complementary input, like the electricity sector, reduce their water demand. Here, the increased fuel cost alters production decisions that in turn affect water demand. A carbon price thereby reduces water usage and can improve water scarcity issues.

Figure 4.4

Steps for Quantifying Direct Benefits from Water Quantity



Source: World Bank.

4.3.1.1. Water Extraction

As discussed in section 4.2, water extraction and conveyance are energy-intensive activities, and carbon pricing will increase the price of energy inputs based on the carbon content of fuels used. Groundwater pumping is a key example of how water extraction may be impacted by a carbon price. Methods for estimating impacts include economic partial equilibrium models and bottom-up engineering cost studies.

A general theoretical approach to estimating groundwater extraction due to price changes is presented in Zilberman et al. (2008). The authors point out that increases in energy prices for agricultural water systems will be transmitted through both food markets and water markets. Moreover, irrigated lands that are dependent on groundwater pumping will be particularly sensitive to energy input price changes due to carbon pricing. By shifting the marginal cost of extraction, more efficient uses of water resources will be incentivized. More details on this framework appear in box 4.3.

Box 4.3

Economics of Water Extraction in Agriculture

Zilberman et al. (2008) provide insight into the expected outcomes in agriculture when the marginal cost of energy increases. For water systems that do not require conveyance (such as groundwater pumping for use in agriculture), the social benefit maximizing condition is given by

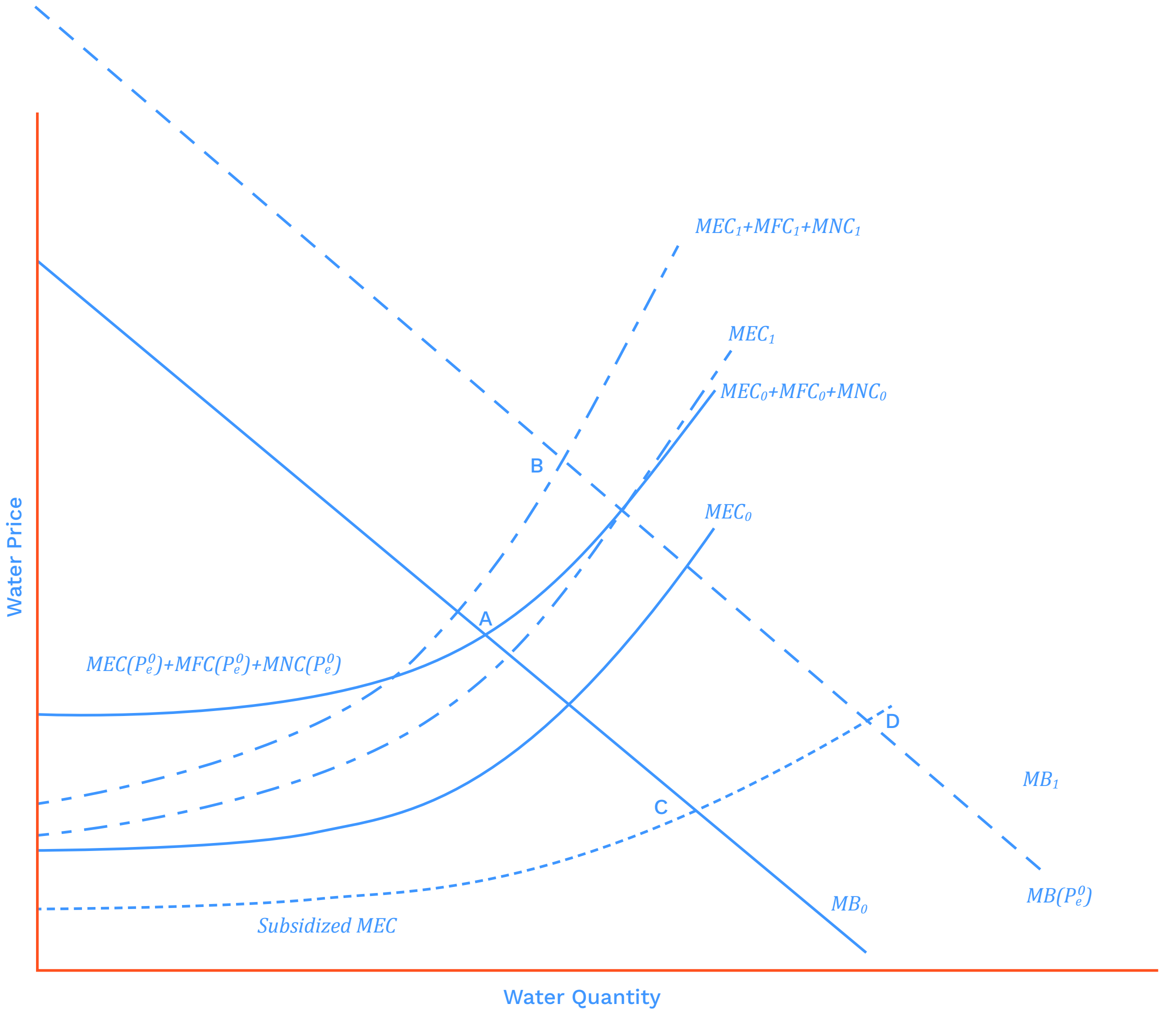
$$MB(x,p_e) = p_w = MEC(x,p_e) + MFC(x,p_e) + MNC(x,p_e).$$

Here, $MB(x,p_e)$ is the marginal benefit of water use in agriculture, where x is the quantity of water and p_e is the price of energy. The marginal benefit of water use will include the effect of food price. As the food price rises, the marginal benefit of an additional unit of water increases. MEC is the marginal extraction cost of water; MFC is the "user cost" of the discounted marginal cost of reduced future benefits due to water use today; and MNC is the marginal externality cost. The sum of these three costs defines the "social" marginal cost curve of water use in this setting. However, the "private" marginal cost may consist of only the marginal energy cost.

Figure B4.3.1 displays graphically both the "social" and "private" marginal cost curves. Subscript 0 indicates the condition before the energy price shock. Subscript 1 indicates the condition after the energy price shock. The figure also includes a subsidized marginal energy cost curve showing how overuse is likely to occur under subsidization.

↓
↓
↓

Figure B4.3.1
Water Use Outcomes under Changing Energy Prices



Source: Zilberman et al. (2008).

Importantly, in figure B4.3.1 we can observe that the socially optimal level of water use is lower when the marginal cost curve includes user costs and externalities. The figure shows the marginal benefit curve rise due to higher food costs. As can be seen here, whether quantity of water use increases or decreases will depend on whether the energy price effect or the food price effect dominates.

Scott (2011) also provides a methodology for assessing changes in aquifer depletion as a result of increasing energy prices in Mexico. In this region, groundwater pumping is sensitive to the price of energy inputs, and the author provides a methodology for computing price elasticities of demand for energy used for pumping. The author finds a substantial reduction in the national groundwater deficit with a 2 percent increase in energy prices, but notes that farmers change behavior only when the cost of water rises to its marginal value. If initial costs of extraction are very low relative to the marginal value extraction cost, an incremental cost increase will do little to alter production decisions.

Additional evidence for changes in groundwater use due to changes in fuel prices comes from Gül et al. (2005). The authors find that the removal of a fossil fuel subsidy in Syria was followed by a significant response in water usage (diesel fuel was the dominant energy source for groundwater extraction). Farmers also shifted away from water-intensive crops in favor of more water-efficient ones as a result of increased extraction costs.

The above studies point to the need to estimate farmer response to increased costs in order to estimate direct benefits for this linkage. Elasticity of demand for water will vary by region due to water scarcity conditions, agricultural market conditions, and availability of alternatives to water-intensive crop production. Studies such as these provide modelers with a methodology to estimate such elasticities and appropriate ranges of values for elasticities when primary research is not possible.

4.3.1.2. Water End Use

Across many sectors of the economy, energy and water are major input factors. Examples include sectors such as heavy industry, electricity generation, and agriculture. Energy and water inputs are often complementary, meaning that production increases require more energy and water inputs (see Wang et al. [2017] for the case of the steel industry). Under a carbon price, increased energy input costs lead to increased marginal cost of production and result in reduced equilibrium production of energy-intensive goods.[21] If energy and water inputs are complementary, we then expect a corresponding decrease in water use. However, increased energy prices may induce changes in production processes or shifts to alternative products that are more or less water-intensive.

Approaches for modeling water end use include partial equilibrium elasticity estimation (see for example Renzetti [1992]) and cost-based models (see Wang et al. [2017]). Partial equilibrium models estimate how end sectors will respond to shocks to energy prices. These approaches, referred to as “top-down” methods, use observed data to estimate elasticities that enable analysts to estimate how demand will change under price changes. Cost-based models, on the other hand, are “bottom-up” models that model fundamental relationships of specific technologies and assume cost-minimizing strategies among actors. Both types of modeling are valid, and the choice of which type of modeling to use will depend on what data are available and whether physical details must be included. Econometric top-down modeling requires observational data that allow inferences about agent behavior changes with respect to an exogenous price change. Bottom-up modeling, on the other hand, requires extensive physical and cost data (for example, the types of equipment used in water-intensive processes and associated marginal and capital cost parameters).

The electricity sector is an example of an end-use sector that will be highly affected by a carbon price. In this sector, engineering cost models are often used to estimate changes in electricity supply by fuel. Such models are known as production cost models.[22] These models take into account engineering constraints of an electric power system, economics of available resources, and expected electricity

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[21] This assumes normal goods in partial equilibrium; more complex effects can be present in the general equilibrium case.
[22] Examples of commercial production cost models include PROMOD, PLEXOS, and GridView.

demand in order to solve for least-cost dispatch solutions mimicking the behavior of an electricity system operator. The advantage of this type of model is the ability to simulate complex engineering constraints that are important in economic outcomes in this sector. Partial equilibrium economic models may also be used, however, where data are not readily available, or high-level estimates are sufficient for analysis.

The operation of electricity-generating resources is likely to change significantly under a carbon price. Generation fired by fossil fuels such as coal and natural gas will experience an increase in marginal costs, and a carbon price will incentivize the use of and investment in alternative sources of electricity. Fossil fuel generators (and certain non–fossil fuel electricity resource types) use water as an input to production. The amount of water used for a particular resource type is referred to as the water consumption factor, measured in cubic meters per megawatt-hour (MWh). For example, a coal unit may consume 2.6 m^3/MWh, while a natural gas combined cycle unit may consume only 0.77 m^3/MWh (Tidwell and Moreland 2016). Because fossil fuel–fired generators tend to have higher water consumption factors than alternatives that do not use fossil fuels, a carbon price is likely to reduce water use and water scarcity. Modeling strategies such as those described above may be used to estimate the water savings. Tidwell and Moreland (2016) provide an example of how this modeling can be implemented at the national level.

4.3.2 Direct Impacts: Water Quality

Figure 4.5 displays pathways for quantifying the water quality impacts of carbon pricing. A carbon price increases the cost of inputs for energy-intensive industries and reduces production. Water contamination externalities associated with these industries will also decrease. Increased water quality may lead to improved human health outcomes, reduction of losses in agriculture due to poor water, and increased freshwater availability. In this subsection we discuss strategies for modeling the direct impacts of carbon pricing in water-intensive industries and provide an overview of strategies for estimating water quality externalities.

4.3.2.1. Water-Intensive Industries

Sectors such as heavy industry, electricity generation, agriculture, mining, and energy resource extraction have high energy input requirements and may be associated with negative water quality externalities (discussed in the next subsection). Because a carbon price will affect the price of energy inputs, energy-intensive industries will experience an increased marginal cost of production that results in decreased output. For industries with negative water externalities associated with production, a drop in production will reduce these externalities.

The agricultural sector is a major contributor to water pollution and will likely be significantly affected by a carbon price (as discussed in the previous chapter). Fertilizer and other chemicals used in agriculture enter waterways, causing reduced oxygen levels and eutrophication (Incera, Avelino, and Solís 2017).[23] The increasing prevalence of hypoxic zones in Europe and North America has largely been attributed to agricultural fertilizer use in those regions (Seitzinger et al. 2010).[24] Fossil fuels–and natural gas in particular–are key inputs to fertilizer production and account for a majority of costs of nitrogen fertilizers such as urea. A carbon price on carbon-based inputs to fertilizer production will increase the price of fossil fuel–based fertilizer, encouraging more efficient use of such chemicals and inducing substitution with alternatives such as organic fertilizers. With lower levels of fossil fuel–based fertilizer application, less fertilizer will reach waterways, reducing the damage to water systems. See chapter 5 on soil health benefits for a more detailed discussion of this mechanism.

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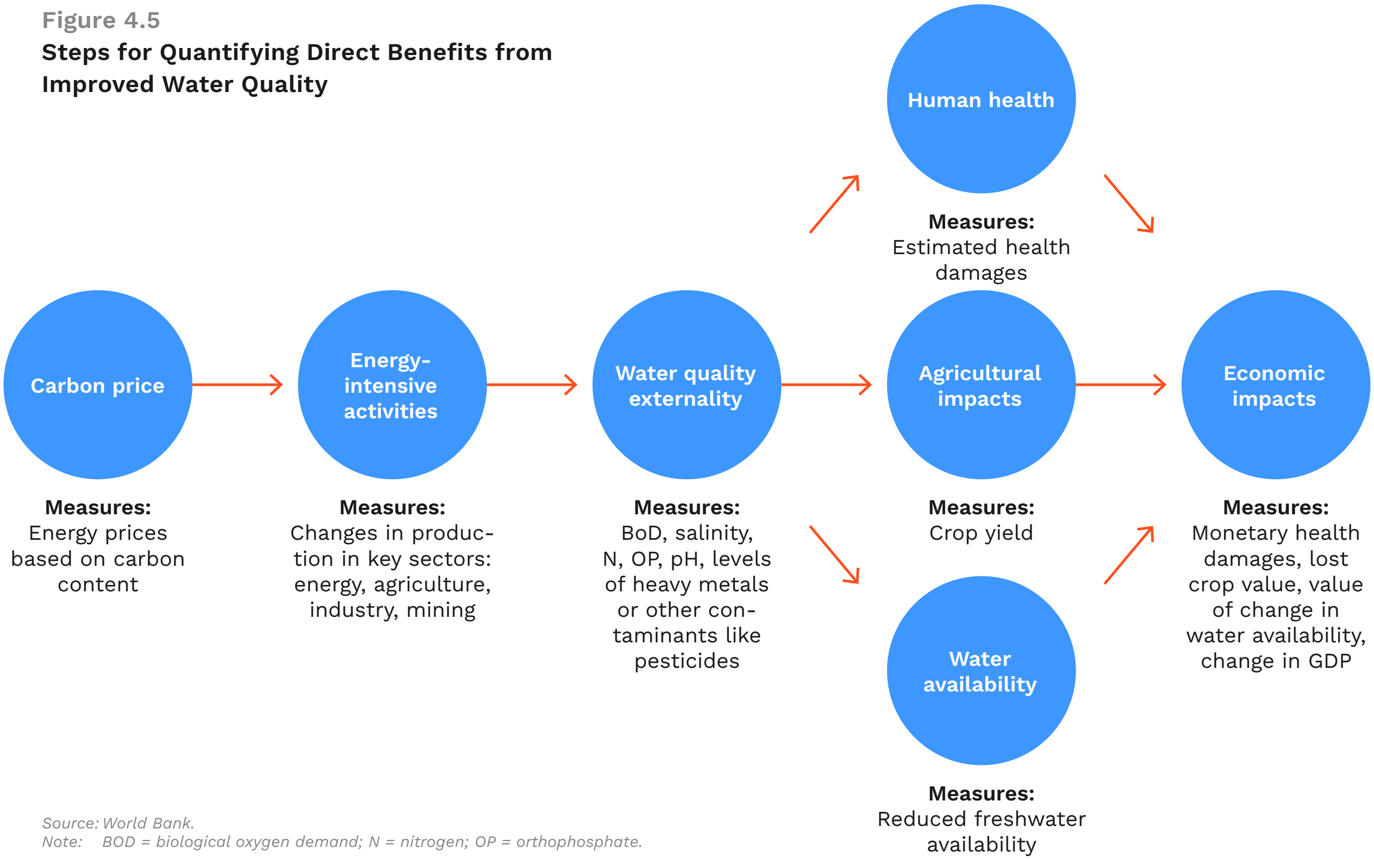
[23] Eutrophication is the process by which excessive accumulation of nutrients (often nitrate and phosphate) causes excessive growth of algae or other species that crowd out other plants, disturbing ecosystems (Lovett 2013).

[24] Hypoxic zones are bodies of water with low oxygen, colloquially referred to as "dead zones."

Figure 4.5

Steps for Quantifying Direct Benefits from Improved Water Quality



Source: World Bank.
Note: BOD = biological oxygen demand; N = nitrogen; OP = orthophosphate.

4.3.2.2. Estimating Water Quality Externalities

The existence and distribution of negative water quality externalities–including acidity, reduced oxygen, heightened nitrogen levels, and contaminants like heavy metals or pollutants from agricultural or industrial runoff–vary greatly across regions and sectors. An empirical study by Osborn et al. (2011) finds and quantifies evidence of methane contamination of groundwater due to natural gas extraction via hydraulic fracturing in the Marcellus and Utica shale formations in the northeastern United States. Pattanayak et al. (2002), a study of water quality benefits of GHG pricing in the US agricultural sector, found average water quality increases nationwide as a result of GHG pricing. The study also found a 9 percent decrease in nitrogen loading into the Gulf of Mexico.[25] Where detailed regional studies such as these are not available, assumptions can be made based on available literature, but a high degree of uncertainty is to be expected, and analysts must bear this in mind. Sensitivity analyses are valuable where parameter uncertainties are high.

In order to estimate water quality impacts, an appropriate metric by which water quality is defined must be developed. A common approach in policy making is to define a water quality index, which identifies the individual components that contribute to water contamination, and specify a formula by which quantifiable measures of such components combine into a single metric of water quality. UNEP (2018) offers guidelines and metrics for water quality (see section 4.2.3) and the US Environmental Protection Agency (EPA) also has a detailed metric for regional water quality assessments.[26] Box 4.4 provides an overview of a study by Pattanayak et al. (2005) that illustrates the process of using the US EPA water quality index to quantify the direct water quality benefits of environmental policy.

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[25] "Loading" refers to the quantity of nutrients entering an ecosystem in a given period of time.
[26] The methodology is attributed to McClelland (1974).

Box 4.4

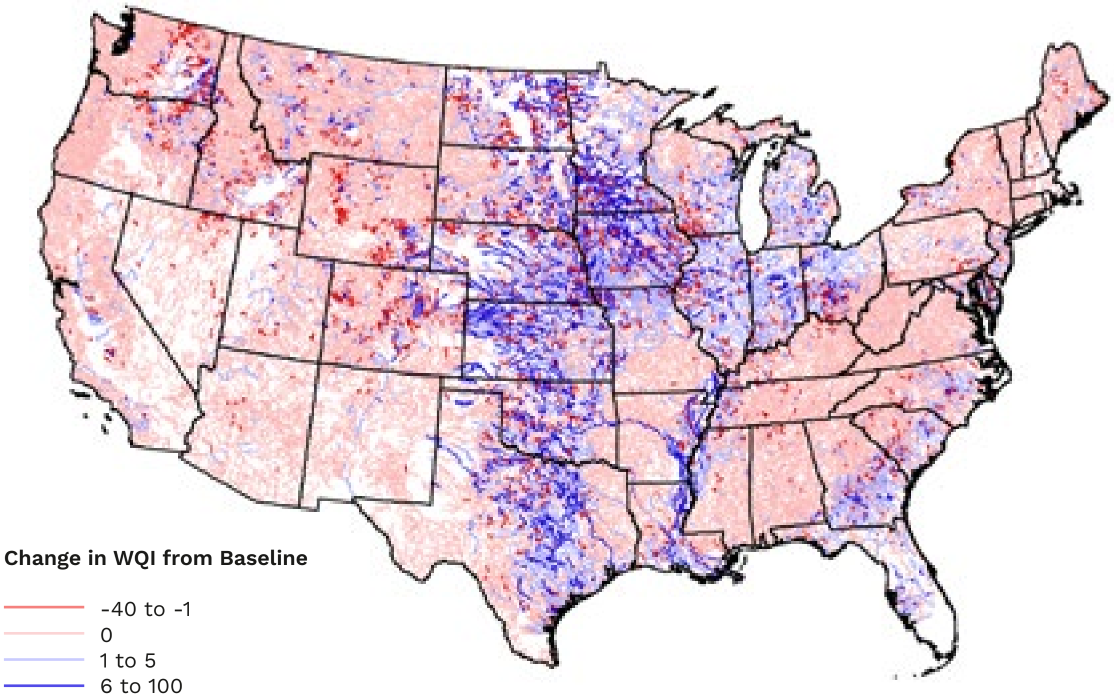
Assessing Water Quality Impacts of Carbon Pricing

Pattanayak et al. (2005) use two models to assess the water quality impacts of carbon pricing due to changes in agricultural activity. The first model is an agricultural sector model for the United States (ASMGHG). ASMGHG represents production, consumption, and international trade by region in the US, simulating market and trade equilibrium, including external trading. Market equilibrium reveals commodity prices, factor prices, levels of production, and GHG emissions. This model is then linked to a water quality model, the National Water Pollution Control Assessment Model (NWPCAM). NWPCAM uses detailed spatial data combined with data representing pollutant and nutrient loadings, simulating transport, deposition, and decay processes in waterways. By linking these two models, the researchers were able to simulate the complex interaction of carbon mitigation in the agricultural sector with water quality outcomes.

The researchers model three scenarios of carbon pricing–$0, $25, and $50 per tonne of carbon equivalent–and measure effects of GHG pricing on economic welfare, land use and land cover changes, GHG emissions, and water quality. In addition to providing land use and land cover benefits, such as increases in forest coverage or soil health improvements, researchers found that the carbon price would also increase the national water quality by 2 percent on average according to the implemented water quality index. Moreover, a carbon price would reduce the amount of nitrogen ending up in the Gulf of Mexico by an estimated 9 percent. Figure B4.4.1 displays water quality improvements under the $25/tonne carbon price (blue indicates water quality improvement); the evolution of the water quality under the three scenarios is shown in table B4.4.1.

Figure B4.4.1

Evolution of Water Quality Index under the 25$/Tonne Scenario



Source: Pattanayak et al. (2005).
Note: WQI = water quality index.

Table B4.1.1

Evolution of Water Quality under the Three Scenarios

			Change in WQI	
ASMGHG region	**Total length of Reach System (Miles)**	**Baseline WQI**	**$25/tonne of CE**	**$50/tonne of CE**
Northeast	45082.80	74.16	0.12	0.02
Lake States	39994.20	65.16	2.64	2.66
Corn Belt	64636.20	57.64	2.57	2.55
North Plains	63724.30	50.29	3.96	3.97
Appalachia	59892.10	79.53	0.20	0.15
Southeast	45107.50	80.90	0.57	0.67
Delta States	35070.70	78.77	2.34	2.40
South Plains	62293.30	55.39	2.96	3.12
Mountain	173854.00	69.37	0.36	0.34
Pacific	73426.50	76.59	0.25	0.21
Total U.S.	**632532.00**	**68.56**	**1.38**	**1.38**

Source: *Pattanayak et al. (2005).*
Note: *WQI = water quality index; CE = carbon equivalent.*

In addition, water quality may be assessed at different levels of aggregation. Aggregation may be geographic (national, provincial, county), and segmentation may be based on source (groundwater aquifers, lakes, rivers) or type of water (environmental, raw water, treated water). The appropriate level of geographic aggregation for water quality assessment will depend on data availability and the regional setting.

As depicted in figure 4.5, water pollution can directly affect human health, result in agricultural losses, and reduce water availability. Identifying additional setting-specific direct impacts will depend on local expertise on water quality issues.

Reddy and Behera (2006) conducted a study near Hyderabad, India, a region affected by industrial water pollution, and found that there were significant risks to human health, including elevated arsenic in local water, damage to crops due to acidification from the polluted irrigation water, and damages to livestock. The economic value of the damages in this setting were considerable.

4.3.3 Indirect Impacts of Water Sector Benefits

Indirect impacts are effects of carbon pricing that are a result of cross-sectoral linkages. For example, if carbon price implementation leads to an increase in electricity prices, industries that use large amounts of electricity will become relatively less competitive with those that use less. The change in relative competitiveness will incentivize shifts in resources from industries experiencing reduced competitiveness to those experiencing an increase. Different industries have differing water intensities that result in different water quality externalities. Therefore, these intersectoral shifts will affect water quantity and water quality. As in other sectors, outcomes of interest include distributional effects (transfers between sectors), structural shifts (for example, competitiveness in agriculture), and impacts related to social welfare (whether effects are progressive or regressive).

Overexploitation of groundwater resources is a threat to water resource sustainability (one whose magnitude is affected by complex intersectoral linkages), and it also reduces the resiliency of water systems (i.e., their ability to cope with and adapt to system demands without undermining the socio-ecological equilibrium). This example illustrates indirect impacts of carbon pricing. Zilberman et al. (2008) provide a theoretical framework to capture indirect effects of intersectoral linkages in surface water exploitation. The authors point out that increases in energy prices for agricultural water systems will be transmitted through both food markets and water markets. Decreased water extraction for agriculture may reduce agricultural output and therefore reduce water pollution. However, if reduced agricultural output leads to increased food prices that harm low-income communities, social welfare issues may arise. See box 4.3 for more details on these mechanisms. Liu et al. (2017) raise similar concerns in global modeling of groundwater extraction and associated land use change. The authors use a detailed partial equilibrium modeling approach to simulate future impacts of water security policies. Box 4.5 provides more detail.

Box 4.5

Achieving Sustainable Irrigation Water Withdrawals

Excessive groundwater withdrawal, the primary contributor to groundwater depletion in many regions of the world, challenges the capacity of water resources to ensure food security and continuous growth of the economy. Policies that target excessive water extraction can overlook the interaction of water sector policy with other sustainability and development goals. Liu et al. (2017) investigate how unsustainable water use is shaped by population changes, affluence, technology, and changing climate conditions. The authors use the SIMPLE-on-a-Grid (SIMPLE-G) model coupled with the global Water Balance Model (WBM) to simulate the impact of reduced unsustainable irrigation water withdrawals on land use change and food supply, under a variety of future scenarios.

The models used in this study provide examples of tools that can be deployed to understand the complexities of large-scale water systems and their linkages to agriculture, land use, and other economic systems. SIMPLE-G is a multi-region, partial equilibrium model of gridded cropland use, crop production, consumption, and trade (Woo et al. 2019). SIMPLE-G is an extension of the SIMPLE model, developed by researchers at Perdue University, which has been used widely to study economic, policy, and development issues related to the global food-water-environment nexus. SIMPLE-G divides the world into georeferenced grid-cell units to account for local environmental conditions, climate change impacts, and water scarcity, and to simulate local land and water use given future trends in the global farm and food system.[a]

Liu et al. (2017) use WBM to simulate surface water resources. WBM is a global gridded model used to represent the land surface portion of the hydrologic cycle. The model couples water balance and transport, simulating water exchange between the land surface and the atmosphere, and simulating horizontal water transport along waterways and subsurface flows.[b] As the authors demonstrate, water resource availability depends on the complex mechanics of the global water system, and models such as WBM can be useful to inform water-related policy decisions.

In comparing three policy interventions–interbasin water transfers, investments in agricultural productivity-enhancing technologies, and the promotion of virtual water trade–Liu et al. (2017) find that pursuing sustainable irrigation may erode other development goals, but these adverse effects are mitigated when coupled with productivity-enhancing technologies. The use of SIMPLE-G coupled with WBM allowed for a systematic comparison of three policy alternatives and a nuanced view of indirect impacts of the policies.

a. More information about SIMPLE-G is at https://mygeohub.org/resources/simpleg.
b. For more information on WBM, see Wisser et al. (2010).

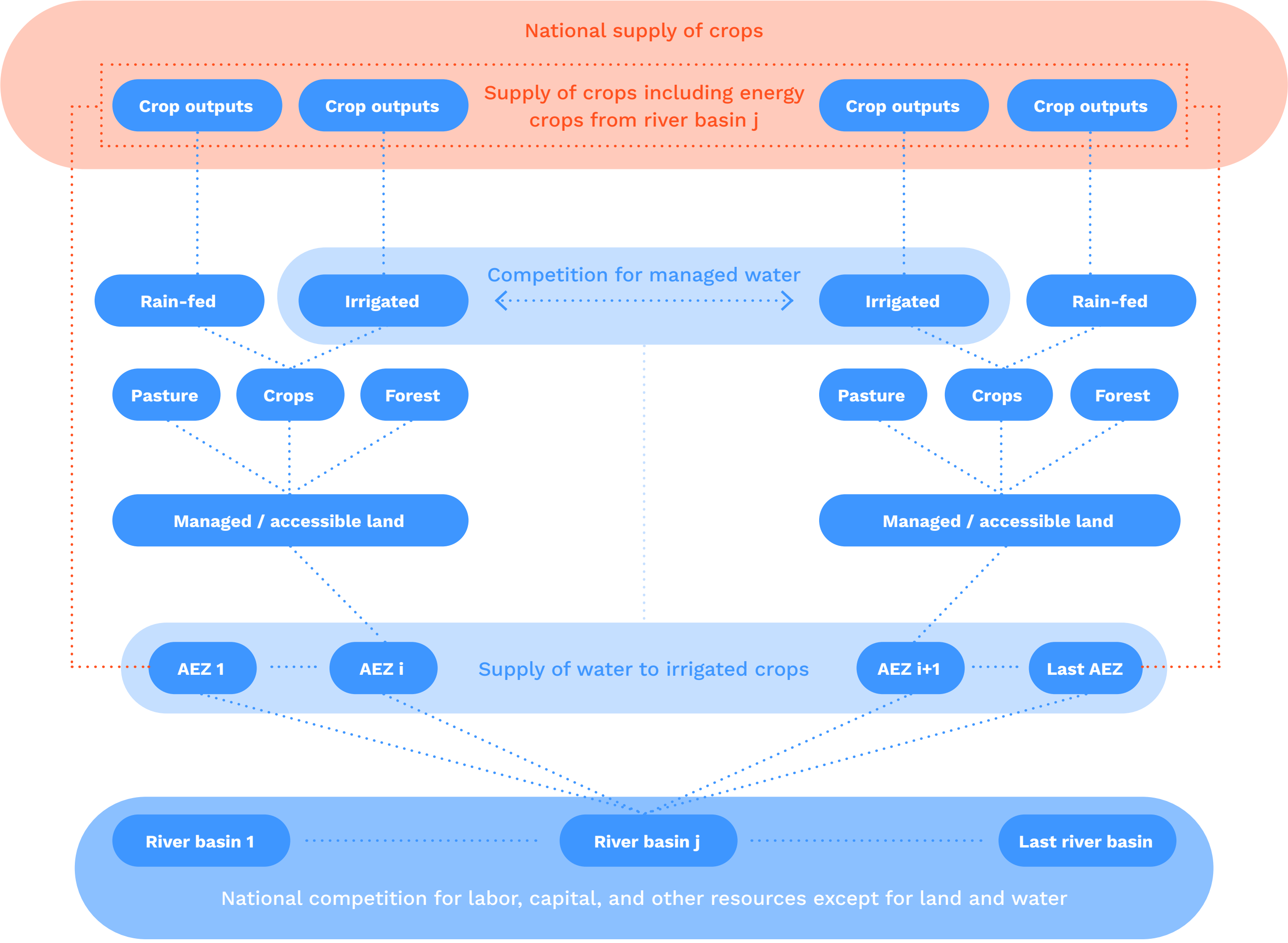
4.3.4 CGE Modeling of Water Sector Benefits

Effects of carbon pricing on the water sector will be widespread, and from a policy-making perspective, trade-offs will often exist between positive and negative impacts. CGE models are useful tools to allow policy makers to better assess these effects, address the needs of a broad array of stakeholders, and assess impacts of complementary policies to mitigate undesirable outcomes. The direct water quality and quantity impacts described above provide structure and metrics that can be included in general equilibrium models to capture important intersectoral trade-offs. Water availability and water quality metrics can have impacts on productivity throughout the economy that can be simulated in a general equilibrium framework.

The Global Trade Analysis Project (GTAP) website is a valuable resource for CGE modeling and offers a wide range of research, training materials, and data resources in addition to the GTAP CGE model. A range of studies have integrated water resources into GTAP databases for CGE modeling. Taheripour, Hertel, and Liu (2013) provide an overview of the structure of a GTAP model extension (called GTAP-BIO-W) that includes land use and water resources in GTAP models and databases by dividing crop sectors into irrigated and rain-fed categories and explicitly including irrigation water in the cost structure of irrigated crops by river basin. Figure 4.6 displays the structure of the GTAP-BIO-W model. In this model, there is competition among industries for labor, capital, and resources (other than land and water). Supply of managed water is exogenously specified at the river basin level, and industries compete for the available managed water. Haqiqi et al. (2016) detail a similar approach to integrate irrigation water into a GTAP model. Calzadilla et al. (2011) use the GTAP-W model to analyze economy-wide impacts of increased sustainable water use in agriculture within a CGE framework.

Figure 4.6

Structure of GTAP-BIO-W



Source: Taheripour, Hertel, and Liu (2013).

Note: AEZ = Agro Ecological Zone.

The remainder of this section presents two examples that illustrate the use of CGE modeling to assess economic impacts of policies related to the water sector. Box 4.6 examines policies to improve water security in Vietnam, and box 4.7 discusses water pricing impacts in Tianjin, China. The section ends with a summary table on quantifying the effects of a carbon price on water resources (Table 4.1).

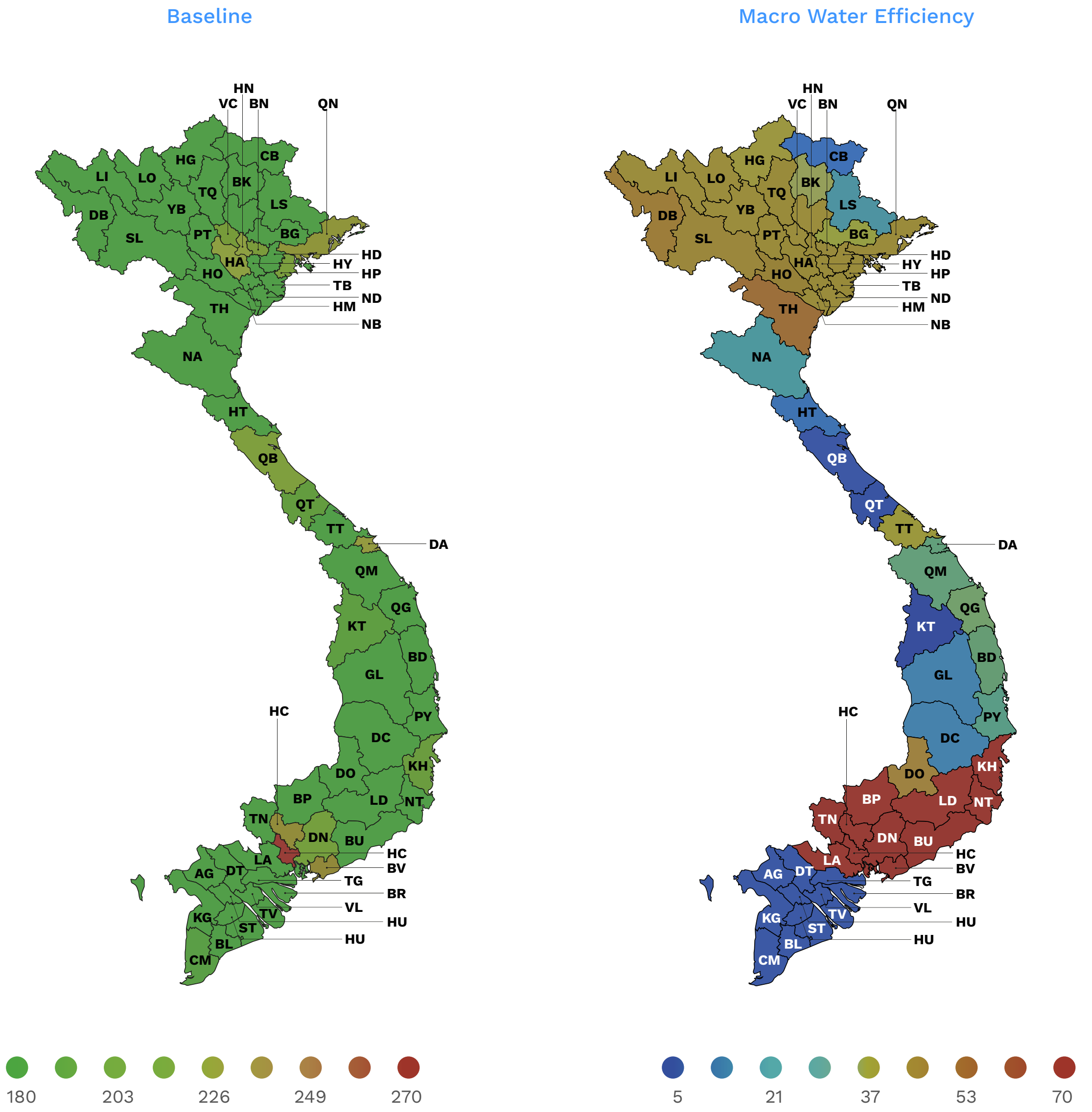
Box 4.6

Water Security in Vietnam

Using a national dynamic CGE model calibrated to spatial water resource data, Roland-Holst (2013) examined opportunities to improve local and national water security in Vietnam. As in many dynamic emerging economies, aggregate water demand in Vietnam has accelerated rapidly in recent decades, with dramatically increased competition in spatial and sectoral allocations. Insufficient investment and maintenance of retention and conveyance infrastructure aggravates this economic rivalry, especially threatening lower-income stakeholders, rural smallholders, and food security generally. Because the CGE model can trade water services through supply chains, in household consumption, and embodied in trade (tourism is the fastest growing water user), it can identify and compare complex effects of direct and indirect policies (including carbon pricing).

Figure B4.6.1

Annual Average Capacity Water Usage, Baseline (left) vs. With Efficiency Measures (projected) (right)



Baseline

Macro Water Efficiency

Source: Roland-Holst (2013).

Note: Capacity shown in maps is aggregate seasonal water use as a percentage of capacity (including existing storage and conveyance). For province abbreviations, see Roland-Holst (2013, 45).

Box 4.7

Subnational Water Resource Allocation and Pricing in China

A study by Ni et al. (2013) uses CGE modeling to address local water policy in Tianjin, China. Economic development and changing climate conditions have led to acute water shortages in many regions of China. The authors use the city of Tianjin as a sample case to study the effects of water pricing policy. The study investigates how water pricing policy affects water consumption and economic activity in the region. The Tianjin dynamic CGE model used in the study was developed jointly by the State Information Center and the China Institute of Water Resources and Hydropower Research. Using official 42-sector input-output tables (produced for every province every five years in China), the modeling takes into account elasticity of substitution for a variety of water resources. With exogenously determined water price differentials across different water sources and uses, the model computes water use response of industry and consumers, effects on water resource stocks, and impact on the Tianjin economy. Scenarios for alternative water schemes are compared to achieve more efficient utilization of water resources under constraints of water supply and prioritizing different uses. These results demonstrate the potential of CGE modeling to simulate the complex interaction of water resource supply and demand with local, regional, or national economic systems to support water-related policy analysis.

The main steps for identifying and quantifying water resource benefits, through the examples of extraction and end use, are outlined in Table 4.1.

Table 4.1

Quantifying the Effects of a Carbon Price on Water Resources

	Step	Notes
1	Determine water system components and valuation	• Identify national water system components of interest (in this guide, extraction and end use were used).
2	Estimate water quantity benefits	• Benefits will vary across countries and regions depending on risk factors (see Reig, Shiao and Gassert [2013] for risk factors). Higher risk factors increase the implicit water value. • Young (2005) provides an overview of water valuation methods in the policy-making context.
3	Identify water quantity metrics	Metrics include • Changes in water scarcity conditions • Reduction in water resource depletion • Changes in agricultural output • Producer and consumer surplus changes • Net costs of water provision (public, private)
4	Estimate the impact of a carbon price on energy input changes	• Estimate increased cost per unit of work or output.
5	Estimate change in energy-intensive activities	• Measure change in production in key sectors like energy, agriculture, and industry. • Factor in water usage of different electricity or production sources.
6	Estimate change in water quality	• Water quality changes can be measured through changes in biological oxygen demand, salinity, nitrogen, pH level, and other metrics.
7	Estimate the economic value of health, water, and agricultural effects	• A financial value for each unit of health effect can be established (see air quality summary chapter). • Water availability can be estimated by measures like the increase in freshwater availability. • Agricultural yield value = implied production x average crop price(s). • Land use and land cover benefits can also be estimated.
8	Estimate indirect effects	• Partial equilibrium models can simulate indirect effects on food and water markets. • Water quantity and quality metrics can also be included in general equilibrium frameworks through their impact on economic productivity. Water services can be traded through supply chains, household consumption, and trade to show the direct and indirect impacts. • The Global Trade Analysis Project models have integrated water resources for CGE modeling.

Source: World Bank.

5.

Soil Health

At a Glance

Soil health benefits

- Key threats to health of soil resources include soil contamination, soil acidification, and altered soil nutrient balance.
- A carbon price may change agrochemical application (fertilizer and pesticides). As fertilizer production is an energy-intensive process, a carbon price may reduce fertilizer rates and lessen the risk of local water contamination through agrochemical runoff.
- Carbon pricing may reduce energy-intensive production like that in heavy industry, which is a significant contributor to air pollution; it can improve soil health by reducing the risk of soil contamination from poor air quality.
- The potential benefits of a carbon price on land use may also be significant, as a carbon price affects the relative competitiveness of sectors that drive deforestation.

Quantifying soil health benefits

- Benefits may be realized by measuring human health outcomes, changes in crop yields and water quality, reduced deforestation rates, and reduced biodiversity loss.
- CGE modeling may be used to quantify indirect benefits related to soil health due to complex intersectoral linkages.

5. Soil Health

5.1 Introduction

Soil resources are a foundation for many economic value chains. Soil health can be defined as "the continued capacity of soil to function as a vital living ecosystem that sustains plants, animals, and humans" (US Department of Agriculture Natural Resources Conservation Service 2019). Food production and food security rely on productive and healthy soils.[27] In addition, soils provide other important ecosystem services such as filtration, water storage, carbon storage, and promotion of biodiversity. They are also a physical and cultural environment for human activities, as well as an archive of geological and archaeological heritage (FAO and Intergovernmental Technical Panel on Soils [ITPS] 2015 2015). In many regions of the world, soil resources face threats to their health and productivity. Soil acidification, for instance, is primarily caused by overfertilization with nitrogen in intensive agricultural practices without the use of lime to correct for soil acidity (Tian and Niu 2015).

In addition, soils are a major store of carbon worldwide. It is estimated that global soil resources contain 1,500 gigatonnes (Gt) of soil organic carbon. Although this amount is much smaller than the carbon contained in the world's oceans (38,000 Gt), it is approximately double what is contained in the atmosphere. The carbon contained in soil is subject to modification by human activity. Widespread tillage depletes this carbon reservoir and disrupts natural carbon cycles (Baker et al. 2007). A broad body of research has focused on the inclusion of sustainable land management in GHG mitigation strategies.[28]

The implementation of a carbon price can have a substantial impact on the health of national soil resources. Many of the key human activities that adversely affect soil health are energy-intensive, and a carbon price would therefore increase the price of inputs to economic activities that damage soil health. In addition, carbon pricing can be directly applied to moderate land use emissions. The World Bank's (forthcoming) publication "Designing Fiscal Instruments for Sustainable Forests" provides a comprehensive discussion of carbon pricing as it relates to this sector. Changes in land use due to carbon pricing applied to associated emissions will have significant implications for soil health.

In this chapter we focus on a conceptual framework to assist policy makers in quantifying the potential benefits to soil health of a carbon-pricing policy.

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[27] *The extent to which agricultural crop yields in a given region improve due to improvements in a particular soil health metric is a nuanced topic. Miner et al. (2020) provide a high-level overview and review of recent literature on this topic.*

[28] *Note that this guide focuses on the benefits of upstream and midstream carbon pricing and associated modeling techniques (see* Carbon Tax Guide: A Handbook for Policy Makers *[PMR 2017] for more details on carbon price implementation). Impacts of carbon emission mitigation measures and carbon sequestration in the agriculture, forestry, and land use sectors are beyond the scope of this document. We refer readers to Braimoh et al. (2016) and World Bank (forthcoming) for more information on these topics.*

5.2 Identifying Benefits and Linkage to Carbon Prices

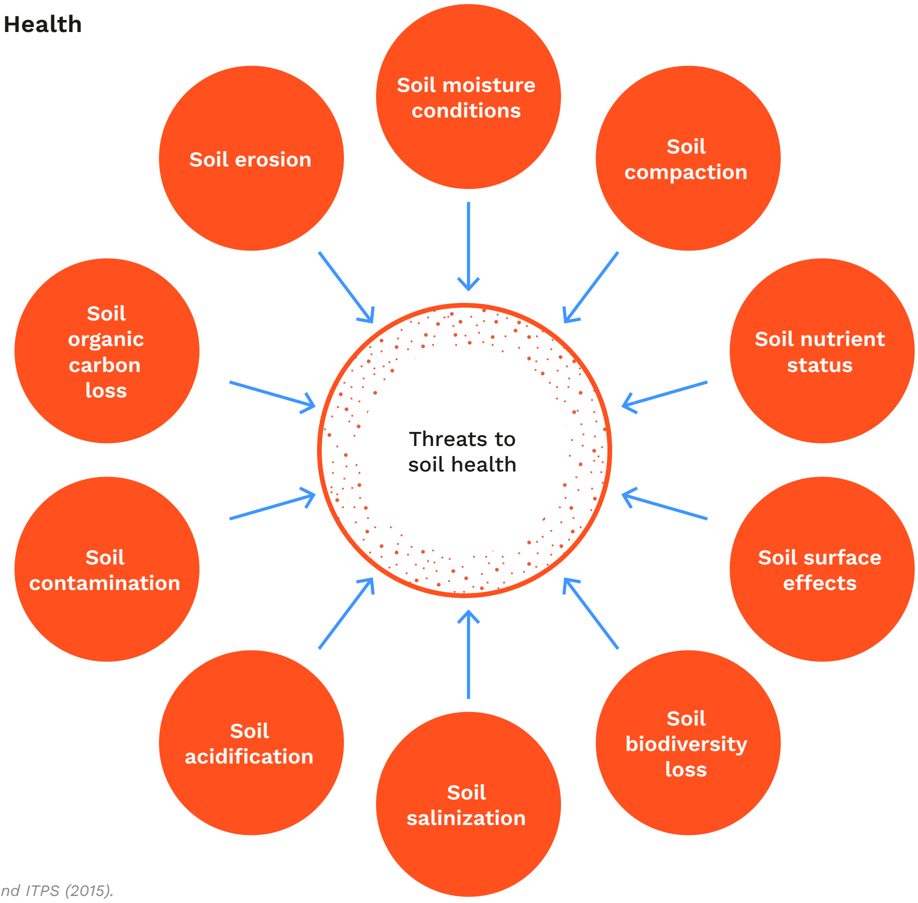
Agriculture is a primary sector of interest for analyzing the soil health benefits of carbon pricing, as the sector is carbon-intensive and has a sizable impact on land cover and land use changes. Atmospheric deposition of pollutants (e.g., ammonium aerosols, NO_X) and direct soil contamination due to carbon-intensive processes throughout the economy also contribute to soil health changes under a carbon price.

In this section we discuss the mechanisms by which soil health is affected as a result of carbon pricing. We begin with a discussion of dimensions of soil health and associated threats. We then discuss how soil health is impacted by fertilizer application, pesticide use, and atmospheric deposition. Finally, we discuss land use changes as a result of a carbon price.

5.2.1 Dimensions of Soil Health

There is a wide array of potential threats to soil across different countries. FAO and ITPS (2015) list the following primary threats to soil health: erosion, organic carbon loss, contamination, acidification, salinization, biodiversity loss, surface effects, nutrient status, compaction, and moisture conditions (figure 5.1).

Figure 5.1
Threats to Soil Health



Source: Based on FAO and ITPS (2015).

Table 5.1 displays three important soil health threats and the processes that cause them. Contamination, acidification, and nutrient balance issues represent the primary threats to soil health globally, although their relative magnitude varies by region- and country-specific conditions.

Table 5.1

Key Threats to Soil Health

Threat	Definition	Primary causes
Soil contamination (or soil pollution)	Intentional or unintentional introduction of dangerous substances on or in the soil	Atmospheric deposition, agriculture, flood events
Soil acidification	Excessively low soil pH, a natural process accelerated by sulfur and nitrogen deposition	Long-term rainfall, draining of soils, atmospheric deposition, use of ammonium-based fertilizers, land use changes
Soil nutrient balance	Concentration in soils of macronutrients—nitrogen (N), phosphorus (P), potassium (K); and micronutrients—calcium (Ca), magnesium (Mg), and Sulfur (S) (among others)	Nutrient additions: soil amendments, wet/dry deposition, atmospheric N fixation, run-on and sedimentation Nutrient losses: harvested products, ingested products, gaseous emissions, erosion, surface runoff

Source: CEC 2006; FAO and ITPS (2015).

Fire is an important additional contributing factor to soil health that impacts soils across multiple soil health dimensions. Anthropogenic fire to clear land and naturally occurring forest fires both contribute to carbon loss, impacts on soil nutrient balance, and altered soil biodiversity. Fires also contribute to atmospheric loading of carbon and other pollutants. For more information on the relationship of fires to soil health, see Certini (2005); FAO and ITPS (2015); Knicker (2007); and Lehmann et al. (2015).

The introduction of a price on carbon is likely to meaningfully impact soil quality through a variety of pathways:

- **Agrochemical application**: Fertilizers and pesticides applied to soil contain nitrogen, phosphorus, potassium, heavy metals, and other contaminants. Overapplication of these substances may lead to soil acidification and other effects, reducing crop yields. Because these fertilizers and pesticides often have a high fossil fuel input, a carbon price may deter the amount produced and used.

- **Atmospheric deposition**: Airborne particulate matter or acid rain can pollute soils and lead to acidification. Sources of atmospheric pollution, such as heavy industry and electricity generation, have high energy-input requirements. The increase in cost of the energy inputs will lead to lower production, thereby reducing air pollution and atmospheric deposition (see chapter 3 for more details on air quality benefits).

- **Spills and other releases**: Spilled products or byproducts from the energy sector, industry, mining, and waste management can lead to soil pollution. With a carbon price reducing production in high-energy-demand sectors, associated output of wastewater will be reduced, and accidental spills that can affect waterways and soils will be less likely.

- **Contaminated water application**: Contaminants introduced into soil resources may cause soil acidification and pollution. Improved water quality due to carbon pricing (see chapter 4) will reduce contaminants in water used in agricultural land application, in turn reducing potential introduction of soil contaminants.

- **Excessive water extraction**: Extraction can reduce soil moisture, adversely affecting soil function and causing groundwater depletion. Because groundwater extraction is energy-intensive, increasing the marginal cost of extraction will lower the groundwater extraction rate, reducing the threat of groundwater aquifer depletion.

In order to model benefits for soil quality, policy makers must develop a representation of these mechanisms that can be used to simulate the expected outcome of both a business-as-usual case and a carbon price scenario. It is the difference between these two scenarios that will result in quantifiable benefits of the policy. For each of the five pathways listed, various products or systems may entail distinct data requirements and assumptions. Agrochemical application, for example, requires data on fertilizers, pesticides, and possibly additional soil amendments.[29] The level of modeling detail will be determined by the modeler based on data availability, specific country conditions, technical resources, and expert judgment.

In agricultural sector research, a commonly used concept is the "yield gap." This is the difference between potential crop yield, where "water and nutrients [are] non-limiting and biotic stress [is] effectively controlled," and actual yield (van Ittersum et al. 2013).[30] Researchers have proposed a similar notion for soil health–the "soil health gap." This gap is defined by Maharjan, Das, and Acharya (2020) as the "difference between soil health in an undisturbed native virgin soil and current health in a cropland in a given agrosystem." These authors represent the gap as

$$SHG_x = (SH)_n - (SH)_m ,$$

where SHG_x represents the soil health gap, $(SH)_n$ represents soil health of native soil, and $(SH)_m$ represents soil health of cropland soil. The definition of soil health for native soil varies regionally and may indicate a specific property or a complex soil health index. In this section we have outlined some of the key components contributing to soil health that should be considered in the definition of a soil health metric. A detailed, comprehensive, and nuanced discussion of soil health is beyond the scope of this guide. We refer readers to Moebius-Clune et al. (2016) for a comprehensive treatment of this topic.

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[29] "Soil amendments are any chemical, biological, or physical materials intentionally added to the soil to improve or support plant growth and development. This definition includes fertilizers as well as materials like manure and compost that add organic matter and enhance soil structure" (University of Massachusetts 2020).

[30] This definition varies slightly for rainfed agriculture, see van Ittersum; et al. (2013) for more details.

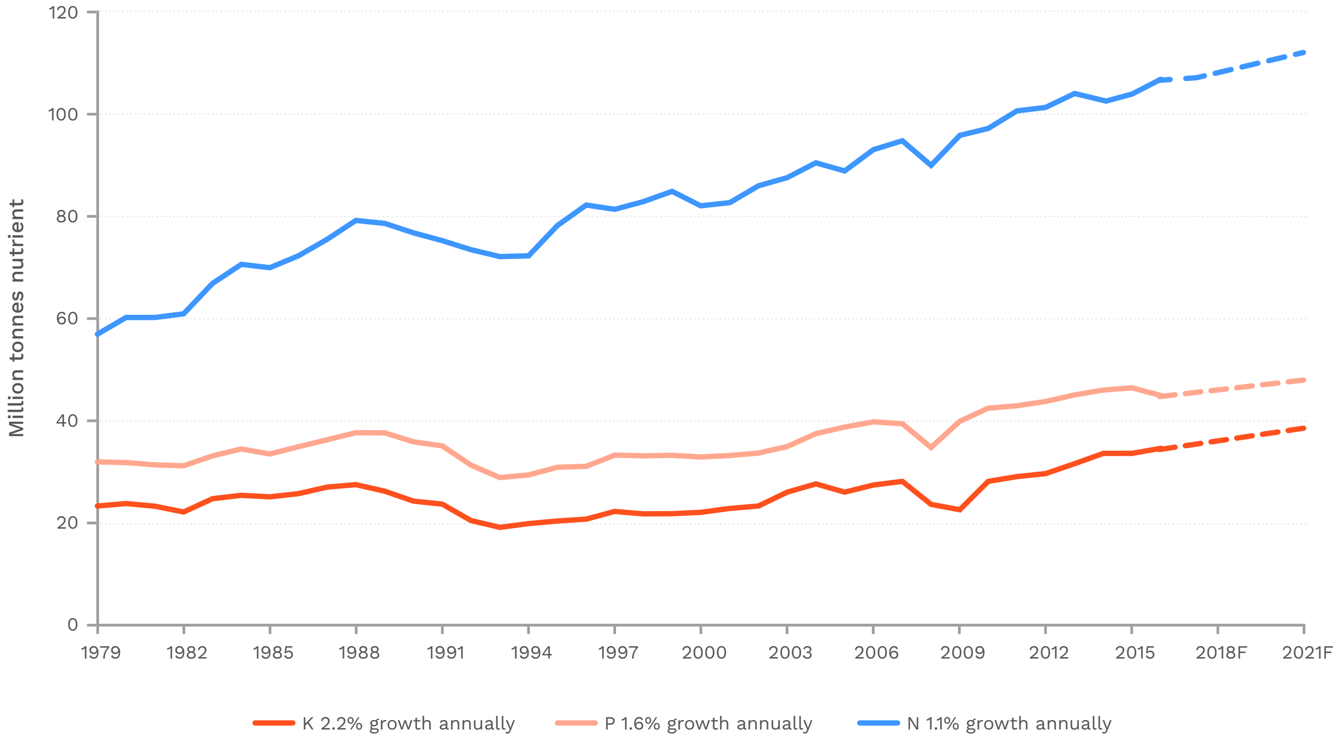
5.2.2 Fertilizer Application and Soil Health

In many regions of the world, the intensive use of synthetic fertilizers and pesticides is a common way to increase agricultural productivity and reduce crop losses. Excessive use of fertilizer nutrients, however, can have adverse effects on soil. It may increase soil salinity, increase soil acidification, and introduce heavy metals, among other effects (Rodríguez-Eugenio, McLaughlin, and Pennock 2018).

There are three primary soil macronutrients: nitrogen (N), phosphorus (P), and potassium (K). Fertilizers containing these nutrients are applied to increase the nutrient availability in agriculture, and demand for N, P, and K soil nutrients has grown steadily in recent decades (see figure 5.2). The three primary agricultural products—rice, wheat, and corn—account for approximately half of all fertilizer consumption.

Figure 5.2

Global Demand for Soil Nutrients, 1979–2021



Source: IFA (2017); Yara (2018).
Note: The dotted line shows the compound annual growth rate from 2014–16 (averaged) to 2021.

Excessive N application is the primary cause of soil acidification and salinization worldwide. Excess nitrogen can lead to the accumulation of nitrates in soil and result in leaching into groundwater (Rodríguez-Eugenio, McLaughlin, and Pennock 2018).[31] Field application of nitrogen fertilizers is heterogenous across the globe, with certain regions experiencing much higher rates than others much higher rates than others. Excessive P fertilizer application also may result in runoff to local water systems, leading to eutrophication (Rodríguez-Eugenio, McLaughlin, and Pennock 2018). K fertilizers are generally considered to have less of an environmental impact than N and P fertilizers (Hasler et al. 2015).

Hasler et al. (2015) provide a "cradle-to-field" life-cycle assessment of fertilizer products, including extraction of raw materials, fertilizer production, transportation, and field application. The authors study the following impact categories: climate change, soil acidification, eutrophication, fossil fuel depletion, and resource depletion. The authors also point out that N fertilizer production and field application lead to high nitrous oxide (N_2O) emissions.

Nitrogen fertilizer production is an energy-intensive process and thus will be affected by carbon pricing. Approximately 100 million tonnes of N fertilizer is used globally; of this total, urea accounts for approximately half (Hasler et al. 2015). Urea also has the highest growth rate among nitrogen fertilizers, because it accounts for most new production capacity additions (Yara 2018). With no policies limiting the use of urea, overapplication would result in greater soil acidification.

5.2.3 Pesticides and Soil Contamination

Among the wide variety of chemicals used in pesticides, many have been shown to negatively impact the soil's ecosystem and fertility in the long run. Pesticides may reduce the growth of microflora; they also kill some microorganisms and boost others, leading to imbalances. Pesticides also lead to biochemical reactions such as nitrogen fixation, impact the mineral composition of soils, and result in enzymatic activity (Gill and Garg 2014).[32]

Pesticide use has increased dramatically in many regions of the world in recent years (Rodríguez-Eugenio, McLaughlin, and Pennock 2018), and pesticide production is an energy-intensive process. Energy inputs include both process energy (required for the manufacturing process) and inherent energy (inputs that are retained in the chemical structure of the final product). The share of inherent energy in pesticide production varies depending on the chemical; typical values are 40–45 percent of the total, with total energy requirements ranging from less than 100 megajoules (MJ)/kg up to over 500 MJ/kg (Audsley et al. 2009; Green 1987).

Due to the high energy intensity of the pesticide production process, a carbon price will increase the cost of production, in turn reducing demand for and use of high-energy-content pesticides. This mechanism may incentivize more sustainable approaches to pest management, like crop rotation strategies; more information is in Barzman et al. (2015).[33] In addition to achieving similar yields with lower pesticide inputs, sustainable pest management can improve long-term soil health.

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[31] Barak et al. (1997) provide a detailed study on the relationship between nitrogen fertilizer application and soil acidification.

[32] Enzymes increase the speed of biochemical reactions in plants and help keep the soil healthy by getting rid of waste (Turan et al. 2017). Chemical fertilizers try to stimulate this process artificially, but a enzymatic activity that is too high is also a problem.

[33] The European Union (EU) Framework Directive 2009/128/EC on the sustainable use of pesticides required EU member states to develop National Action Plans that include the eight principles identified by Barzman et al. (2015).

5.2.4 Atmospheric Deposition

Atmospheric deposition is the mechanism by which particles emitted into the air are widely deposited onto soils. Atmospheric deposition can occur due to local pollutants, for instance from pesticides in agriculture, or due to dispersed pollutants, for instance, from sulfur dioxide emissions from industrial processes or electric power generation. Atmospheric deposition affects soil health degradation in various regions, primarily through soil acidification, which reduces crop and forest growth and increases mortality risks for plants. It can also reduce nutrients in the soil and water, reducing crop yields.

Economic activities that are significant contributors to air pollution (such as heavy industry and electricity generation) are often highly energy-intensive (see chapter 3 for more on air pollution). Increasing the marginal cost of production through a carbon price can lead these industries to reduce production in equilibrium, resulting in lower air pollution and thus lower soil deposition of contaminants.

5.2.5 Land Use Change and Deforestation

Deforestation is a major challenge in many developing countries. In recent decades, deforestation rates have been particularly high in South America and Africa. While natural disasters such as wildfires contribute to deforestation, the primary driver of forest loss globally is land clearing and conversion to other uses such as agriculture and urbanization. Often the economic activities that drive deforestation are associated with exports of agricultural commodities such as palm oil and livestock products. Moreover, countries that are major oil or mineral exporters are host to more than 60 percent of the world's tropical forests (Cust 2020). These extractive industries have important interactions with the economic sectors that most threaten forests in these regions.

Implementing a carbon price will affect the relative competitiveness of sectors that drive deforestation, thus impacting deforestation rates. With lower domestic demand for fuels, fossil fuel–producing countries will export a greater portion of domestic production, increasing net exports. For net importers of fossil fuels, reduced demand will decrease imports. In either case, the increase in net exports will put upward pressure on the exchange rate. International agricultural commodity markets are highly price sensitive, and the increase in exchange rate will make the agricultural commodities less competitive and reduce deforestation pressure from these sectors. This mechanism works in a way similar to the so-called Dutch disease, where extractive industries have been found to crowd out other domestic industries through exchange rate increases (Cust 2020).

The benefit of reduced deforestation as a result of carbon pricing will be important to consider in the quantification of benefits of carbon price implementation. For countries with acute deforestation challenges, the benefits through this channel are likely to be significant. The forthcoming World Bank publication "Designing Fiscal Instruments for Sustainable Forests" provides a useful reference for more details on this mechanism and other issues in deforestation and land use changes as they relate to carbon tax policy.

5.2.6 Soil Health Benefit Metrics

Some key metrics by which soil health benefits may be measured include the following: (1) changes in crop yields due to healthier soils or to surplus or scarcity of limiting factors such as soil nutrients; (2) value of land, or land productivity, representing realized or potential productivity of land that may provide ecosystem services or may be cultivable; (3) land use changes and deforestation; (4) producer surplus changes (e.g., changes in net revenues to farmers); (5) consumer surplus changes (e.g., changes in costs of food commodity baskets, which change food expenditure for consumers); (6) changes in food scarcity, which may have implications for public health outcomes; and (7) other indirect effects such as changes in international competitiveness, which may affect livelihoods. These metrics are displayed in Figure 5.4. This list is not meant to be exhaustive but may suggest where the largest benefits are likely to accrue. Researchers should consider region-specific conditions and determine benefit metrics that are most appropriate for the setting.

Figure 5.3

Metrics for Assessment of Soil Health Benefits

Soil health benefits

- Changes in crop yields
- Value of land, or land productivity
- Land use changes and deforestation
- Producer surplus changes
- Consumer surplus changes
- Changes in food scarcity
- Other indirect effects

Source: World Bank.

5.3 Measuring and Modeling Impacts

A carbon price will have both direct and indirect benefits for soil health. For quantifying direct impacts, such as damages due to nitrogen fertilizer application, economic partial equilibrium models and bottom-up fundamental models are available. Bottom-up approaches often leverage econometric techniques for parameter estimation. On the other hand, general equilibrium models are often used to capture the indirect effects. These effects result from the first-order direct effects influencing other sectors of the economy.

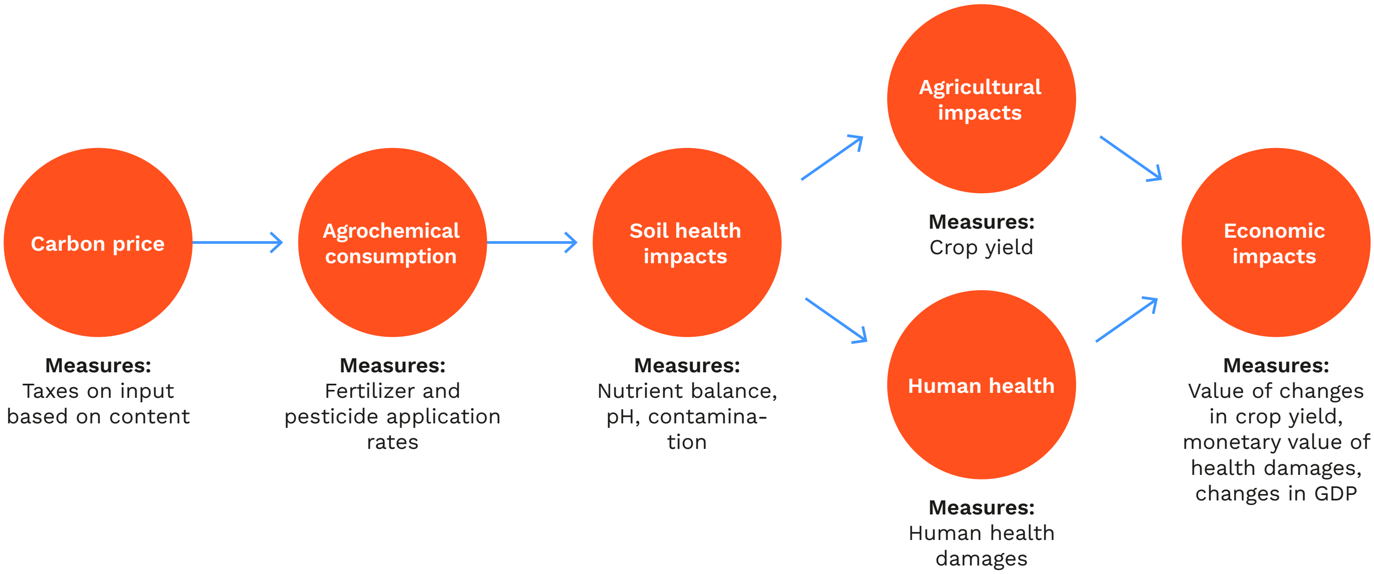
In this section, we begin with a discussion of the modeling of direct impacts of a carbon price on soil resources. Here, we provide an overview of modeling direct impacts of carbon pricing on agrochemical application in the agricultural sector. We then provide an overview of approaches to quantifying soil quality externalities. Finally, we provide a discussion of general equilibrium methods to include indirect impacts in economy-wide benefit analysis.

5.3.1 Direct Impacts of Carbon Pricing on Soil Health

Figure 5.5 illustrates the steps involved in measuring the economic impacts of a carbon price on soil health. Implementing a carbon price will lead to changes in agrochemical consumption, in turn leading to improved soil health impacts (improvements to agricultural productivity and human health). Finally, economic impacts are estimated. Note that impacts to water resources and atmospheric deposition pathways are not included here; these pathways are discussed in the previous chapters on air pollution (chapter 3) and water resources (chapter 4).

Figure 5.4

Steps for Quantifying Direct Benefits from Improved Soil Health



Source: World Bank.

Economic partial equilibrium approaches may be used to estimate the changes in agrochemical use that will occur in response to a carbon price. In order to quantify the behavior of producers and consumers within the supply chain, analysts estimate the price elasticity of demand for relevant goods. The study by Griliches (1958) is a seminal work on the estimation of demand curves for fertilizers in agriculture.

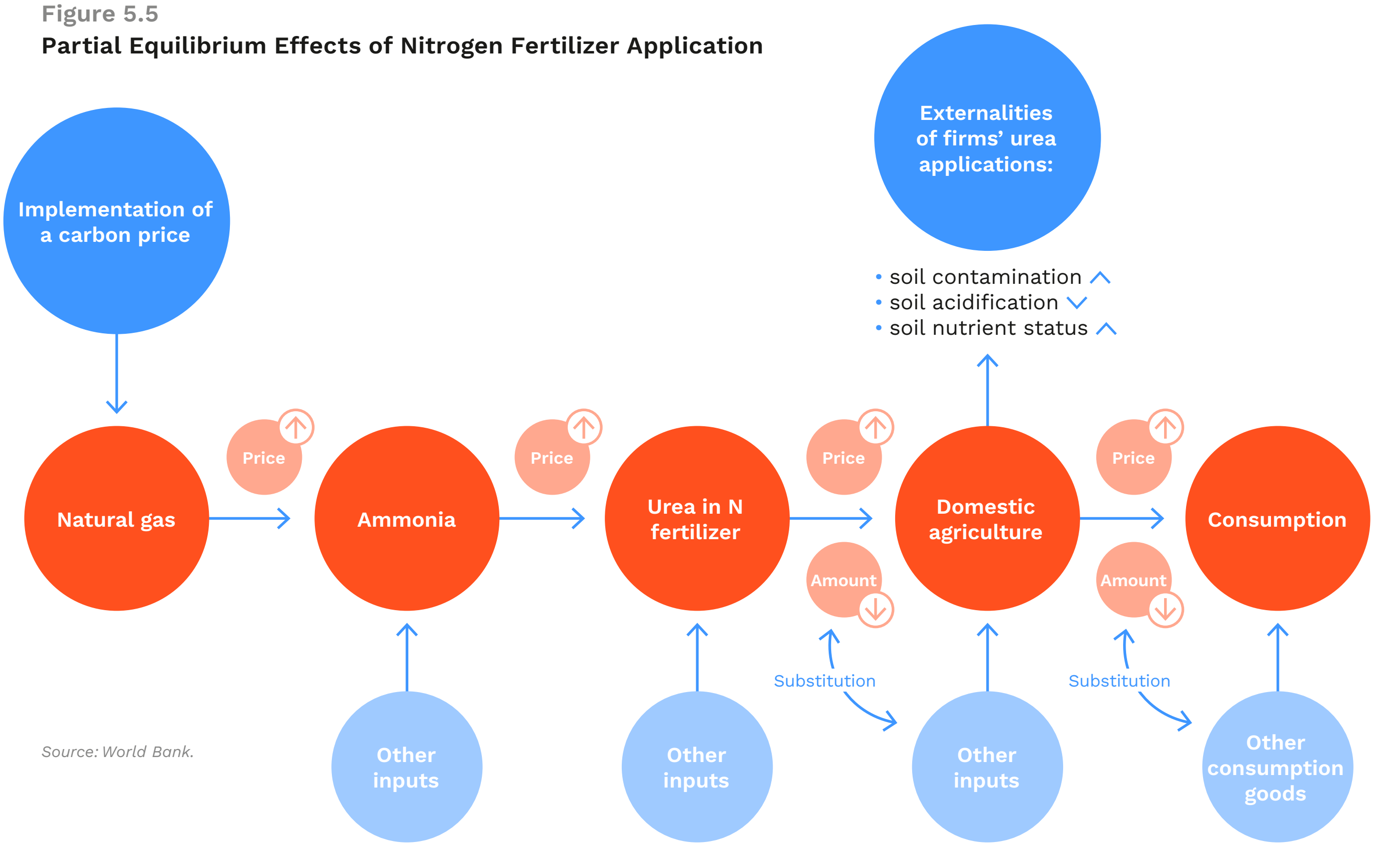
The mechanism leading to soil health changes as a result of a carbon price due to excessive fertilizer additions is as follows:

1. Implementation of a carbon price leads to a higher price of natural gas.
2. As natural gas is a primary input to a variety of agrochemicals, the price of these chemicals increases.
3. Demand for chemicals, and thus their field application, reduces due to reduced demand and substitution to less carbon-intensive inputs.
4. Lower rates of field application lead to reduced adverse effects of excessive application (such as soil acidification).

As a concrete example, let us consider changes in the use of urea fertilizer due to a carbon price. Ammonia is the primary input to urea production; it accounts for most of the energy used in the production process and is generally produced with natural gas. Thus, an increase in the cost of the input fuel will increase the marginal cost of domestic agricultural production. This will result in improved soil health as a result of less domestic agricultural production. However, this may lead to a rise in agriculture prices, which may have regressive distributional impacts that need to be borne in mind and addressed. Equally, this assumes ammonia production is domestic. However, in many locations ammonia products are imported rather than produced domestically. Thus, a carbon price will have an impact on urea production only if a carbon price was imposed on imports based on the carbon content of the good. This example demonstrates the notion of a complete linkage from a carbon price to a measurable outcome (see Figure 5.6). Box 5.1 illustrates this further with a fictitious case study and sample calculations.

Figure 5.5

Partial Equilibrium Effects of Nitrogen Fertilizer Application



Source: World Bank.

Box 5.1

Modeling Externalities of Nitrogen Fertilizer Application

Suppose Country A uses a large amount of urea fertilizer as a nitrogen soil amendment. Ammonia is the primary input for urea production, and natural gas is the primary input for ammonia production. Further, let us suppose that before the imposition of a carbon price, the price of natural gas is $4 per million BTUs (MMBtu), and at this price natural gas costs account for 80 percent of the total cost of ammonia production. Assume the marginal cost of ammonia is $175/tonne.[a]

In urea production, suppose that 1 tonne of urea production requires 0.6 tonne ammonia, 5 MMBtu of natural gas, and $25 of other inputs. Suppose that researchers have estimated that marginal damages in Country A associated with each additional tonne of urea applied is $10.

Further suppose that before the carbon price, Country A uses 300,000 tonnes of urea fertilizer annually, and the price elasticity of demand for urea fertilizer is -0.35.

Now suppose Country A imposes a carbon tax that results in a 15 percent increase in the price of natural gas. Here, assume that the amount of natural gas used in ammonia production and amount of ammonia used in urea production are fixed, that no cost-effective substitutes are available, and that the price of other factors of production remains constant.

With the information given, analysts can estimate the soil health benefits due to the carbon tax. First, we can express the marginal cost ($/tonne) of ammonia thus:

$$MC_{A0} = \$175 = X(\$4) + Y = \$140 + \$35 = P_{A0}.$$

Here, *X* is the amount of natural gas input (MMBtu) per tonne of ammonia, and *Y* is the dollar amount of other inputs. By assumption, the amount of natural gas used and the cost of other inputs remain unchanged after the tax. Thus, after the tax we have the following:

$$MC_{A1} = X(\$4 \times 1.15) + Y = \$161 + \$35 = \$196 = P_{A1}.$$

We see here that this results in a 12 percent increase in the price of ammonia (P_A), by the assumption that price equals marginal cost. Similarly, we have the following for the price of the nitrogen fertilizer, urea:

$$MC_{U0} = 0.6(\$175) + 5(\$4) + \$25 = \$150 = P_{U0}$$

$$MC_{U1} = 0.6(\$196) + 5(\$4 \times 1.15) + \$25 = \$165.6 = P_{U1}.$$

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↓
↓

Since the price elasticity of demand for urea fertilizer is assumed to be -0.35,

$$-0.35 = \frac{(\Delta Q / 300{,}000).}{0.15}$$

Solving for ΔQ, we find that there is a reduction in demand of 15,750 tonnes. With a marginal damage of $10 per tonne, the benefit is $157,500.

Various simplifying assumptions have been made for the purpose of this example. One such assumption is that the increase in prices for inputs to domestic agricultural production will affect prices and demand for agricultural products, which will in turn lead to lower production. This is an example of cross-sectoral interaction that can be modeled with the CGE approaches discussed in this guide. The structure illustrated here can be extended to include these types of interactions.

a. Numbers in this example are based in part on Yara (2018).

The mechanism described in Figure 5.6 applies to other soil amendments and pesticides where demand elasticities vary across regional settings. If budgetary and technical constraints allow, analysts may model impacts on a variety of time scales. In the short run, demand for certain goods may be highly inelastic, but in the longer run, economic agents may adjust to new pricing models by reallocating capital, changing the mix of crops grown, and so on.

Demand for pesticides will similarly be affected by a carbon price. Because of the high energy inputs to pesticide production, the carbon price imposes an additional cost on the most energy-intensive chemicals, resulting in changes in demand. Box 5.2 discusses lessons learned from pesticide taxation in Europe.

Box 5.2

Price Elasticity of Demand for Pesticides in Europe

Four European countries have pesticide taxes: France, Norway, Sweden, and Denmark. Their experience gives us an idea of what the effects of a carbon tax would be, since it would increase the price of pesticides just as a pesticide tax does. Böcker and Finger (2016) analyzed the results of the taxes implemented in these countries and found two results of interest for benefit estimation.

First, the researchers observed substitution toward pesticides less heavily taxed when substitutes were available. Second, when the tax was announced, farmers hoarded the agrochemicals that were subject to taxation, delaying realization of the benefit, so that benefits were observed only in the long term. Policy makers and modelers can draw two lessons for modeling benefits. First, limited availability of substitutes may create perverse incentives that mitigate benefits in the short run. Second, long-run benefits may be significantly different than those in the short run, and such temporal aspects should be considered.

5.3.2 Estimating Monetary Value of Damages

In most cases, a policy maker will need to conduct a cost-benefit analysis, weighing the expected costs of policy implementation against expected benefits. In order to conduct such analyses, it is necessary to quantify scenario benefits in monetary terms. In general, we seek to define a function that takes changes in a benefits metric as an input and gives economic damages (in dollar terms) as an output. Such a function is referred to as a damage function. The benefit value will be the difference between the damage function evaluated at the business-as-usual level minus the damage function evaluated at the carbon policy scenario level. For example:

$$Value = D(SQI_{BAU}) - \mathrm{D}(SQI_{CT}),$$

where $D()$ is the damage function, SQI_{BAU} is the soil quality index under the business-as-usual, case, and SQI_{CT} is the soil quality index under a carbon pricing scenario. This is an example where a soil quality index is used as the metric of soil health, but the damage function may take multiple forms. For example, it may directly take as an input nitrogen fertilizer application and/or atmospheric sulfur concentrations.

There is an alternative to a soil quality index that has been used to quantify damages due to soil acidification from air pollution and excessive agrochemical use; this is the “exceedance of critical loads” of chemical elements or pollutants (e.g., nitrogen and sulfur). In this context, load refers to the atmospheric deposition over time (Lovett 2013). As defined by Nilsson and Grennfelt (1988), a critical load is the “highest load that will not cause chemical changes leading to long-term harmful effects on the most sensitive ecological systems.” Deposition levels above critical loads are referred to as “exceedance of critical loads” and result in damages to soil health causing agricultural losses and forest and ecosystem damage (Williston et al. 2016). For a study that models exceedance of critical loads of nitrogen in ecosystems throughout Europe under GHG pricing scenarios, see Rafaj et al. (2013), whose methodology is discussed in more detail in Box 5.3.

Box 5.3

Modeling Exceedance Levels of Acid Deposition in Europe under GHG Pricing

Rafaj et al. (2013) examine the benefits of climate change mitigation policies in Europe through 2050. The authors use the Greenhouse Gas and Air Pollution Interactions and Synergies (GAINS) model to simulate traditional air pollutant emissions under a business-as-usual scenario and a 2° climate goal scenario. Scenario development in turn relies upon projections of energy consumption using the Prospective Outlook for the Long-Term Energy System (POLES) model. The authors report estimates of benefits due to air pollution and water and soil ecosystem damage.

The GAINS model is used to explore cost-effective strategies to mitigate air pollution and greenhouse gas emissions given an exogenously defined projection of future economic activity and costs of abatement. Outputs include emissions that cause damage to soil and waterways by depositing compounds that induce acidification and eutrophication.[a]

The POLES model is a global energy sector simulation model. It is a detailed partial equilibrium model including regional and sectoral representation of energy-intensive sectors of the economy and endogenously determined energy prices. The model includes “learning by doing” and “learning by research” effects and determines detailed energy balance accounting. The POLES model is a useful tool for policy makers seeking to simulate the evolution of energy demand internationally and assess policy implementation.[b]

Rafaj et al. (2013) leverage both the GAINS and POLES models to estimate an array of benefits of climate policy implementation in Europe. The authors estimate forest area with acid deposition exceeding critical loads to 2050 and find that under both the baseline scenario and the GHG mitigation scenario, the exceeded area was reduced. Under the GHG mitigation scenario, there is a 15 percent additional reduction in exceeded area relative to the baseline scenario. The difference is shown in figure B5.3.1.

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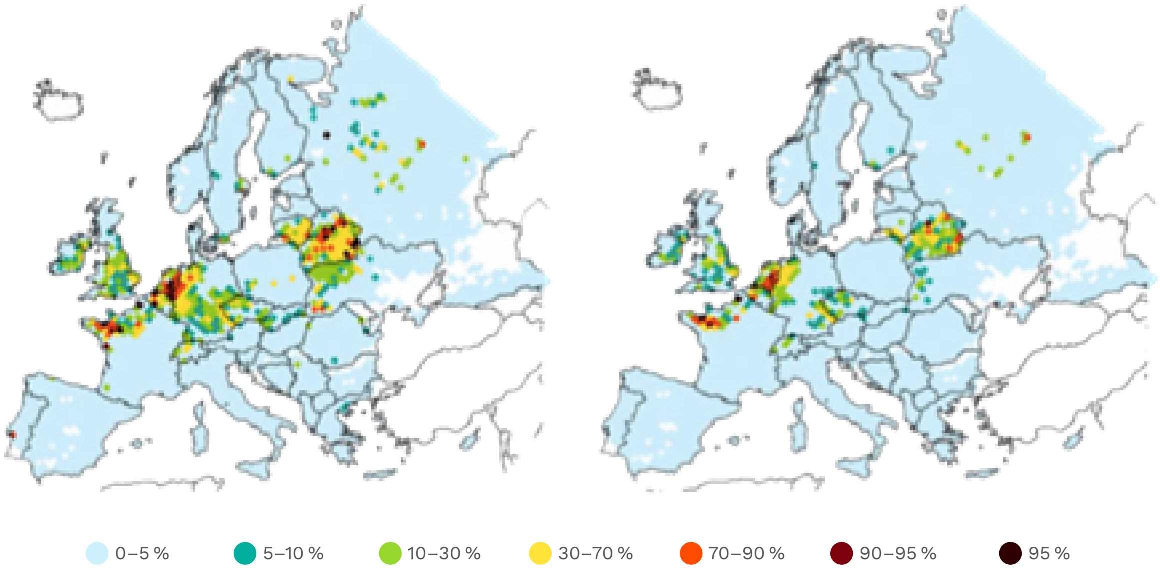
Figure B5.3.1

Exceedance of Critical Loads for Acidification in Europe Predicted in 2050: Business-as-Usual Scenario (left) vs. Mitigation Scenario (right)



Source: Rafaj et al. (2013).

a. For more on the GAINS model, see International Institute for Applied Systems Analysis (IIASA), "About GAINS," https://iiasa.ac.at/web/home/research/researchPrograms/air/GAINS.html.

b. For more on the POLES model, see EU Science Hub, "POLES Global Energy Model," https://ec.europa.eu/jrc/en/poles.

There is a large body of literature surrounding the estimation of monetary damages due to incremental changes in soil quality (or incremental changes in soil health threats, such as nitrogen fertilizer application); see Kaitala, Pojola, and Tahvonen (1992); Hansen and Ribaudo (2008); Von Blottnitz et al. (2006). Damages are likely to vary significantly across regions and countries, and care must be taken in estimating damages for the country under study.

Economic damages due to soil health degradation may arise from several causes:

1. Reduced yields in agriculture resulting in economic losses
2. Reduced availability of cultivable land
3. Losses and reduced health of forested area
4. Human health impacts due to toxin exposure

Researchers may use estimates in changes of the above to estimate the monetary value of the benefit. Von Blottnitz et al. (2006) provide an example of a damage estimation methodology. The authors report estimated monetary damages due to the use of synthetic nitrogen fertilizer application. For total life-cycle impact, the authors estimated total economic damages of €0.31/kilogram of nitrogen (kgN), with soil health damages accounting for a portion of this total. The estimated damages due to $N_2$0 release from fertilizer in soil and water eutrophication are estimated to be €0.12/kgN and €0.03/kgN, respectively, for a total of €0.15/kgN. These values are considered to be very large compared to a market price of approximately €0.5/kgN at the time of the study.

5.3.3 Indirect Impacts

Indirect impacts due to soil health are likely to be substantial. Because soil health is central to agriculture, policy makers should consider the economy-wide effects due to carbon pricing through CGE modeling. Outcomes of interest include distributional outcomes (transfers between actors), structural outcomes (for example, issues of competitiveness), and welfare-related outcomes (whether effects are progressive or regressive).

CGE models are powerful tools for estimating soil health benefits of carbon pricing because they can capture intersectoral linkages in the economy. In this section we illustrate how CGE models can be used to estimate and quantify indirect effects of carbon pricing on soil health and associated benefits. The examples in this section offer guidance about using CGE models to elucidate the direct and indirect impacts of carbon pricing and related policies on soil health. The applications sometimes include OECD economies, which provide examples of what more extensive and intensive data resources could offer policy makers in developing countries.

The net benefits of carbon pricing for soil health are not immediately clear. On the one hand, increasing the inputs to the agricultural sector can reduce production and improve soil health. However, if these increases also make domestic agricultural prices more expensive, they can reduce domestic competitiveness. Shocks in this sector can lead to structural changes, as agents shift resources to different crops in response to financial incentives. For example, under carbon pricing farmers may shift away from food crops toward bioenergy resource crops, which will affect both the food and energy sectors. CGE models can help policy makers map out these changes and determine where complementary policies may be necessary to avoid losses to particular actors in the economy or to mitigate adverse effects. For instance, it may be necessary to implement policies that avoid increases in food prices for low-income communities or that support smallholder agriculture. Such complementary policies in this case may leverage carbon policy revenue to support domestic agriculture through direct subsidy, soil management incentives, or other policy instruments. Carbon-pricing revenue may also be used to support GHG mitigation measures in the agriculture, forestry, and other land use (AFOLU) sector; measures such as forest management policies, soil restoration programs, and livestock management have the potential to increase benefits achieved from the carbon price. In many instances, countries that have implemented carbon prices and also implemented such mitigation measures have achieved improved decarbonization and additional benefits in the AFOLU sector and beyond (Climate Change Advisory Council 2019). More guidance on revenue use can be found in the PMR’s “Using Carbon Revenues” (World Bank 2019b).

In the remainder of this section we provide examples of studies that have used CGE modeling to simulate economic impacts of policies affecting the agricultural sector. Box 5.4 describes use of a GTAP global CGE model to assess carbon pricing effects on fertilizer use, and resulting economic impacts. Box 5.5 describes CGE modeling of a national economy for policy assessment in the developing world.

Box 5.4

Carbon Pricing and Fertilizer Use

Sturm (2011) uses a CGE modeling framework to assess the impact of the European Union Emission Trading System (EU ETS) on the fertilizer industry. The author modeled the 2013 proposed inclusion of production of ammonia and nitric acid under the EU ETS. As covered activities under the EU ETS, production of mineral fertilizers that rely on these inputs would incur a price premium acting as a carbon price. In this paper, the impact of the EU ETS is implemented as a carbon price on the production and use of mineral fertilizers for analysis with the GTAP global CGE model. In order to represent the fertilizer industry, the author decomposes the “chemical, rubber and plastic products” sector (crp) of the GTAP database and introduces a new sector representing the fertilizer industry (FERT). In addition, she modifies the production structure to introduce the substitution possibility between the land and the fertilizers by choices of crops and agronomic practices. The author finds a decrease in production of fertilizers in the EU due to the ETS. A decrease in use of fertilizers was also found, but the decrease was mitigated by an increase in imports. In addition, the modeling found a slight decrease in net exports of grains. This modeling demonstrates how GTAP CGE models and databases can be used to model linkages from carbon pricing to the fertilizer industry, agricultural production, and other sectors of the economy.

Box 5.5

Distributional Impacts of Public Spending in Agriculture

In Benfica et al. (2017), the authors focus on distributional impacts of public spending in the agricultural sector of Mozambique. They evaluate a five-year agricultural investment plan, including fertilizer subsidies and agricultural research and extension programs. Using a recursive-dynamic computable general equilibrium model with 56 sectors and three subnational regions, they assess how changes in sector productivity lead to growth and poverty outcomes.[a] Input-output coefficients are taken from a national social accounting matrix for Mozambique and are used to estimate crop value added (Arndt and Thurlow 2014; McCool, Thurlow, and Arndt 2009). The authors econometrically estimate investment impacts on farm productivity and then use these results to calibrate investment functions in a spatially disaggregated CGE model. The CGE analysis presented in the study found that the plan’s benefit-cost ratio and poverty impacts justified implementation. The study illustrates how CGE modeling can be used to capture important intersectoral linkages in the agricultural sector. For example, the authors note that returns were found to be greater when increased resources were devoted toward research and extension services and away from irrigation.[b]

a. For details on recursive-dynamic computable general equilibrium models, see Diao and Thurlow (2012).
b. Extension is the provision of information and advisory services to farmers; see International Food Policy Research Institute, “Agricultural Extension,” https://www.ifpri.org/topic/agricultural-extension.

Table 5.2 outlines the key steps in quantifying the direct and indirect benefits to soil health through a carbon price.

Table 5.2

Quantifying the Effects of a Carbon Price on Soil Health

	Step	Notes
1	Estimate change in agrochemical consumption	• Changes in fertilizer and pesticide application rates can be estimated by economic partial equilibrium approaches based on the demand curves for specific fertilizers and pesticides.
2	Estimate changes in soil health	• Possible metrics include nutrient balance, pH, and contamination levels.
3	Estimate health and agricultural impacts	• See quantification notes for air quality in table 3.3.
4	Consider impacts to air quality and water resources	• Changes in air and water quality will also affect soil health. Further guidance on quantifying these benefits are provided in the air quality and water resources chapters in the guide.
5	Estimate the change in the monetary value of damages to soil health	• The benefit value will be the difference between the business-as-usual damage function to soil quality and the damage function with a carbon price.
6	Estimate indirect impacts to soil health	• Indirect impacts are likely significant given that soil health is central to agriculture. • CGE models can help estimate indirect impacts. This can be done by introducing a new sector (the fertilizer industry, for instance) to the model, as well as by modifying the production structure to introduce substitution possibilities between land and fertilizer by choices of crops and agronomic practices.

Source: World Bank.

6.

Transportation

At a Glance

Carbon pricing can reduce the prevalence of both road injuries and congestion.

- Empirical evidence shows higher gasoline prices lead to reduced traffic accidents and congestion.
- Corrective gasoline pricing affects road safety by reducing vehicle miles traveled. In the short term, it does so by reducing trip frequency and distance for nonwork trips and by changing commute modes and driving behavior (e.g., encouraging fuel-efficient driving). In the long term, carbon prices may encourage drivers to switch to more fuel-efficient vehicles or relocate closer to work.
- Apart from vehicle fuel efficiency, the same steps relate carbon prices to reductions in congestion. However, the literature on gasoline pricing and congestion is limited, and more work is needed to fully understand the relationship.
- Transportation benefits include significant health and economic benefits, which can be quantified through a variety of metrics. For accidents these include fatalities, nonfatal injuries, medical costs, property damage, and forgone wages and expenditures. For congestion these include negative health outcomes, travel delays, reduced benefits of urban agglomeration, additional fuel use, and travel time variability.
- Direct benefits can be used as inputs into CGE models, and the related linkages and overall benefit to the macroeconomy can be measured. For instance, economic goods and services may be sensitive to congestion, which could shrink business markets and raise production costs.

6. Transportation

6.1 Introduction

Carbon pricing presents the potential for numerous benefits in the transportation sector, which deserve special attention because of the importance of this sector to a global low-carbon transition: the sector accounts for almost a quarter of global CO_2 emissions (Sims et al. 2014). By increasing the price of fuels, a carbon price can send a signal to drive less and choose lower-transport options like low-carbon fuels or public transport. At the same time, influencing consumer behavior through fuel pricing alone may be challenging, as other factors–like a tendency to over-discount future fuel savings, work-home location, and societal norms–also play a role (Greene, Evans, and Hiestand 2013). Nevertheless, a carbon price can help reduce road transport emissions and also help reduce traffic accidents and congestion, resulting in health and economic benefits.[34] Road traffic deaths are now the eighth leading cause of death worldwide across all age groups, moving ahead of such categories as HIV/AIDS, tuberculosis, and diarrheal diseases. They are also the leading cause of death for children and young adults ages 5–29 years (WHO 2018). Congestion can also cause significant health problems by affecting air quality and reducing time for healthy activities. More broadly, these all have a negative impact on productivity and economic growth. For instance, sitting in traffic is estimated to have cost the UK and the US almost $98 billion in 2019 alone (Reed 2019). By disincentivizing vehicle miles traveled, carbon pricing can reduce local air pollution, the number of traffic accidents, and congestion. These benefits are particularly attractive for developing countries, where these issues are a major concern. For each benefit, a different approach is required for the mechanism by which the benefit is achieved, and the way costs are quantified. These approaches are discussed in detail below.

6.2 Identifying Benefits and Linkage to Carbon Prices

6.2.1 Road Injury

As the world continues to urbanize and personal transportation options become more varied and accessible, road traffic deaths continue to climb. Some 1.35 million deaths globally were reported in 2016 (WHO 2018). But the public health concerns go beyond mortality. Lack of road safety contributes to inactivity, making individuals less likely to walk, cycle, or use public transportation if road networks are unsafe or unreliable. Fewer people cycling, walking, or using public transport also contributes to the other leading causes of death globally, such as heart disease, stroke, pulmonary disease, and diabetes.

Road traffic deaths disproportionately burden low- and middle-income countries. Taken together, low- and middle-income countries report 93 percent of all traffic fatalities, but account for only 60 percent of the world's vehicles (figure 6.1). The average rate of traffic deaths per capita is also over three times higher in low-income than in high-income countries (WHO 2018) (also see figure 6.2).

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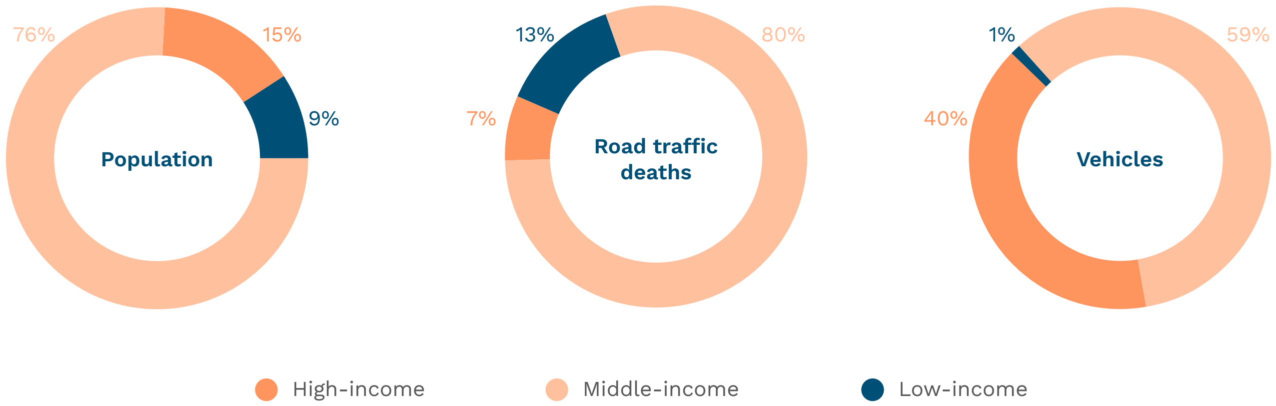
[34] Reduced damage to the road network is also sometimes discussed among transportation benefits, although it is less important than the other categories and is not discussed here.

Figure 6.1

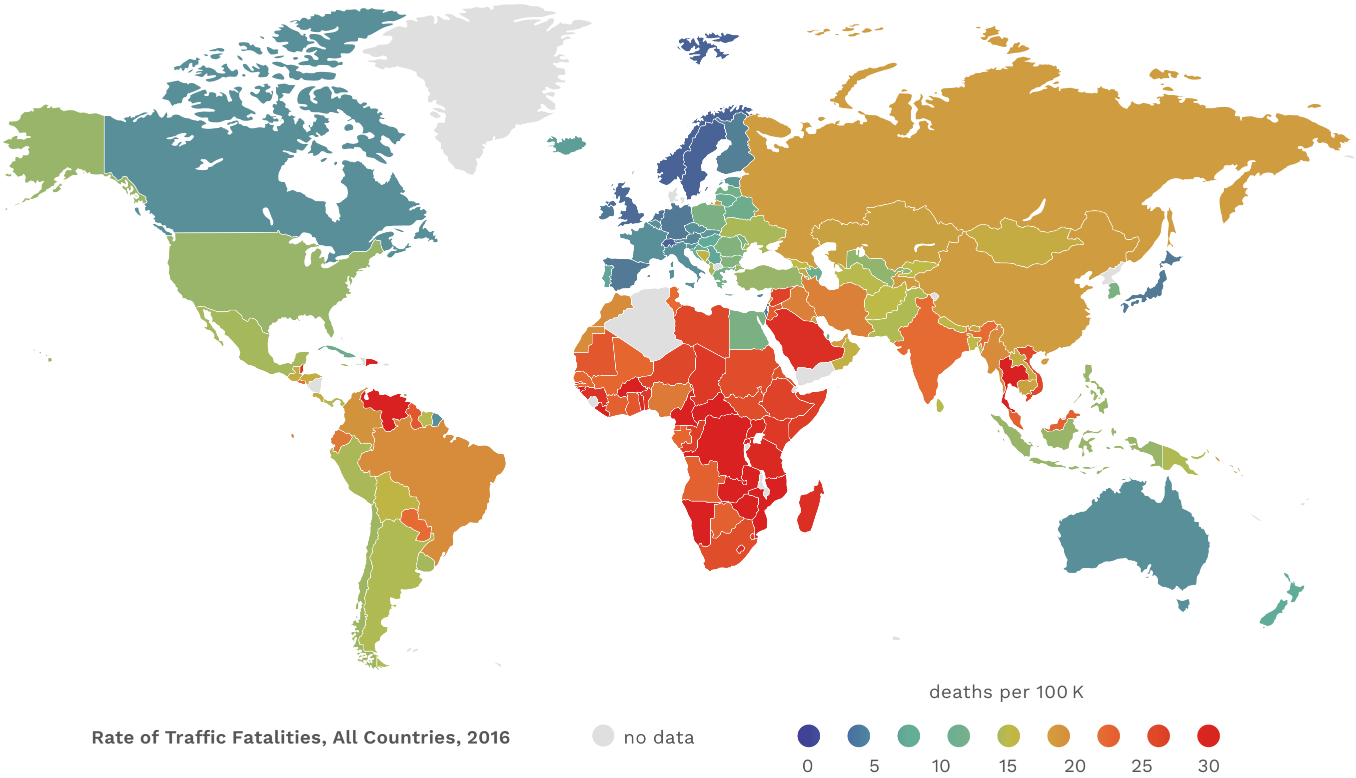
Proportion of Population, Road Traffic Deaths, and Registered Motor Vehicles by Country Income Category, 2016



Source: WHO (2018).

Figure 6.2

Traffic Fatalities



Source: WHO (2018).

Traffic deaths are significant from a human welfare perspective, but evidence also suggests that the excess burden of traffic deaths reduces economic growth (see box 6.1). For example, the World Bank estimates that halving road deaths over a 24-year period could increase GDP in low- and middle-income countries by 7.1 percent to 22.2 percent (World Bank Group 2017). Road accidents disproportionately affect people in their most productive economic years, decreasing the supply of labor, limiting productivity, and ultimately leading to reductions in output. The loss of productive life years also reduces the ability of people to acquire additional education and skills, adding a further drain on the economy.

Box 6.1

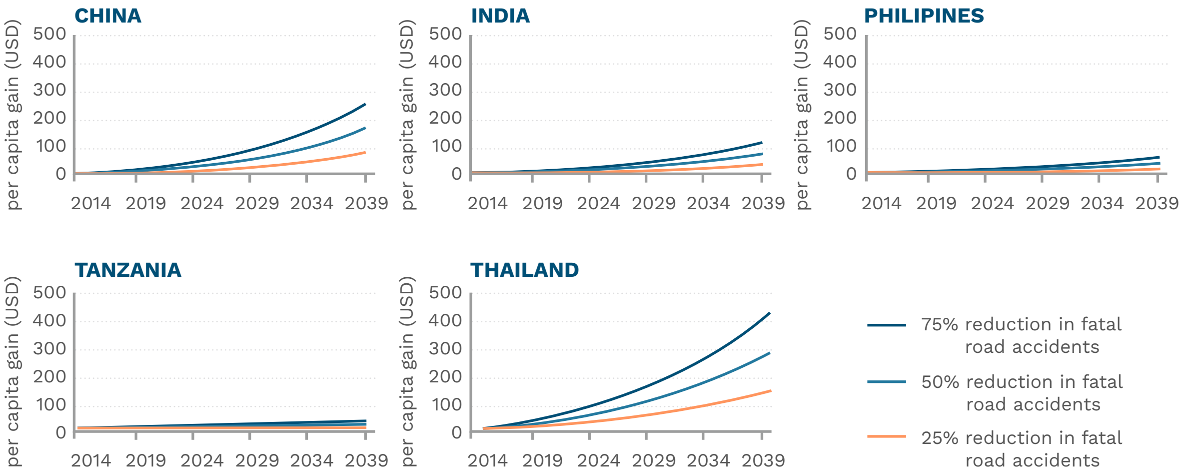
The High Toll of Traffic Injuries: The Macroeconomic and Welfare Benefits of Reducing Road Traffic Injuries in Low- and Middle-Income Countries

Despite the overwhelming evidence of the heavy burden of road traffic injuries in low- and middle-income countries, measuring the magnitude of this burden is difficult. Most estimates that focus on the developing world are imprecise and draw on findings from high-income settings that have limited relation to developing country settings. Original research by the World Bank overcomes this issue by considering the economic impacts of road traffic injuries in five low- and middle-income countries (China, India, the Philippines, Tanzania, and Thailand).

Road traffic injuries disproportionately affect the most economically productive segment of the population, which in theory would depress GDP growth rates. The World Bank study confirms this hypothesis, finding evidence of a strong macroeconomic effect from reducing road traffic injuries. The study shows that reducing road traffic mortality and morbidity by 50 percent and sustaining this reduction over a period of 24 years would generate an additional flow of income in the five countries–equivalent to 7.1 percent of 2014 GDP in Tanzania, 7.2 percent in the Philippines, 14 percent in India, 15 percent in China, and 22.2 percent in Thailand.

Figure B6.1.1

Estimated GDP per Capita Gain Associated with a Reduction of Road Traffic Fatalities, by Year and Intervention Scenario (US$ per capita)



Source: World Bank Group (2017).

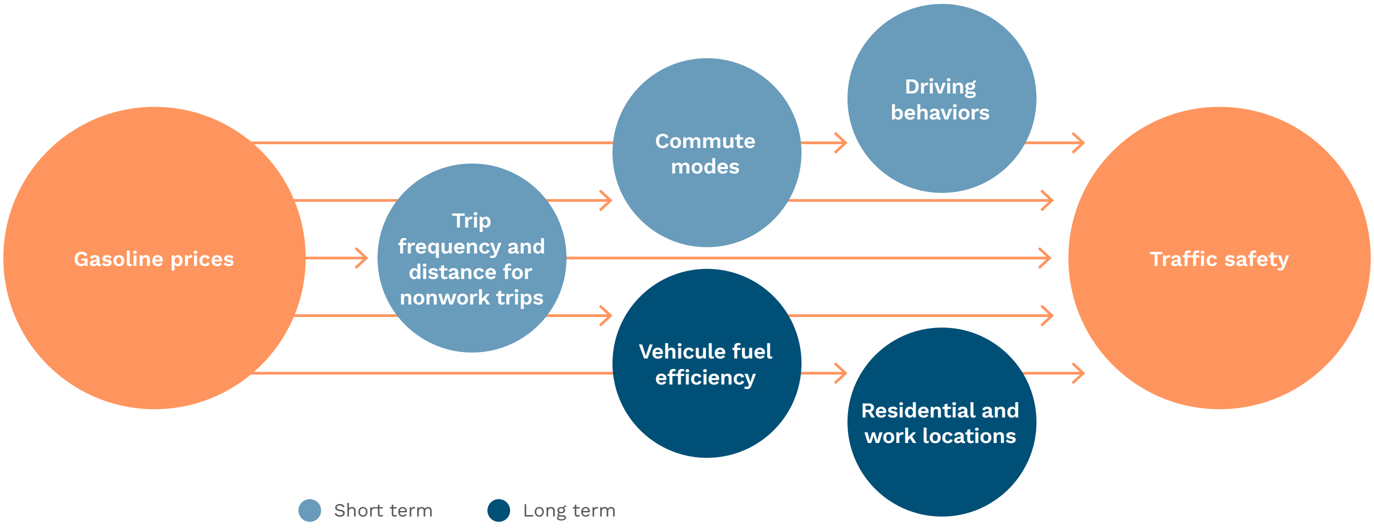
Unlike other major categories of mortality, traffic accidents are both fully predictable and preventable (World Bank Group 2017). Given proper investment and effective policies, road safety can be improved, and traffic deaths and injuries can decline. Carbon pricing presents the opportunity to reduce these preventable deaths through corrective fuel pricing. Correcting fuel prices can reduce the risks of accidents by incentivizing more efficient road use (Chi et al. 2013b), although this effect is highly dependent on the country in question and the vehicle ownership rates. Although low- to middle-income countries are less reliant on cars, increasing wealth and low fuel prices have seen vehicle ownership levels dramatically increase. Furthermore, populations in low- to middle-income countries are more sensitive to changes in fuel prices than those in high-income countries, suggesting carbon pricing can shape transport choices.[35]

6.2.2 Road Injury and Fuel Prices

The mechanism by which carbon pricing can reduce accidents is multifaceted but is primarily related to gasoline prices and traffic safety. Chi et al. (2013a) conceptualize gasoline prices relating to traffic safety through five intermediate steps: trip frequency and distance for nonwork trips, commute modes, driving behaviors, vehicle fuel efficiency, and residential and work locations. These mechanisms are outlined in figure 6.3.

Figure 6.3

Conceptual Framework of the Relationship between Gasoline Prices and Traffic Safety



Source: Chi et al. (2013a).

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[35] *Transport is also affected by a variety of nonprice factors, such as availability of public transport and home and employment locations. Carbon pricing will not affect nonprice factors, especially for those with limited transport options. However, in aggregate across a country, carbon pricing and sufficiently expensive fuel prices will affect personal transportation decisions.*

The first three mechanisms are short-term effects that would occur immediately after gasoline prices increase. First, increased gasoline prices may change non-essential vehicle travel by encouraging drivers to make fewer trips or travel shorter distances. They may also lead to more multipurpose trips, as opposed to single-purpose trips. Second, higher fuel prices can encourage changes to commute modes, encouraging drivers to take public transit, carpool, bike, or walk. Third, increased fuel prices can change driving behavior by encouraging operators to drive in a more fuel-efficient manner–for instance, by driving slower in noncongested conditions and reducing sudden speeding and braking.[36] All three of these mechanisms would result in fewer vehicles on the road or change driving behaviors and reduce the risk of accidents.

The last two mechanisms are long-term effects. Increased fuel prices over time might encourage drivers to switch to more fuel-efficient vehicles, which are typically newer and have improved safety features. Furthermore, fuel-efficient vehicles are lighter and less likely to cause significant damage to other road users.[37] Finally, persistent increases in gasoline prices might induce workers with long commutes to relocate to be closer to work or search for employment closer to their current residence. Both changes would decrease the number of vehicle miles traveled (VMT) and reduce traffic accidents.

It should be noted that higher gasoline prices can potentially increase serious accidents if individuals switch to less protected transport options. For example, increased gasoline prices could encourage drivers to change from cars to motorcycles or bicycles, which offer less protection in the event of an accident and could led to more serious injury. There is empirical evidence that increases in fuel prices are associated with more motorcycle traffic fatalities (Wilson, Stimpson, and Hilsenrath 2009; Zhu et al. 2015). However, as motorcycles grow as a share of overall traffic, increased fuel prices again lead to less use of motorcycles, which reduces fatalities. This dynamic suggests that the effect of higher fuel prices can be ambiguous, and other research has found a net decrease in motorcycle fatalities in response to higher fuel prices (Zhang 2020).

Looking at total accidents, however, there is strong evidence that increases in motor fuel prices do reduce traffic fatalities. Globally and within countries, empirical evidence repeatedly shows an inverse relationship between gasoline prices and road fatalities (Chi et al. 2013a, 2013b; Grabowski and Morrisey 2004, 2006; Haughton and Sarkar 1996; Leigh and Wilkinson 1991; Sivak 2009; Burke and Teame 2018; Burke and Nishitateno 2015).

The most comprehensive work on gas prices and road fatalities comes from Burke and Nishitateno (2015), who draw on data from 144 countries between 1991 and 2010. Their analysis suggests a significant negative correlation between gasoline price and road deaths, with an estimated mean elasticity between -0.3 and -0.6 in the long run. They find that that 35,000 road fatalities per year could be potentially avoided by the removal of fuel subsidies on a global scale.

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[36] *In congested settings, increased fuel prices can increase vehicle speeds by reducing congestion (Zhang and Burke 2020; Burger and Kaffine 2009).*

[37] *Lighter vehicles might also be more prone to damage when hit. This effect might reduce the total number of crashes but could lead to more severe accidents.*

6.2.3 Fuel Prices versus Taxes

As the empirical evidence clearly demonstrates, there is a negative price elasticity between vehicle accidents and gasoline prices. However, one important distinction is the difference between estimating gasoline demand elasticity based on gasoline price and estimating it based on gasoline tax. Researchers often assume that the response to a gasoline tax change is the same as to a commensurate change in gasoline prices including tax. Li, Linn, and Muehlegger (2014) explicitly assess consumer responses to gasoline taxes by differentiating gasoline tax and tax-exclusive gasoline prices. They find robust and convincing evidence that changes in gasoline taxes are associated with greater changes in gasoline consumption and vehicle choices than corresponding changes in tax-inclusive gasoline prices. The authors suggest that this differential effect is driven by perceived persistence and salience. Tax prices may be perceived as more persistent than changes to gasoline prices due to other factors (such as oil prices). Given the fixed costs of adjusting driving behavior and vehicle ownership, consumers are more likely to respond to persistent rather than transitory price changes. In regard to salience, gasoline tax changes tend to be more documented by the media than gasoline price changes, and thus more salient to consumers (Li, Linn, and Muehlegger 2014). Regardless of the mechanism, this work demonstrates that gasoline tax changes are significant in changing gasoline consumption.

This finding is reinforced elsewhere in the literature. Marion and Muehlegger (2011) find evidence from the United States that state and federal gasoline taxes are passed on fully to consumers and are incorporated into the tax-inclusive price in the month of the tax change. Taken together with Li, Linn, and Muehlegger (2014), this research suggests that gasoline increases through carbon pricing will be fully passed on to consumers, increasing the price of gasoline. This increase in gasoline prices will reduce vehicle accidents, which is a direct benefit of carbon pricing. Carbon pricing could therefore be an attractive policy tool to help reduce the burden of vehicle accidents through changing fuel prices.

6.2.4 Congestion

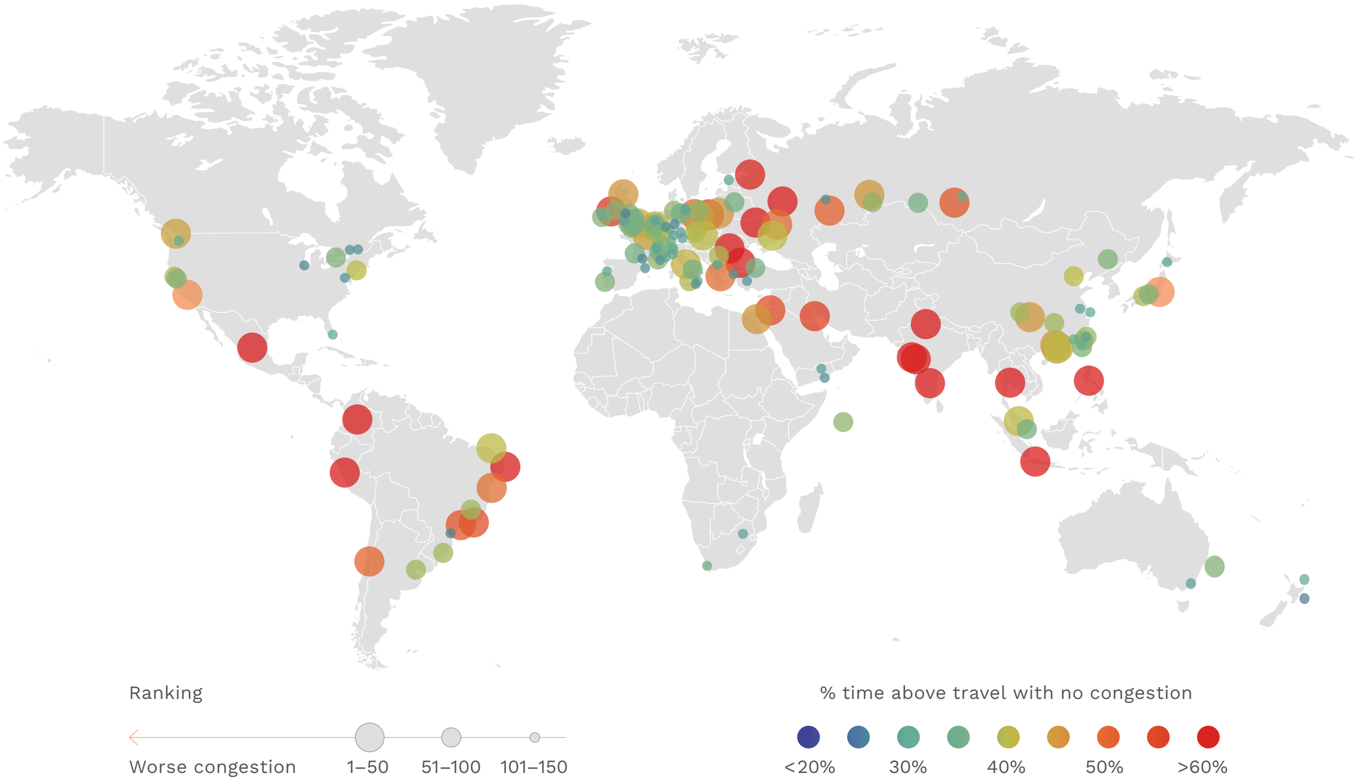
Rapid and sustained urbanization has led not only to an increase in road injuries but also to road congestion. Traffic congestion is typically defined as a situation in which the demand for road space exceeds the supply. Congestion reduces travel speeds and can eventually trigger “facility breakdown.” This occurs when a road can no longer accommodate more vehicles, which causes a decrease in the road’s overall capacity as more vehicles try to enter the road. For example, a highway that is designed to accommodate vehicles at 60 mph can accommodate nearly 2,300 cars per lane per hour. If congestion increases enough to trigger a facility breakdown, this same roadway may accommodate fewer than 700 cars per lane per hour (Reed 2019).

As the world urbanizes and personal transport options become less expensive, congestion has increased precipitously and now constitutes a global problem. As seen in Figure 6.4, many of the world’s most congested cities are in low- to middle-income countries.

Successful traffic management in developing countries is particularly a problem, as cities are often not well planned. Critical congestion areas, where the road networks converge and a large amount of traffic needs to pass through the congested areas, are especially prevalent in developing countries (Jain, Sharma, and Subramanian 2012). Furthermore, the enforcement of traffic laws in developing countries is often limited, weakening the incentive for drivers to follow traffic rules. Other factors that contribute to higher levels of congestion include underfunding for public transit and the increasing perception of private vehicles as necessities rather than luxuries.

Figure 6.4

World Ranking of Congestion, by top 150 Cities



Source: TomTom (2020).

Increased congestion presents negative externalities to both public health and the economy overall. From a public health perspective, increased congestion leads to worse health outcomes, as longer commutes lead to less time for healthy behavior such as exercise, relaxation, or socializing. Hansson et al. (2011) find that increased commutes are linked to measures of reduced happiness such as decreased energy, increased stress, and increased work absences due to illness. Longer commutes have also been shown to negatively affect physical health by increasing blood pressure and increasing the risk of obesity (Hoehner et al. 2012).

From an economic cost perspective, congestion costs are typically quantified by monetizing travel delays. These costs, in terms of lost time and transport costs, are the easiest to quantify and are often the most commonly cited costs of congestion. They are also typically the largest overall cost category as well, and can be economically significant. In the United States, they represent nearly 96 percent of total congestion costs (Schrank, Lomax, and Eisele 2019). Meanwhile, the Asian Development Bank (2010) estimates that road congestion costs Asian economies 2–5 percent of GDP per year.

Some studies have considered the more complicated linkages to the overall macroeconomy as well. Research in the United States has attempted to measure the larger economic effects by considering how various producers of economic goods and services are sensitive to congestion. Weisbrod, Vary, and Treyz (2003) measure the impact of congestion on business costs, productivity, and output and find that congestion shrinks business markets and raises production costs. Their work argues that the positive externalities associated with agglomeration economies operating in large metropolitan areas are diminished with congestion.

There are other economic costs of congestion that are harder to quantify. Congestion could lead to additional fuel use because fuel efficiency is lower in stop-and-go traffic. However, the link between congestion and fuel consumption is complicated; some congestion could increase fuel efficiency if it lowers speeds, but keeps traffic flowing. Using data from research in the United States (Schrank Lomax and Eisele 2019), we estimate that the added fuel costs of congestion account for approximately 4.4 percent of total congestion costs, suggesting additional fuel costs are a minor cost category.

Other costs include costs associated with the variability of travel time. Individuals may choose to leave earlier or later to avoid congestion, and this choice will affect their arrival time at the intended destination. This behavior can incur costs either from the wasted time of an early arrival or penalties from a late arrival. Additionally, congestion can lead to uncertainty about travel times, making scheduling difficult. Various studies have suggested that travel time variability raises the overall costs of congestion by about 10 percent to 30 percent (Fosgerau et al. 2008; Peer, Koopmans, and Verhoef 2012). The negative externalities associated with both accidents and congestion are summarized in Figure 6.5.

Figure 6.5

Negative Externality Metrics for Accidents and Congestions

Road injury costs

- Fatalities
- Nonfatal injuries
- Medical costs
- Property damage
- Forgone wage/expenditure
- Indirect multiplier effects

Congestion costs

- Negative health outcomes
- Travel days
- Reduced benefits of urban agglomeration
- Additional fuel use
- Travel time variability
- Indirect multiplier effects

Source: World Bank.

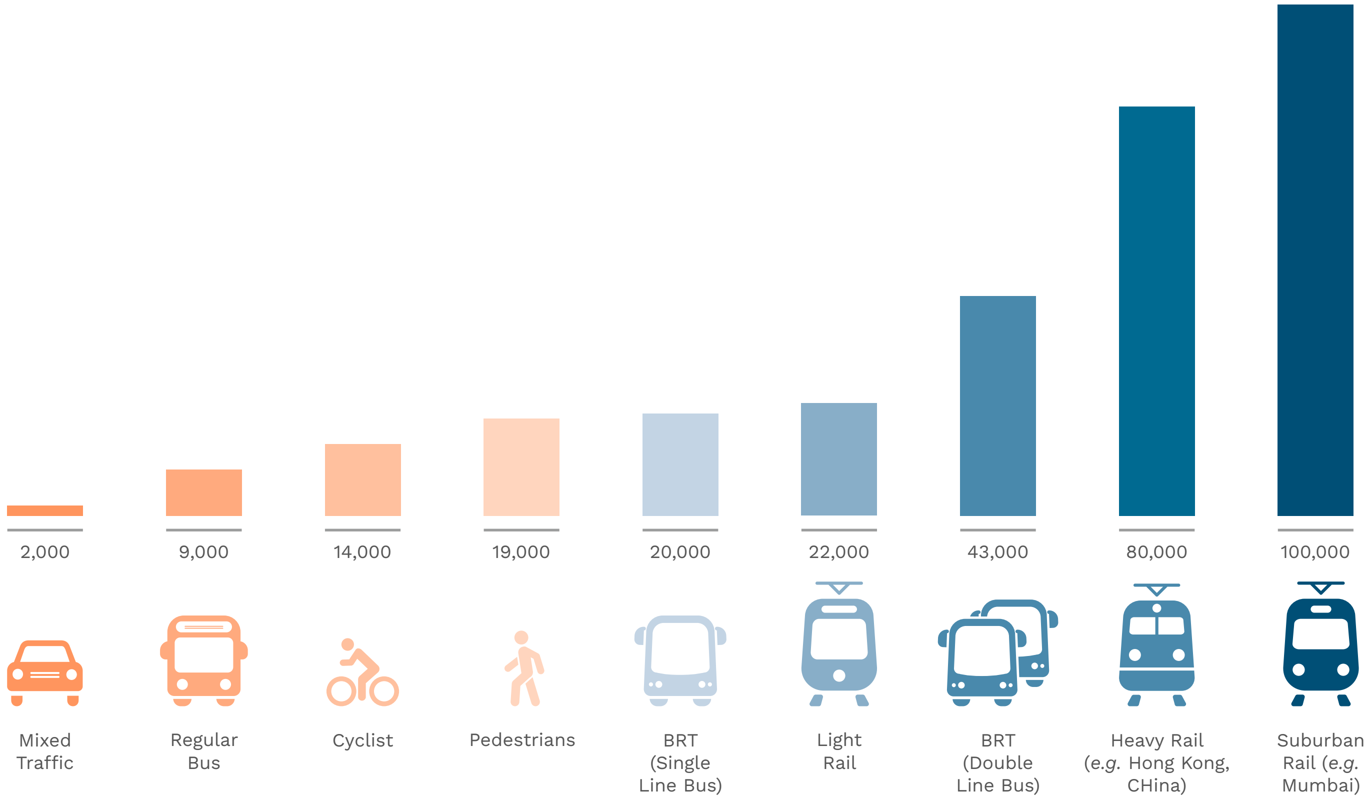
6.2.5 Congestion and Fuel Prices

Gasoline prices and congestion are related through the same intermediate steps as gasoline prices and road accidents (see Chi et al. [2013a] and section 6.2.2). The four intermediate steps are trip frequency and distance for nonwork trips, commute modes, driving behaviors, and work locations. The fifth step that Chi et al. (2013a) outline–vehicle fuel efficiency–is not related to congestion so does not apply here.

Arguably the most effective short-term mechanism in reducing congestion is encouraging road users to change commute modes to more spatially efficient methods, such as bicycles or public transport. This switch can greatly increase road capacity and reduce congestion. Road capacity can commonly be measured through corridor capacity, which refers to the number of people who can be transported over a given road width in the course of a given time period. As Figure 6.6 illustrates, the car is the most spatially inefficient method for commuting, and corrective fuel prices encouraging the use of other commute methods are therefore an effective policy tool to help reduce congestion.

Figure 6.6

Corridor Capacity (people per hour on a 3.5-meter-wide lane)



Source: Hickman et al. (2011).
Note: BRT = bus rapid transit.

Other short-term mechanisms do not result in substitutions but rather affect driving behavior. Increased gasoline prices could encourage drivers to make fewer trips and drive shorter distances. Taken together, these would suggest fewer vehicles on the road overall, which would ease congestion and increase vehicle speeds. Finally, driving in a more fuel-efficient manner–at a consistent speed as opposed to suddenly braking and accelerating–could affect congestion and positively affect the speed of flowing traffic.

In terms of long-term mechanisms, persistently high gasoline prices might encourage drivers to change either residential or work locations in order to save time commuting. Drivers might change jobs to be closer to their current residence, or more likely move to a location closer to their work. Although moving can be costly, the choice could be made to move to a more transit-rich location, such as near light- or heavy-rail stations, which would ease congestion.

There is limited empirical research that considers the effect of gasoline prices on congestion. Burger and Kaffine (2009) find evidence that a $1 increase in fuel prices reduces congestion and increases freeway vehicle speeds by approximately 7 percent during rush-hour periods in Los Angeles. Burke, Batsuuri, and Yudhistira (2017) consider fuel tax reform in Indonesia and find that the removal of fuel subsidies has reduced congestion. They find an elasticity of motor vehicle flows on toll roads between -0.1 and -0.2. Zhang and Burke (2020) find evidence that higher gasoline prices decrease vehicle speeds in off-peak traffic periods and increase speed in congested periods. While the effect on speed is ambiguous in noncongested settings, both studies provide evidence that increased fuel prices decrease congestion.

Related work considers the relationship between gasoline prices and VMT, which can be used as a direct input into congestion models. Haughton and Sarkar (1996) estimate the elasticity of VMT with respect to gasoline price in the United States from 1970 to 1991 and find a negative relationship between gasoline prices and VMT. They find a price elasticity between -0.16 and -0.07 in the short run and between -0.58 and -0.21 in the long run. Outside the United States, Johansson and Schipper (1997) consider 12 countries in the period from 1973 to 1992 and find a fuel price elasticity for VMT between -0.47 and -0.06. These elasticities can be used in a congestion model to measure the relationship between gasoline price and congestion.

In the United States, Wang and Chen (2014) consider the effect of fuel prices on travel demand for different income groups. While VMT may decrease as a result of rising fuel prices, the authors also consider whether individuals might switch to more fuel-efficient cars and in turn drive more (known as the rebound effect). They find differential impacts among income groups, with fuel price elasticities for VMT between -0.41 and -0.35 for the highest income groups and -0.24 for the lowest income groups. Accounting for income may therefore provide a more accurate measure of benefits. The behavioral mechanisms that explain the distributional impacts between elasticities and VMT are not known and are outside the scope of the study. Wang and Chen (2014) also find weak evidence of a rebound effect, suggesting that increasing fuel prices is effective in reducing VMT.

In the next section we explain how fuel price elasticities for VMT can be used to inform a benefit model for congestion. However, VMT is only one aspect of congestion, and more work is needed to demonstrate the relationship between fuel prices and congestion in order to more fully model the benefit of reducing congestion.

6.3 Measuring and Modeling Impacts

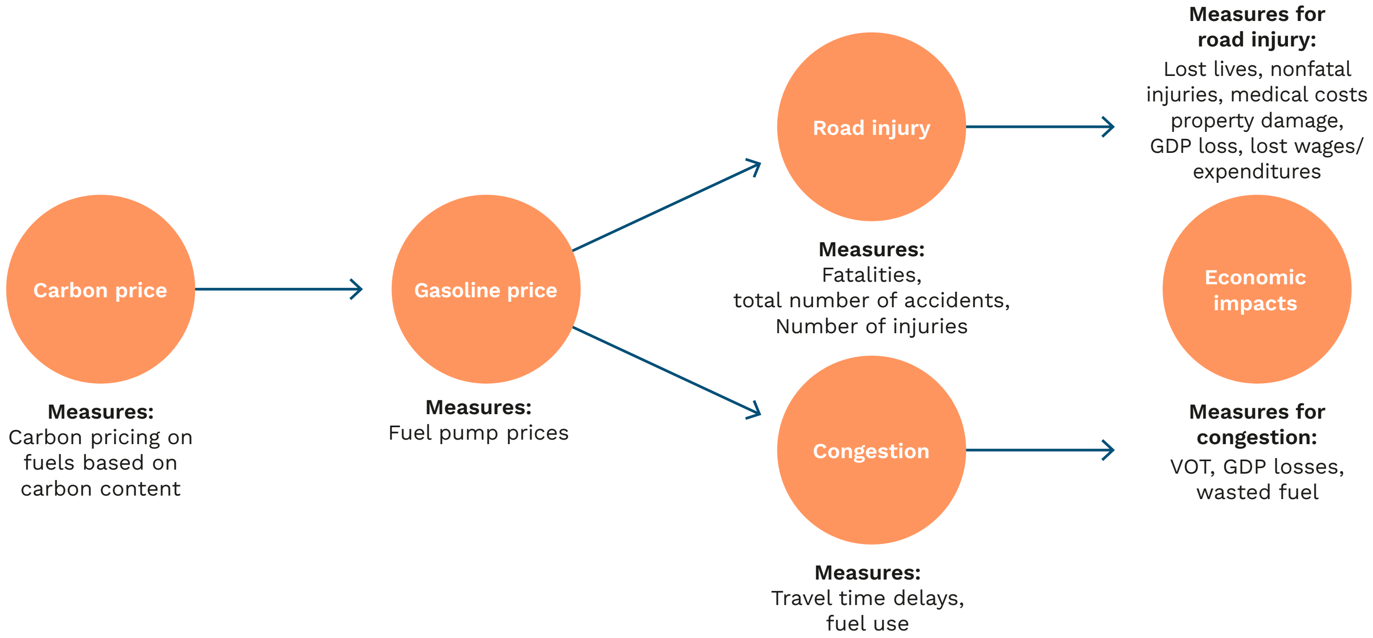
Various analytical tools can be used to quantify the benefits of road injury and congestion reductions. In the following section we focus on a specific set of techniques that policy makers can use to measure benefits from a carbon price. The primary estimation strategy for vehicle benefits relies on a combination of partial equilibrium, econometric, and CGE models. Each of these is considered a “top-down” model that is characterized by its depiction of market behavior in response to price changes (e.g., how vehicle use changes in response to changes in gasoline price). These modeling techniques and their application to carbon pricing are discussed in greater detail in the World Bank’s *Carbon Tax Guide* (PMR 2017) and *Carbon Pricing Assessment and Decision Making: A Guide to Adopting a Carbon Price* (PMR forthcoming 2021).

6.3.1 Overview of Modeling Approach

The benefits of road injuries and congestion are both quantified using a similar method. First, carbon prices are related to gasoline taxes and gasoline prices, and then the change in gasoline prices is related to either the level of accidents or the level of congestion. The change in accidents or congestion is then quantified into benefits. A simplified overview of a road injury and congestion benefit model is presented in Figure 6.7.

Figure 6.7

Road Injury and Congestion Benefit Flow Chart



Source: World Bank.

6.3.2 Gasoline Prices

The first step in modeling transportation benefits is relating the carbon price to a fuel tax and ultimately to gasoline prices. For example, the per unit price of carbon would be related to the amount of carbon in gasoline. For gasoline, which has 8.89 kg of CO_2 per gallon, each dollar of the carbon price translates into approximately an additional $0.01 per gallon in the tax of gasoline (Hafstead and Picciano 2017). Empirical evidence suggests that gasoline taxes are passed fully on to consumers, and therefore the relevant change in tax can be fully applied to the retail price of gasoline (Li, Linn, and Muehlegger 2014; Marion and Muehlegger 2011).

This completes the first link in the benefit model. Once carbon pricing is related to gasoline prices, the resulting change in gasoline prices needs to be related to road injuries or congestion.

6.3.3 Road Injury Elasticity Estimation

Road injury elasticities can be taken from existing estimates in the literature; or if national data are available, they can be calibrated for specific countries. If existing elasticity estimates are used from the literature, then the impact of the change in gasoline prices on road injuries can be determined using a partial equilibrium model. Price elasticity is a measure of how responsive the quantity demanded is to a change in prices. In the context of road injuries, an elasticity measures how accidents respond to a change in gasoline prices. Numerous studies across a variety of countries and time periods estimate these elasticities and can be used in a partial equilibrium model. In the simplest model, the percentage change in accidents will be the product of the elasticity and the product of the change in price of the gasoline price, as shown in equation (1) and further amplified in box 6.2:

$$\Delta\ Accidents = \%Accident\ Elasticity \times \%Gasoline\ Price\ Increase.$$

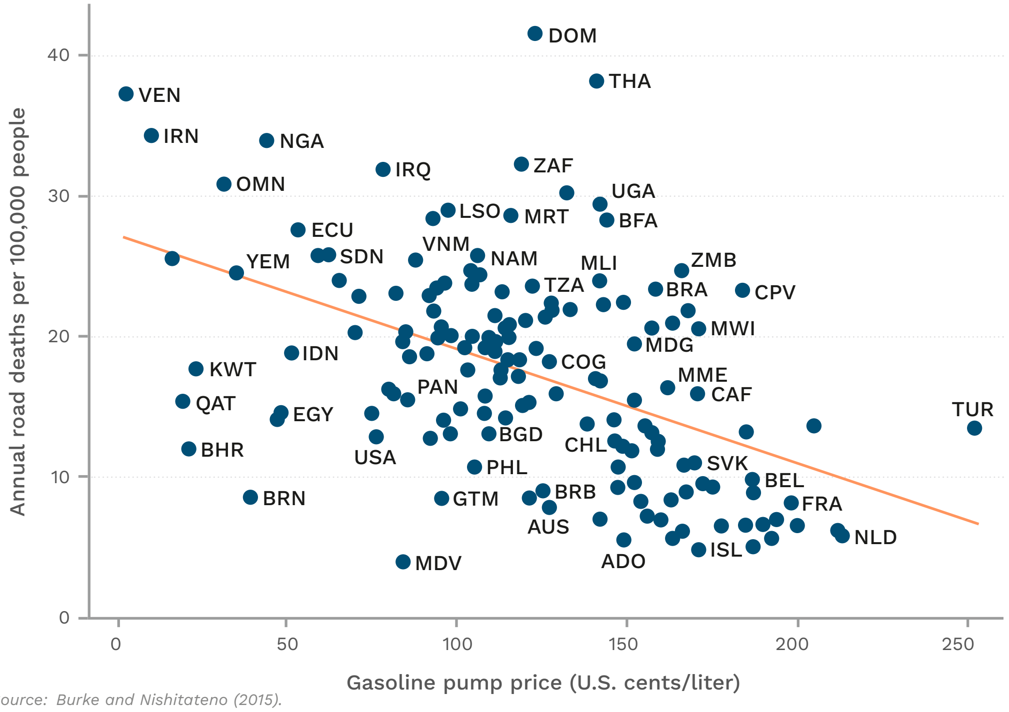
Box 6.2

Evidence Linking Increased Gasoline Prices with Reduced Vehicle Accidents

Empirical work demonstrates that increased gasoline prices reduce vehicle accidents in a variety of settings. As shown in the figure below, a negative relationship is found between road death rates and gasoline pump prices at the global level.

Figure B6.2.1

Deaths and Gasoline Pump Prices, 2010



Source: Burke and Nishitateno (2015).

One of the leading studies is by Burke and Nishitateno (2015), who utilize a data set of 144 countries from 1991 to 2010 to illustrate the effect of gasoline price on road fatality rates. They estimate the gasoline price elasticity of road deaths based on the following regression model:

$$D_{c,t} = \alpha + \beta_1 \ln G_{c,t} + \beta_2 \ln Y_{c,t} + \beta_3 \ln P_{c,t} + \gamma X_{c,t} + \delta_c + \omega_t + \varepsilon_{c,t}$$

where D is road deaths in country c in year t, G is the gasoline price in 2010 US cents, Y is gross domestic product in real purchasing power parity–adjusted US dollars, P is population, and X is a vector of additional controls included in later estimations. Further, δ_c and ω_t are country and year fixed effects, ε is an error term, and β_1 is the primary coefficient of interest and estimates how the change in gasoline prices affects the change in road deaths.

The model results indicate a mean long-term elasticity between -0.3 and -0.6 for gasoline prices and road fatalities. In other words, a 10 percent increase in gasoline price leads to a 3–6 percent average reduction in road fatalities.

Alternatively, original elasticity estimates can be calculated for specific countries. This technique would require the use of econometric modeling and can be done following a methodology similar to that used in Burke and Nishitateno (2015). This framework, along with demographic and macroeconomic variables, allows an econometric estimation technique for specific countries.

Original elasticity estimates offer a more accurate quantification approach but have significant historical data requirements. The leading roadside fatality database comes from the International Road Federation, which publishes an annual World Road Statistics database that includes fatalities along with a variety of other transportation indicators.[38] WHO also reports data on traffic accidents,[39] including fatalities, as well as other useful covariates, such as mode of transport during death, prevalence of seat beats, helmet enforcement, etc. However, these data use a broader definition of road accident deaths than the World Road Statistics database, so aggregate numbers of fatalities are not comparable.

Policy makers can obtain fuel tax information from the transport agency or ministry. Otherwise, time series fuel price data are available from Enerdata's Global Energy and CO_2 database,[40] which spans 186 countries from 1970 onward. Other demographic and economic variables are used as controls and could come from the World Bank's World Development Indicators and World Governance Indicator databases.[41] Relevant covariates might include GDP per capita, population density, rule of law indicator, and others.

With the relevant data, regression analysis can produce country-specific estimates for road fatality elasticities from changes in gasoline price. If a log-log model is used, these changes would be represented in percentage terms that allow intuitive interpretation. For example, an X percent increase in gasoline prices would result in a Y percent decrease in road fatalities. This change can then be monetized using a method discussed in the next section to calculate the benefit.

6.3.4 Congestion Elasticity Estimation

The ideal way to relate carbon pricing to congestion costs is through empirical work that estimates the elasticity of gasoline prices and congestion. Congestion elasticities can be taken from existing estimates in the literature or calibrated locally if national data are available. With these elasticities, a partial equilibrium analysis could then be used. The percentage change in congestion will be a product of the elasticity and the change in the gasoline price caused by the introduction of a carbon price, as shown in equation (2):

$$\Delta\ Congestion = \\ \%Congestion\ Elasticity \times \%Gasoline\ Price\ Increase.$$

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[38] World Road Statistics Datawarehouse, International Road Statistics, https://worldroadstatistics.org/.

[39] Road Safety, World Health Organization Data Platform, https://www.who.int/data/gho/data/themes/road-safety.

[40] Global Energy & CO_2 Data database, Enerdata, https://www.enerdata.net/research/energy-market-data-co2-emissions-database.html.

[41] World Development Indicators database, World Bank, https://datacatalog.worldbank.org/dataset/world-development-indicators; World Governance Indicators database, World Bank, https://info.worldbank.org/governance/wgi/.

Compared to those for accidents, existing elasticity estimates for congestion are limited in the literature. Original elasticities can be estimated through a regression analysis modeling technique, which could estimate the effect of gasoline prices on congestion. The econometric estimation strategy would relate congestion to gasoline prices using a panel data set of country-time-level data. Along with demographic and other economic control variables, this approach would isolate the effect of a change in gasoline prices on congestion.

Although methodologically sound, this approach has significant data requirements, and time series databases on congestion are limited. The Mobility in Cities database offers transportation data for more than 60 cities worldwide across a 20-year period.[42] Data include average speeds that can be used to develop a measure of congestion,[43] as well as a variety of relevant covariates (see box 6.3). Congestion data are improving, owing to the rise of mobile communication devices that have allowed new measures of congestion from providers such as Waze, Google Maps, Inrix, and TomTom. These new data sets contain highly localized and accurate data, but are comparatively new and limited in the length of time they cover. Other useful transportation covariates might include average annual car-kilometers, road length or capacity, and per capita car use. As discussed in the road injury section, fuel price data are available from Enerdata, while other economic variables are available from the World Bank.

Other variables may serve as a proxy. For example, there is a large body of research considering the impact of gasoline prices on VMT (see box 6.4), and VMT is a direct input into typical congestion models. As VMT decreases, congestion falls; and therefore increases in gasoline prices can present quantified reductions in congestion via VMT.

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[42] Mobility in Cities Database, International Association of Public Transport, https://www.uitp.org/publications/mobility-in-cities-database/.

[43] Congestion is often measured as a travel delay. Delays are quantified by comparing the average road network speed to the free-flow state. Free flow is simply the average speed that a motor vehicle would travel if there were no congestion or adverse weather conditions. Travel delays can be estimated by the difference in free-flow speed from the measured average speed.

Box 6.3

Estimating Country-Level Congestion Data

One of the central issues in modeling congestion is the limited amount of congestion data. This is particularly an issue at the country level, as most congestion indexes are modeled at the city level. Since carbon pricing policies are typically applied at the national level, total congestion costs at the country level are needed to better inform benefit estimates.

One approach to overcome this issue follows the work of Parry et al. (2014), who use a city-level database across a variety of countries to establish the statistical relationship between congestion delays and transportation indicators. These results are then extrapolated to the country level using similar transportation data at the country level.

City-level travel delay estimates are regressed on a variety of transportation indicators. The reduced form of the model is as follows:

$$\ln y_i = \beta_0 + \beta_1 \ln GDP_i + \beta_2 \ln GDP_i^2 + \beta_3 \ln KM_i + \beta_4 \ln KM_i^2 + \beta_5 \ln RD_i + \beta_6 \ln RD_i^2 + \beta_7 \ln CAR_i + \beta_8 \ln CAR_i^2 + \varepsilon_i \quad (1),$$

where y_i is travel delay in city i; GDP_i is metropolitan GDP per capita in city i; KM_i is annual car-kilometers (indicator of traffic mobility) in city i; RD_i is road length or capacity per car in city i; and CAR_i is cars in use per capita in city i.

The relationship modeled in equation 1 can be used to forecast estimates from the city level to the country level. Using the estimated coefficients above, the following model is used to predict travel delays at the country level:

$$\ln \bar{y}_i = \bar{\beta}_0 + \bar{\beta}_1 \ln GDP_i + \bar{\beta}_2 \ln GDP_i^2 + \bar{\beta}_3 \ln KM_i + \bar{\beta}_4 \ln KM_i^2 + \bar{\beta}_5 \ln RD_i + \bar{\beta}_6 \ln RD_i^2 + \bar{\beta}_7 \ln CAR_i + \bar{\beta}_8 \ln CAR_i^2 + \varepsilon_i \quad (2),$$

where $\bar{y}_i$ is predicted travel delay in country i; GDP_i is GDP per capita in country i; KM_i is annual car-kilometers (indicator of traffic mobility) in country i; RD_i is road length or capacity per car in country i; and CAR_i is cars in use per capita in country i.

Predicted average delays at the country level are shown in table 9 using this methodology. The average delays at the country level are about one-quarter to one-half of those at the city level. This makes sense intuitively, as city-level data focus on large cities with the most severe congestion. Country-level data incorporate congestion in rural areas and smaller to mid-size cities where congestion is less.

Table B6.3.1

Country-Level Travel Delays and Other Characteristics, Region Average, 2007

Region	Number of countries	Predicted average delay (hours/km)	Country GDP (2007 US$ per capita)	Annual km driven per car (thousands)	Road capacity (km/car)	Cars per capita
Africa	45	0.0046	2,300	36.3	1,395	0.03
Asia	33	0.0053	9,900	16.3	362	0.11
Europe	43	0.0025	26,900	9,4	65	0.35
Latin America	11	0.0049	5,100	21.9	185	0.09
North America	11	0.0048	12,100	19.5	103	0.15
Oceania	7	0.0028	11,900	18.1	290	0.20
All countries	**150**	**0.0041**	**12,400**	**21.0**	**551**	**0.16**

Source: Parry et al. (2014).

Box 6.4

Correlation between Increased Gasoline Taxes and Fewer Vehicle Miles Traveled

Empirical evidence has shown that increased gasoline taxes are correlated with fewer VMT. Haughton and Sarkar (1996) estimate the effect of gasoline prices on VMT across 50 US states from 1970 to 1991. They find that VMT nearly doubled over the sample period despite the short-term interruption of two oil shock periods (figure 42). The reduced form of their model is as follows:

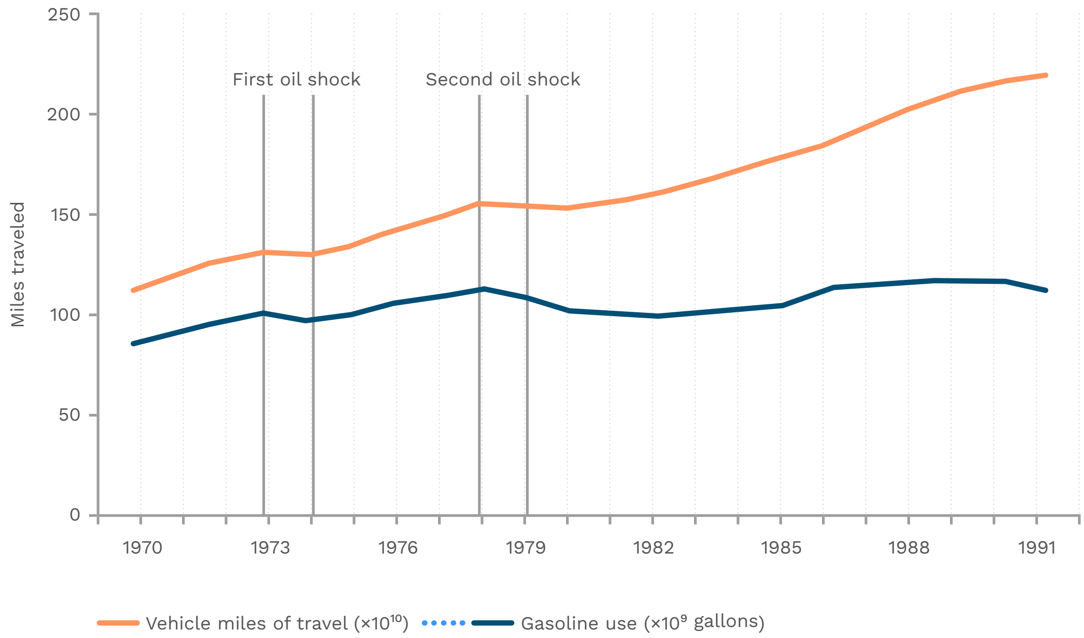
$$vmd_{t} = b_{0}+b_{1}P_{gasoline\ per\ mile} + b_{2}\frac{pers.\ inc.}{population} + b_{3}\frac{drivers}{road\ mileage} + b_{4}\frac{drivers}{adult.pop}$$

$$+ b_{5}D74 + b_{6}D79 + (1-\lambda)vmd_{t-1} + \varepsilon$$

where vmdt is vehicle miles driven in year t, and PGasoline per mile is the price of gasoline per mile. All variables are in log form and other variables serve as controls. The primary coefficient of interest is b1, which estimates the effect of gas prices on VMT.

The authors find that the short-run elasticity estimate of miles driven is between -0.09 and -0.16, while the long-run elasticity is about -0.22. Their estimates suggest a rapid response to a change in gasoline price.

Figure B6.4.1:
Vehicle Miles and Gasoline Consumption



Source: Haughton and Sarkar (1996).

Using VMT requires a less technical approach that might be appropriate for policy makers interested in a rough approximation of the benefit. For example, using existing estimates of the fuel price elasticity of VMT, carbon pricing could be related to a reduction in VMT through a partial equilibrium model.

The change in VMT can then be related to congestion through a model measuring the flow of traffic. Transportation engineers model travel delay as a power function of traffic volume, and empirical estimates provide calibration of parameters. With assumptions for how VMT relates to traffic volume, the reduction in VMT could be related to travel delays, which is the standard measure of congestion.

6.3.5 Road Injury: Direct Economic Impacts

The direct economic impacts of road injury benefits can be measured by converting the reduction in accidents attributed to carbon pricing into benefits. Fatality costs are typically quantified using estimates of the value of statistical life (VSL).[44] In the most basic quantification scheme, the reduction in fatalities would be related to costs by multiplying each fatality by the country-specific VSL. Although fatalities from road injuries are the most consistent metric to estimate, they do not fully capture all costs associated with road injuries. Some major additional costs include nonfatal injuries, the associated medical costs, and property damage costs.

Estimating these costs is often difficult due to data limitations. While fatalities from road injuries are well reported, detailed data on nonfatal injuries are much less available, and estimating medical and property costs often requires microdata that are unavailable. To overcome the significant data requirement burden, one solution is to scale these unobservable costs by an estimated scalar. For example, using accident cost data from a five-country case study, Parry et al. (2014) estimated the ratio of the omitted accident costs to the costs of fatalities. For each country, road injury fatalities were monetized using VSL and additional costs were estimated using a combination of local data on the average total costs of accidents (including medical, property damage, and nonfatal injury costs). For each country, five-point estimates for the ratio of other costs to fatality costs were calculated by dividing total other accident costs by fatality costs. Using these five estimated ratios, a function that best fits the estimates was estimated to forecast results to additional countries. For a more detailed discussion of this methodology, see Parry et al. (2014, annex 5.6).

6.3.6 Road Injury: Indirect Economic Impacts

Premature deaths have costs beyond those typically associated with the death itself (as measured by VSL), and these larger effects are classified as indirect effects. Indirect costs associated with premature deaths are discussed in greater detail in section 3.2.2 on health benefits of improved air quality, but they include all the economic contributions that a person would have made for the rest of his or her life, including innovation, education, labor, and spending contributions, as well as the forgone wages that would have been spent in other parts of the economy and that can have significant multiplier effects.

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[44] For further discussion on how VSL estimates are derived, please refer to section 3.2.2 on health benefits of improved air quality.

Other direct cost categories have indirect effects as well. For example, reductions in vehicle property damage would affect other related sectors such as autobody shops; the insurance market might also see changes, as reductions in personal injury could affect health care spending. These impacts have second-order effects (and beyond) as well. For example, a large reduction in accidents could affect the manufacturing of automobile parts and the related suppliers. These multiplier effects are often larger than the direct effects and are worth consideration.

These macroeconomic effects can be measured through models that consider the linkages across sectors. Such models include input-output or multiplier models, or CGE models.

6.3.7 Congestion: Direct Economic Impacts

Direct congestion costs comprise travel delays to road users, excess fuel consumption, and reductions to economic productivity. The largest component of direct congestion costs is travel delays to all road users. Travel delays can be measured using a metric for the value of travel time (VOT) and assumptions about the average vehicle occupancy. Empirical work estimates the VOT of personal travel to be about half the market wage (Parry et al. 2014).[45] In general, the VOT is higher for work commutes than other trips, as there are larger financial penalties for being late to work than for leisure or other activities. Given that most delays occur during the commuter peak period, Parry et al. (2014) have assumed a slightly higher VOT of 60 percent of the market wage. In order to estimate country-specific VOT, prevailing market wages at the country level are needed. These data can be obtained from relevant local governments or from the International Labor Organization global wage database.[46]

Excess fuel consumed is another component of total congestion cost. To measure the additional costs associated with wasted fuel, estimates are needed for the amount of fuel consumed in congestion versus the amount consumed in free-flow conditions. This amount is difficult to estimate, but one approach uses a model that measures emissions from mobile sources in conjunction with traffic speed data. Using emission rates along with speed and volume data, gas consumption rates can be calculated and compared between congested and free-flow conditions. The difference in fuel can then be monetized using local fuel costs. A drawback to this approach is that excess fuel costs are small compared to the VOT share, and given the data limitations this category might not be worth the effort to model. Data from Schrank, Lomax, and Eisele (2019), for instance, suggest that excess fuel represents only 4.4 percent of total congestion costs in the United States in 2017.

6.3.8 Congestion: Indirect Economic Impacts

Reduced congestion will also result in indirect economic impacts. Less travel time means an increase in leisure opportunities, leading to more spending on goods and services. Furthermore, as previous research has found, markets operate more efficiently without congestion (Weisbrod, Vary, and Treyz 2003). Congestion reduces access to markets by limiting access to skilled labor and specialized inputs, in turn increasing production costs and reducing the efficiencies of urban agglomeration (Weisbrod, Vary, and Treyz 2003). Therefore, linkages across virtually all sectors of the economy would be impacted, and due to the multiplier effect, these economic benefits would be significant. Once again, these impacts are best measured through a model that fully captures the connected sectors, such as a CGE model.

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[45] Here market wage refers to the real average monthly wages of all employees in a given country.
[46] ILO Global Wage Database, International Labor Organization, https://www.ilo.org/travail/areasofwork/wages-and-income/WCMS_142568/lang--en/index.htm.

6.3.9 CGE Modeling

Both accidents and congestion benefits can be used to augment CGE models. Direct economic effects can be used as inputs into the model, and the greater economy-wide effects would be measured through the relevant linkages. Transportation benefits can be incorporated into a CGE modeling framework as follows:

Avoided premature deaths (accidents) can be captured by allowing the population parameter to change with the carbon price. As fatal accidents decrease, population levels increase, and the associated wages and expenditures from increased population create induced indirect effects across the economy.

Changes in labor productivity and supply (accidents and congestion) can be accounted for in a variety of ways. Road accidents tend to disproportionately affect the most productive labor cohort, decreasing the labor supply and limiting productivity. Thus, decrease in accidents would affect both the size of the labor force as well as the labor productivity parameter in a CGE model. Congestion also affects labor productivity and supply, as increased congestion limits the efficiency of labor markets and productivity. A summary of the key steps in accounting for transport benefits is found in table 6.1.

Table 6.1
Quantifying the Effects of a Carbon Price on Transport (Health and Economic Impacts)

	Step	Notes
1	Estimate the impact of a carbon price on gasoline prices	• Calculate unit price for each fuel type if not specified. • Relevant change in fuel tax can be applied to retail price of gasoline (assume full cost pass-through).
2	Estimate impact on road injuries	• Road injury elasticities can be taken from existing estimates in literature or from national data if available. • Original elasticities can also be calculated; see Burke and Nishitateno (2015) for methodology that can be adapted and applied to an econometric estimation technique. • Partial equilibrium models can relate impact of change in gasoline prices to road injuries. In the simplest model: change in accidents = % accident elasticity x % gasoline price increase.
3	Estimate direct economic impacts of road injuries	• Convert reduction in accidents as a result of the carbon price to economic benefits. • Fatality reductions can be multiplied by country-specific VSL. • Costs of nonfatal injuries, associated medical spots, and property damage costs can be estimated, but this step is difficult due to data limitations. One solution is to scale these costs by an estimated scalar (see Parry et al. [2014]).
4	Calculate indirect cost estimates of reduction in road injuries	• Calculation of indirect costs of reducing road injuries is similar to calculating indirect costs associated with premature death due to air quality; see section 3.2.2. • Other impacts, like reductions in vehicle property damage, may also be worth considering. These macroeconomic effects can be estimated through input-output models, multiplier models, or CGE models.

	Step	Notes
5	Estimate congestion elasticity	• Estimates in existing literature can be used, or estimates can be locally calibrated if national data are available. • Original elasticities can be estimated through regression analysis modeling, but there are significant data requirements. • A partial equilibrium analysis can be used; change in congestion = % change in congestion elasticity x % change in gasoline price. • VMT can serve as a proxy to get a rough approximation of the benefit through a partial equilibrium model. The change in VMT can be related to congestion through a model measuring traffic flow, relating reduction in VMT to changes in travel delays.
6	Estimate direct economic impacts of changes in congestion	• The largest component is travel delays, which can be measured using a metric for VOT and assumptions about vehicle occupancy. • Country-specific VOT can be estimated using prevailing national market wages. • Excess fuel consumption can be difficult to estimate, and given that the costs are small compared to VOT, estimation may not be worth the effort. • Macroeconomic costs like limiting access to skilled labor and specialized inputs are much harder to identify and contingent on the specific urban area in question.
7	Estimate the indirect economic impacts of congestion	• CGE modeling can identify economic impacts like improvements in market efficiency by inputting the direct economic benefits into the model. • Avoided premature deaths can be captured by changing the population parameter. • Labor productivity and supply changes can account for congestion and road accidents.

Source: World Bank.

To conclude, examples in the following boxes show how CGE models have been used to account for transport benefits from reduced congestion and through carbon pricing measures. Box 6.5 discusses a CGE modeling framework that considers the impact of congestion on output, finding that reduced congestion leads to economic growth. Box 6.6 considers how congestion affects the labor supply in Switzerland, and shows that accounting for congestion is crucial for fully modeling the benefits of carbon pricing.

Box 6.5

CGE Assessment of Urban Congestion in the Philippines Showing Economic Growth Resulting from Reduced Congestion

Like many other rapidly urbanizing low- to middle-income countries, the Philippines is experiencing increased congestion as the economy grows, a middle class emerges, and aged infrastructure deteriorates. Congestion adversely affects the quality of life in major Philippine cities such as Manila, but in addition, traffic has stifled productivity, preventing the labor force from reaching its full potential. In 2014, to assess both the costs and effects of traffic flows in Manilla, the Japan International Corporation Agency developed a “Dream Plan” that calls for specific infrastructure projects to ease congestion.

In a study by Folsom (2016), several simulations were performed using the International Food Policy Research Institute standard CGE model both to examine the impacts of infrastructure development in the Philippines and compare strategies for financing the necessary investment. The analysis found that substantial economic growth across all sectors of the Philippine economy will follow implementation of the Dream Plan, and that a partnership in which the costs are shared between private investment and foreign savings is the best of the financing options considered.

Box 6.6

Integrating Big Data and General Equilibrium Modeling for Transport Benefit Assessment

A paper by Landis and Rausch (2019) considers how congestion affects the aggregate and distributional welfare effects of two regulatory strategies for decarbonizing private transport: a market-based approach using carbon pricing, and a command-and-control approach based on technology or emissions-intensity standards for private transportation. To capture the behavioral responses of heterogeneous households to regulation and consistently value the monetary and time costs of commuting, the authors integrate three types of data–(1) spatial household-level data on the location of residence and work, (2) road network and traffic data from Google, and (3) household survey data on expenditure and income–into a dynamic general equilibrium model that features preexisting fuel taxes and technology choice between internal combustion engine and electric vehicles.

The primary contribution of the paper is demonstrating that the inclusion of congestion benefits in modeling fundamentally changes the policy comparison between a market-based and a command-and-control approach to decarbonizing the transport sector. Specifically, the authors find that when congestion benefits are considered, carbon pricing yields aggregate welfare gains superior to those associated with regulation through technology standards. This discrepancy is explained by the tendency of carbon pricing to decrease transportation service demand, which leads to less congestion. On the other hand, technology standards implicitly subsidize the services of private transport, increasing congestion. Without accounting for congestion, emissions standards outperform carbon pricing, as standards distort market factors less.

Thus incorporating congestion externalities into CGE modeling is a necessary step for measuring the benefits of carbon pricing. Furthermore, the effect described above is found both in aggregate welfare and distributional implications. For all groups outside of high-income earners with low congestion exposure, carbon pricing yields improved welfare over vehicle standards. The analysis suggests that carbon pricing, along with targeted measures to alleviate the burden for low-income households, can be an efficient and equitable instrument for decarbonizing private transport.

7.

Fiscal Policy

At a Glance

- Carbon pricing is a unique opportunity for revenue generation with limited distortionary impacts on the economy.
- Replacing conventional taxes with a carbon price incentivizes the expansion of the formal sector.
- A carbon price tends to fall on energy, like oil and gasoline, that flows through centralized infrastructure that is relatively easy to monitor, making tax evasion harder.
- A carbon tax is relatively easy to administer and can build on existing fuel excise infrastructure.
- Existing evidence on carbon pricing suggests it is often progressive.
- Most fiscal policy benefits are indirect and can be estimated through CGE modeling.

7. Fiscal Policy

7.1 Introduction

Fiscal policy seeks to raise revenues while minimizing distortions to the economy. Finance ministries in developing countries need to balance this trade-off while generating enough revenue to increase public investments that can spur development. However, tax enforcement is often lax, meaning that tax avoidance is common. Moreover, raising tax revenue in developing countries is often complicated by the informality of a large share of the economy: economies with dual formal and informal sectors cannot easily be taxed through direct conventional taxation and can only imperfectly be taxed through value added taxes. Within this context, increasing tax revenues causes very uneven rates, with formal sector entities carrying a disproportionate amount of the tax burden. Raising this tax wedge between the formal and informal sectors also incentivizes firms in the formal sector to move into the informal sector in order to avoid taxation, both undermining development and shrinking the tax base itself.

A carbon price has the potential to address many of these challenges. Upstream carbon prices on fuel, for example, have the advantage of covering many people, including the informal sector, without needing to directly collect income taxes. An upstream carbon price also provides limited opportunities for evasion.

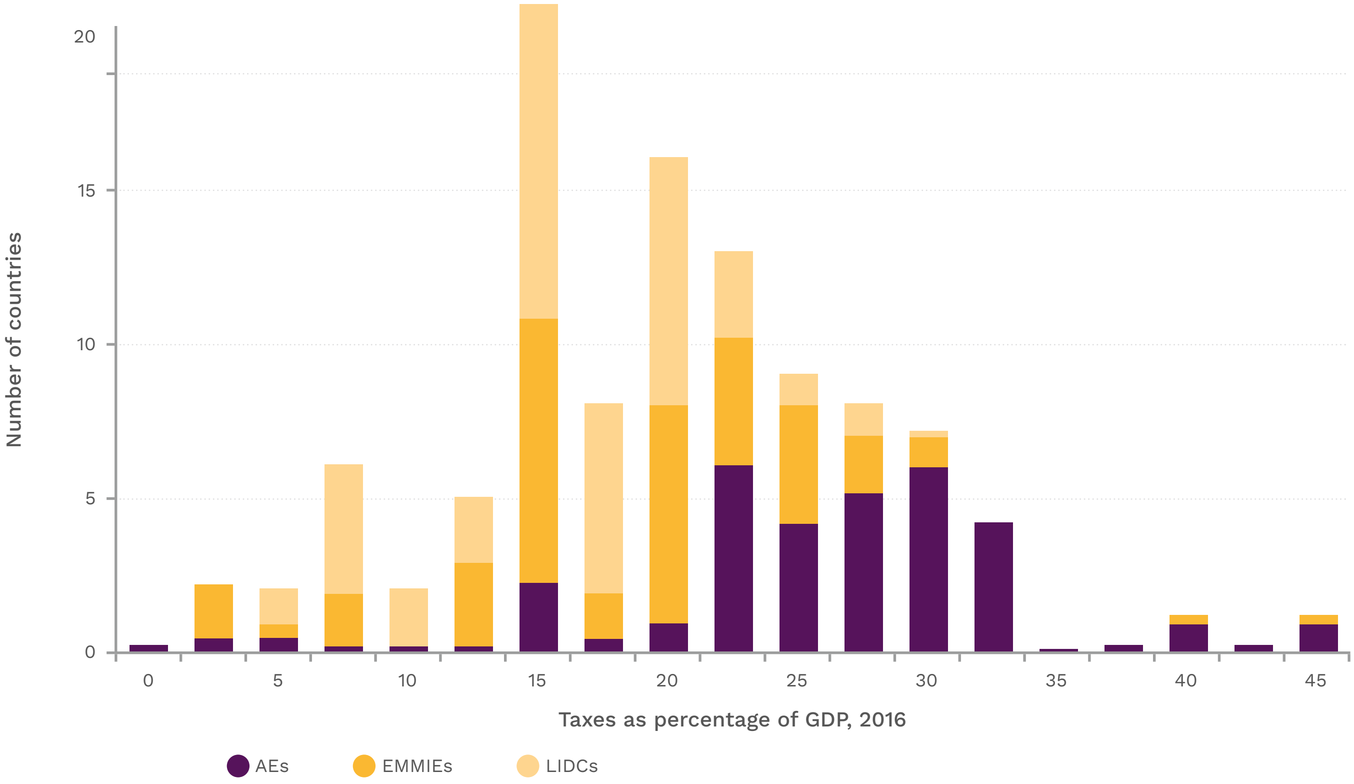
In light of these considerations, an upstream carbon price has the potential to increase tax revenue by expanding the tax base through coverage of the informal sector and to reduce the level of tax evasion while also lowering tax administration costs. As a result, the impacts of a carbon price are less distortionary than those of traditional taxes. This chapter discusses each of these benefits separately and provides guidance on how to quantify them.

7.2 Generating Revenue

The current ubiquity of carbon fuels means that their potential as a source of tax revenue is quite substantial in most countries. For developing countries, which face a challenge in generating enough revenue to fund public investments, the potential benefits of a carbon price can be substantial (see figure 7.1).

Figure 7.1

Greater Fiscal Depth in Higher-Income Countries



Source: Heine and Black (2019), drawing on IMF (2017).

Note: The histogram shows the number of countries, grouped by income level, that achieve different levels of tax revenue as a percentage of GDP. AE = advanced economy; EMMIE = emerging and middle-income economy; LIDC = low-income developing country.

A carbon price has the potential to raise substantial government revenue. Collectively, governments around the world raised more than $53 billion from carbon taxes or ETSs in 2020 (World Bank Group, forthcoming) and more than $500 billion from broader fuel taxes (Marten and van Dender 2019). In general, carbon pricing revenues increase with higher carbon prices and greater coverage of emissions sources. These relationships are illustrated in Figure 7.2 which shows current revenues from carbon pricing instruments in countries around the world as a function of the carbon price and share of GHG emissions covered.[47] Though not displayed in the figure, the level of free allocation in an ETS or exemptions in a carbon tax will also be inversely correlated with the amount of revenue raised.

The fiscal benefits from carbon pricing are maximized when countries use the revenues either to reduce more distortive taxes (a revenue-neutral tax shift) or to substitute for increases in other taxes that would have been required in the absence of the carbon price, given that (as discussed in the next subsection) these designs help increase formalization.

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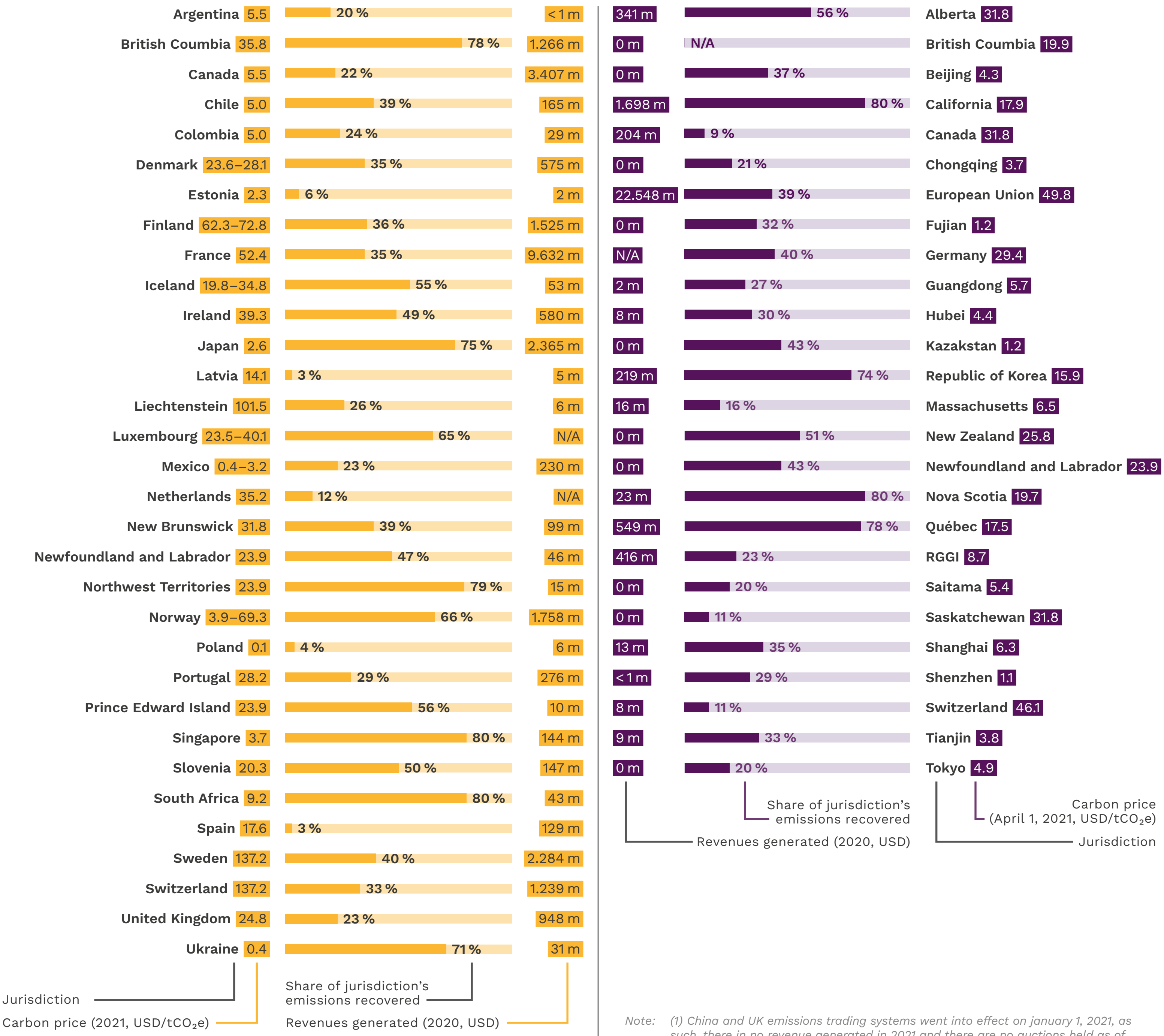
[47] The absolute magnitude of revenue raised will of course also depend on the size of the country and intensity of carbon fuel usage.

Figure 7.2

Revenue, Price, and Share of Emissions Covered for Implemented Carbon Pricing Initiatives



Note: For Luxembourg and the Netherlands carbon tax, revenue figures are indicated with N/A as these carbon pricing initiatives only went into effect on January 1, 2021. For Denmark, Finland, Iceland, Luxembourg, Mexico and Norway carbon taxes, the prices ranges indicate the upper and lower bounds ot the carbon tax levied on different fossil fuels and fluorinated gases.

Note: (1) China and UK emissions trading systems went into effect on january 1, 2021, as such, there in no revenue generated in 2021 and there are no auctions held as of April 1, 2021. These two systems are not presented in this figure.
(2) 2020 revenue figures are not included for certain jurisdictions either had no auctioning (Beijing, Chongqing, Fujian, Kazakhstan, New Zealand, Saitama and Tokyo), received no compliance payments (British Columbia, Newfoundland and Labrador and Saskatchewan), or the ETS went into effect on January 1, 2021 (Germany)

Source: World Bank (2021).

7.2.1 Taxing the Informal Economy

The informal economy refers to commercial, financial, and related activities that operate outside the regulatory and fiscal reach of government. For many countries, the informal economy presents an obstacle to development: informal firms face a disincentive to take on additional workers if they fear attracting attention from tax authorities. Business activities are constrained in the informal sector in part because liability systems and contract and property law are absent, and formal credit is not available (Acemoglu, Johnson, and Robinson 2001). Informality also prevents the economy from allocating resources optimally; instead of being allocated by productivity, resources under informality are allocated by "fiscally effective" productivity (Markandya, González-Eguino, and Escapa 2013)–i.e., productivity after accounting for uneven taxation. Each of these factors means that countries could see large gains in output simply by shifting activities out of the informal sector and into the formal sector.

A challenge to shifting firms into the formal sector is that tax systems in developing countries often incentivize the more productive parts of the informal sector to remain informal. This occurs because the formal sector is taxed more heavily than the informal sector, so that labor taxes affect the decision on whether or not to participate in the formal economy. For example, when Pakistan increased its tax rate on partnerships, affected firms were found to be significantly more likely to move into the informal sector than similar firms unaffected by the reform (Waseem 2018). Moreover, because the base of the direct taxes is small, developing countries need high nominal rates to reach any revenue target. But when nominal rates are raised, the tax base shrinks further because some agents strategically drop out of the formal sector and become informal (or avoid joining the formal economy to stay untaxed). As a result, the ability of a finance ministry to raise revenues through direct taxes is severely constrained. When the ministry raises conventional tax rates, the informality problem becomes larger.

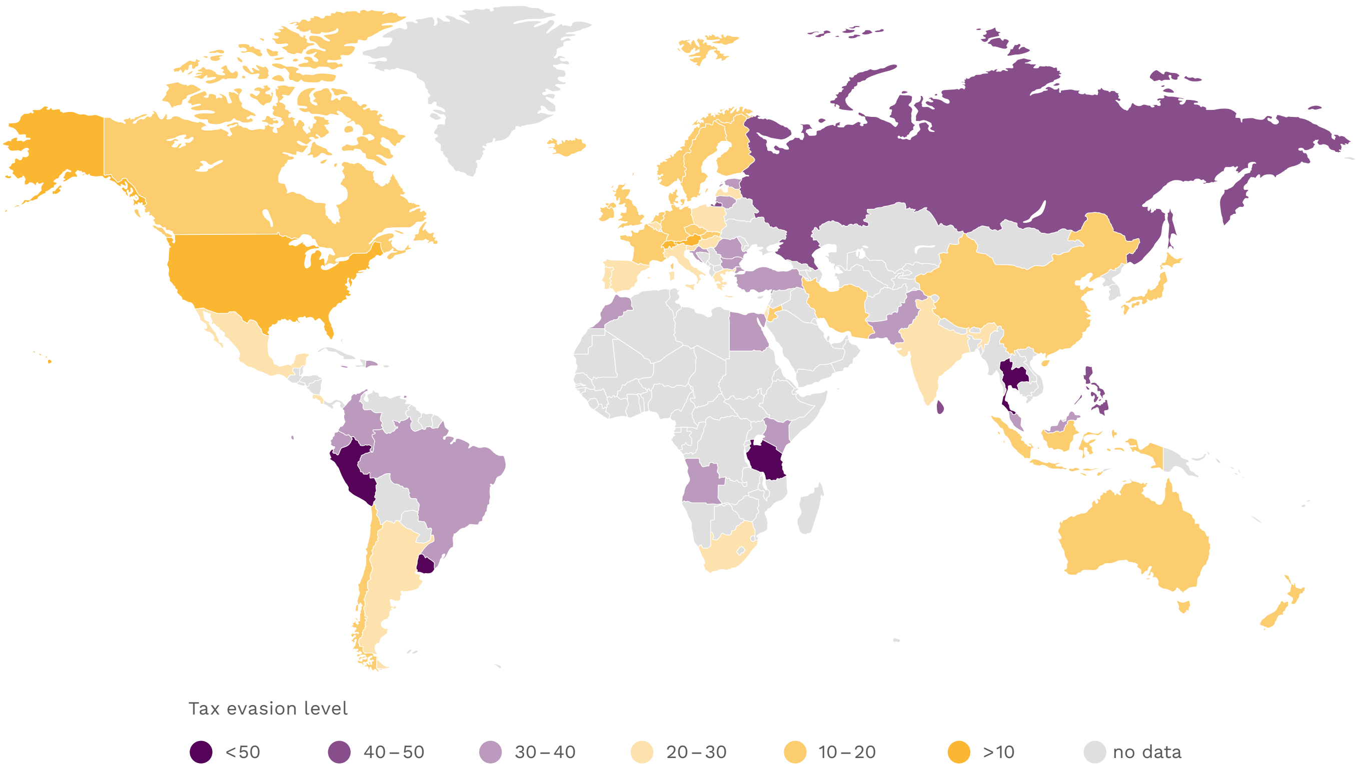
Carbon pricing is a unique opportunity to address this problem. When an upstream carbon price is implemented, it covers both the informal and formal sectors, and reduces the incentives for economic actors to remain informal. This effect is especially strong if, in addition to taxing the whole economy through an upstream carbon price, the carbon revenues are used to reduce the rates of conventional taxes on the formal sector. For example, when Colombia cut its payroll tax by half (which affected only the formal sector), informality decreased by four percentage points (Fernández and Villar 2017).

7.2.2 Limiting Tax Evasion

Carbon pricing presents an opportunity for increased tax efficiency by reducing tax evasion. Carbon prices tend to fall most heavily on energy inputs, like oil, electricity, and gasoline, that are used in both the informal and formal economies. Because these inputs flow through centralized infrastructure that is relatively easy to monitor, a carbon price is harder to evade than taxes on labor or income, or the VAT. Therefore, if the tax base is shifted in a revenue-neutral way toward carbon pricing, overall tax evasion could be reduced. By capturing a higher proportion of the tax base, any costs of environmental reforms can potentially be offset by the increased revenue associated with a wider tax base. Given that tax evasion is more prevalent in lower-income countries see (Figure 7.3), this policy has particular appeal in a developing country context.

Figure 7.3

Tax Evasion Level by Income



Source: Tax evasion level: Khlif, Guidara, and Hussainey (2016); per capita GDP: World Bank data.

Available evidence suggests that using a carbon price to reduce tax evasion can drastically reduce the welfare costs of controlling emissions, such as drag on the economy from increased fuel prices. The impact is largest in countries with high levels of tax evasion. For example, Liu (2013) finds that shifting the tax base from easily evaded taxes to a carbon tax can lower costs in China and India by 89 percent and 97 percent respectively, a potentially substantial benefit.

7.2.3 Reducing Tax Administration and Compliance Cost

An additional benefit of carbon taxes[48] in particular is the reduced administrative cost. Compared to other tax schemes, carbon taxes can be relatively simple and straightforward to implement. For example, administering and enforcing taxation of individual wages is significantly more complex than imposing upstream fuel taxes. Indeed, Bento and Jacobsen (2007) show that environmental taxes can increase the efficiency of the tax system while improving environmental outcomes. Because of this simplicity, administrative costs tend to be lower than they are for other tax policies that raise similar levels of revenue. In addition, because limited administrative capacity is required for implementation, carbon taxes are well suited to environments with limited capacity, as is the case in many developing countries.

7.3 Limiting Distortionary Impact of Taxation

Economists have long called on policy makers to tax economic rents as opposed to profits in order to encourage entrepreneurship. Economic rents are the economic gains received that are independent of risk taking and effort, such as rents owing to a market monopoly. These are in contrast to economic profit, which refers to the economic gains that account for risk-adjusted alternatives. Economic rent is traditionally viewed as unearned revenue, while profit refers to surplus income that is earned through choices. Thus a tax on profit may discourage effort, whereas a tax on rents has no effect on effort.

Taxing rents is politically difficult for a variety of reasons. First, distinguishing between pure rents and profit is difficult in practice, and most earnings are typically from a combination of the two. Second, even if rents could be identified, tax rates could be passed on to consumers. Carbon pricing overcomes these two issues. The extraction of fossil fuels generates a larger share of rents than other economic activities, while pass-throughs of taxes to consumers tend to be lower for fossil fuel consumption than for other goods, especially in developing countries (Neuhoff and Ritz 2019)—and less than complete pass-through implies a portion of the carbon price will be passed backward onto fuel rents. Moreover, while motor fuel taxes to consumers are commonly passed on to consumers in the US, the proportion passed on in lower-income countries is smaller, as fuel demand is more elastic (Parry et al. 2006; Sterner 2012; Stolper 2016); thus the relatively higher-income groups are charged at higher rates.

Carbon pricing is therefore an effective policy tool to capture the rents associated with natural resource extraction. Carbon prices provide a much-needed form of revenue while simultaneously providing the benefit of shifting the tax burden from profits to rents, a move that can potentially raise output.

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[48] This subsection on reducing the administrative burden refers to carbon taxes only. All other mention of carbon pricing in this report refers to both ETSs and carbon taxes.

7.4 Distributional Implications of Fiscal Policy with Carbon Pricing

Increasing equity is a key objective of fiscal policy, and concerns about the distributional impacts of a carbon price are among the most common political obstacles to securing public support for such policies. Carbon pricing is often assumed to be regressive because focus is put on expenditure impacts, and low-income households are thought to spend a higher percentage of their income on energy than higher-income households. But evidence used to support this argument tends to come from high-income countries, where the distribution of consumption patterns across income groups may differ from that in low-income countries. In fact, available evidence on the distributional impacts of carbon pricing in low- and middle-income countries suggests that a carbon price is often a progressive policy even when focusing only on expenditure effects. When income and expenditure effects are considered jointly, carbon pricing is broadly found to be progressive.

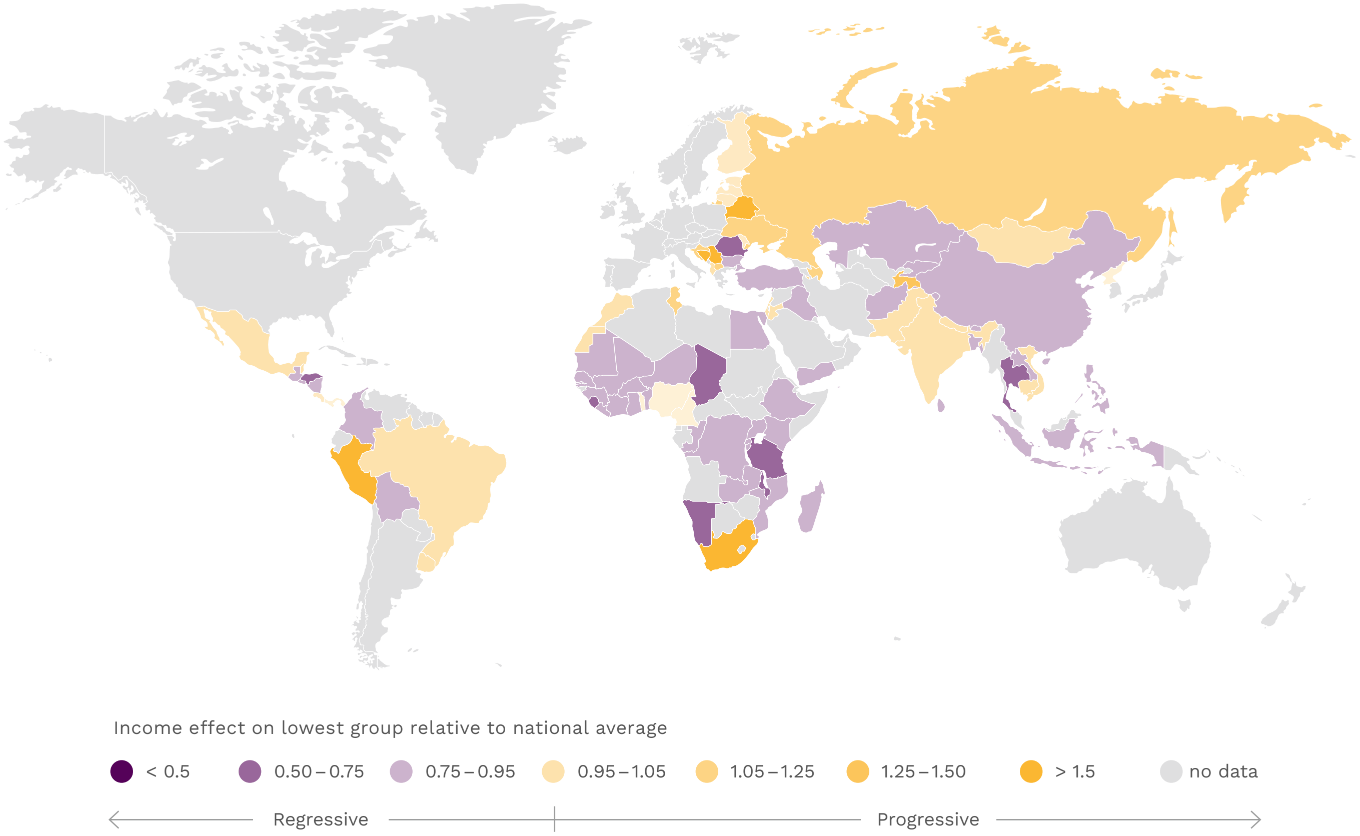
Dorband et al. (2019) estimate the distributional impact of moderate carbon taxes and find that carbon pricing is a progressive policy in most low- and middle-income countries. It may have regressive impacts in high-income countries, they find, because of differences in energy expenditure shares across income groups within these countries. In high-income countries, the highest-income groups tend to have lower energy expenditure shares than low-income groups. However, in low-income countries, low-income groups are more likely to have lower energy expenditure shares than high-income groups within the same country. Dorband et al. provide evidence that, for most countries with per capita incomes below $15,000 per year, carbon pricing has progressive distributional effects.

Figure 7.4 shows the results of their estimates by country. Across the 87-country sample of low- and middle-income countries considered by Dorband et al. (2019), only Belarus, Serbia, Montenegro, and South Africa are estimated to have substantial regressive impacts from a moderate carbon tax even before factoring in revenue use. In contrast, most other countries in Africa, Asia, and Latin America are estimated to have progressive outcomes. Moreover, the study considers only distributional impacts that occur through differences in consumption patterns. Other channels, such as changes in factor incomes, are not considered. Overall distributional effects are therefore likely to be even more progressive than these estimates suggest.

In addition to affecting consumption patterns through commodity prices, carbon pricing also affects factor prices. Low-carbon industries tend to be more labor-intensive than higher-carbon industries. Additionally, labor is a less carbon-intensive production factor than capital. Carbon taxes therefore affect these factors differently (Goulder et al. 2019); and because ownership of capital is unequally distributed across the income distribution, changes to returns from factors in favor of labor are therefore progressive (Dissou and Siddiqui 2014). These impacts are seen through different channels. Because capital is more carbon-intensive, a carbon price induces structural change, which leads to increased labor intensities in production. This shifts the relative returns of labor and capital in the economy away from capital and toward labor.

Figure 7.4

Estimated Distributional Impacts of a Moderate Carbon Tax



Source: Dorband et al. (2019).

In addition, carbon prices are typically not fully passed through to product prices (Neuhoff and Ritz 2019), and thus the burden is on firms rather than consumers. A share of that incidence will be borne by owners of capital and another share by labor; but again, since capital is unequally held across the income distribution, the effect is to make the distribution of carbon pricing more progressive.

These channels for progressive impacts are often omitted in discussions of the distributional impacts of carbon pricing, which tend to focus on the potentially regressive aspects of carbon pricing policies (Metcalf 2019). When these channels are accounted for, most studies find that carbon prices are overall progressive in developing countries.

7.5 Measuring and Modeling Impacts

There are many potential fiscal benefits associated with a carbon price, and figure 7.5 lists the metrics that can be used to quantify them. However, the extent to which they are easily quantifiable varies. This section provides guidance on measuring and modeling these impacts.

Figure 7.5

Metrics to Quantify the Fiscal Policy Benefits of a Carbon Price

- Revenue
- Size of informal sector
- Level of tax evasion
- Tax administration/compliance costs
- Household income distribution
- Returns to labor and capital
- Labor intensity of production

Sources: World Bank.

7.5.1 Direct Impacts

The primary direct fiscal impact of a carbon price is increased government revenue. This benefit is typically straightforward to quantify. In most cases the revenue raised from carbon prices can be derived from government accounts and budgets. When data from government accounts are unavailable, an approximate estimate of revenues for a carbon price can be expressed by multiplying the GHG emissions covered by the tax by the nominal carbon price; for an ETS, the number of allowances auctioned in a year is multiplied by the nominal carbon price.

7.5.2 Indirect Impacts

Because of the complexity of fiscal incidence, CGE models are popular tools for research in public finance. As we have already seen, carbon pricing also has complex and heterogeneous indirect effects. In OECD economies, CGE models have been very popular for carbon pricing and other climate policy assessment. Historically, these studies have been preoccupied with relatively fine points of efficiency gains and losses, and have devoted much attention to a concept known as the "double dividend." This concept recognizes that it is possible to improve both environmental and economic conditions by imposing an environmental tax and recycling revenues to reduce other preexisting taxes. If it exists and is net positive, a double dividend would certainly qualify as a benefit, but controversy has raged for years over the necessary and sufficient conditions for the existence of the double dividend.[49]

In this guide, we pay only scant attention to the double dividend. This decision was made for several reasons, but primarily because most developing countries face so many market imperfections that comparing best and second-best policy options is unproductive. Rather, it is far better to devote attention to large fiscal and efficiency gaps, such as cyclical volatility of resource revenue, forgone taxes and fees from informal activities, and cost barriers to effective collection (including evasion and corruption).

In any case, most benefits associated with fiscal policy are indirect and are thus best assessed through a CGE modeling framework. This requires defining metrics that can be quantified and used within a CGE model. Again, this guide is not a CGE textbook, but it suggests and gives examples of some appropriate metrics and discusses how they can be incorporated into a CGE modeling framework in order to help capture the indirect benefits discussed above.

7.5.2.1. Carbon Pricing Revenues

Approaches to quantifying carbon pricing revenue were described in the previous subsection (7.5.1). These revenues can enter into the CGE model directly as government revenue, drawn from whatever instrument is chosen for the carbon price (producer, consumer, fuel, mileage, etc.).

Section 7.2 described several reasons why a carbon price could generate additional revenue (inclusion of the informal sector, reduction in evasion, lowering of collection costs). These related benefits can also be modeled directly. For an example of how tax evasion reductions associated with environmental taxes can be incorporated in a CGE model, see Liu (2013), who includes the choice of whether to evade taxes in the firm maximization problem and shows that a carbon tax limits a firm's choice to evade taxes.

7.5.2.2. Share of the Labor Force in the Formal Sector

Although recent efforts have made strides in explicitly incorporating informal activities into a CGE modeling framework,[50] most CGE models still do not explicitly model the informal sector. Without a modeled informal sector, actors leaving the informal sector and entering the formal sector can be modeled as an increase in the workforce (since those workers in the informal sector were previously acting outside of the model). Moving beyond this impasse will require more credible efforts to develop informal sector data–not merely as an aggregate percentage of GDP or labor force, or some other aggregate, but functionally. We must remember that the agency of tax behavior is microeconomic, just like the structure of CGE models.

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[49] See Freire-González (2018) for an exhaustive review of this literature.

[50] Davies and Thurlow (2010) use labor force surveys to parameterize the size of the informal economy and then model the choice to enter the formal economy in South Africa; Sinha and Adam (2006) and Paquet and Savard (2009) also develop CGE modeling frameworks for the informal sectors in India and Benin, respectively.

Thus the models can yield their insights only when calibrated to appropriately structured data; but traditional National Income and Product Account and other macroeconomic accounting data have serious gaps–among them the "informal sector" category. This could be innocuous if informal activity were residual, small, and relatively uniformly distributed across economic activities. In developing countries, however, the opposite is true, and informal activity can be a very substantial share of the overall economy and dominate certain classes of activity. With respect to carbon price benefits, the distortion can be even greater.

The so-called CGE micro modeling literature suggests how one might address this problem, using household survey data to input more detailed local activities than are recorded in national labor force participation data. Especially in the rural sector, macro data suggest that labor is "underutilized" or in surplus, when in fact much work is informal, secondary, or otherwise unrecorded. The vast reserve of *Living Standards Measurement Study* information produced under sponsorship of the World Bank and other development partners could significantly advance work in this area.

7.5.2.3. Reduction of Distortionary Taxes

Different tax instruments have very different revenue, compliance, productivity/efficiency, and other performance characteristics. Indeed, in developing countries disparities in tax efficiency are likely to be much greater than in developed countries, and in this context carbon pricing has many very attractive features. To the extent that public revenue can be raised from a carbon price on energy at lower administrative and social cost and with more certainty, letting it substitute for less efficient sources makes sense. When distortionary taxes are in place, they will be captured by prices in the relevant sectors. As these taxes are reduced or removed entirely, prices in those sectors will be affected.

7.5.2.4. Labor Intensity of Production

The relevant shares of labor and capital in production can be modeled as a function of the carbon price where introduction of the carbon price, or increases in the stringency of coverage, increase the relative share of labor's contribution to production. This approach would require a CGE framework or, for a single sector, a neoclassical production function that permits factor substitution. The Leontief framework with constant value-added shares would not be appropriate.

7.5.2.5. Returns to Labor and Capital

As soon as a carbon price component (e.g., a fuel tax) is introduced into the price system of a CGE model, wages, rents, and any other factor prices are automatically linked to it. In other words, returns to labor and capital can be endogenized so they are a function of the carbon price. See also section 8.3.1.

7.5.2.6. Household Incomes across the Income Distribution

Household incomes across the distribution will be an important output to evaluate when assessing the impact of a carbon price and will be affected by changes in returns to production and changes in commodity prices. However, in most cases the distributional aspects of the carbon price will be captured in the results without modeling them directly. An exception is cases where revenue is returned as dividends. In that case a direct link can also be modeled so that household income changes as a function of the carbon price directly (because it affects the amount of the dividend that will be received).

In any case, thanks to huge investments in longitudinal survey data, income distribution is one of the easiest elaborations of traditional representative consumer CGE models. Because these models all tie household income and consumption to the overall economy (production, trade, factor markets, etc.), such disaggregated models will automatically deliver detailed information on the welfare effect of price changes (carbon and otherwise).

A summary of how benefits of a carbon price on fiscal policy can be modeled is outlined in table 7.1.

Table 7.1

Quantifying the Effects of a Carbon Price on Fiscal Policy

	Step	Notes
1	Measure direct impact by quantifying the revenue raised from a carbon price	• Derive revenue raised from government accounts and budgets. • Alternatively, an approximate estimate can be derived by multiplying emissions coverage by nominal carbon price for a carbon tax or the share of auctioned allowances by the nominal carbon price for an ETS.
2	Estimate the indirect impacts	• Most fiscal policy benefits are indirect and best assessed through CGE modeling. • Liu (2013) provides an example of how to estimate the indirect benefits of a carbon price on tax evasion. • Most CGE models do not explicitly model the informal sector, but it can be modeled as an increase in the workforce (actors entering the formal sector). Moving beyond this approach requires significantly more work. • The relevant shares of labor and capital in production can be modeled as a function of the carbon price increasing the relative share of labor's contribution to production. • CGE models can also show the distributional income across income groups.

8.

Balance of Payments

At a Glance

- Carbon pricing can increase energy independence and reduce the risk of uncertain external imbalances for importing countries.
- For fossil fuel exporters, carbon pricing promotes energy efficiency at home, freeing more resources to earn foreign exchange.
- For the same exporters, pricing also reduces the risk of Dutch disease, improving competitiveness and investment in other tradable goods and services.

The economic variable that is generally recognized to directly affect the balance of payment is the exchange rate. Links from carbon prices to the exchange are mostly very indirect, though.

8. Balance of Payments

8.1 Introduction

Strictly speaking, carbon prices cannot be said to directly affect the balance of payments (BOPs) because this is a macroeconomic balance. This is because carbon pricing affects both sides of this aggregate variable. Acting on prices of energy and energy-intensive goods and services, carbon prices can strongly affect this balance, but only in rare cases (e.g. smaller, highly energy export or import dependent countries) is the impact strong enough to act in a predetermined direction.

Carbon pricing will increase prices of goods that embody carbon energy services, and this tendency can have pervasive effects on domestic prices and a country's international competitiveness. Increasing the price of carbon-intensive goods reduces their demand (absorption) from both domestic and imported sources. It may also divert domestic output to export markets, with the two effects contributing to increased net exports (or smaller net imports), thus improving the merchandise trade balance on both import and export accounts.

Indeed, the only single economic variable that is generally recognized to directly affect BOPs is the exchange rate. Links from energy prices to the exchange are mostly very indirect, however, acting in the short run through extensive cost and market price pass-through, shifting trade patterns in the medium term, and inducing structural adjustments in the longer term. For this reason, this chapter devotes discussion of measurement to indirect linkages, even in the case of the exchange rate.

8.2 Export and Import Responses

A better understanding of the macroeconomic impacts of carbon prices generally, and the BOP in particular, can be obtained by examining the empirical side of this benefit. This discussion is largely focused on indirect effects.

Since the BOP is part of National Income and Product Account standards, the direct role of prices is relatively transparent. Exports are income entries, originating in foreign exchange, while imports are expenditures that must be remitted likewise. For a small country, both rising exports and falling imports expand the balance, with ensuing indirect effects on the exchange rate and domestic relative prices. Because energy is an essential commodity, short-run demand elasticities are relatively low, so export and import responses will be smaller in percentage terms than domestic price effects. This means export income and import expenses will rise proportionately less than prices.

If higher domestic prices are sustained, importers should be investing in energy efficiency and import substitutes to reduce their exposure to carbon energy price risk. In addition to environmental and other benefits, carbon prices thus promote energy independence while reducing the macroeconomic risk arising from unpredictable and potentially large external imbalances.

From a more general policy perspective, appropriately corrective carbon prices reflect the fact that too many domestic productive resources are being dedicated to certain production activities. Fully accounting for carbon costs sends an essential signal that structural change is needed and shifts investment toward less carbon-intensive patterns of supply and demand. Simply put, putting a price on carbon shifts incentives toward more sustainable future growth. Given the historical volatility of international carbon fuel prices, it also can be seen as an insurance premium for economic diversification that reduces BOP uncertainty.

Of course, each country will find its own opportunities and challenges on this transition pathway. A core challenge will be legacy economic dependence on carbon fuels and constraints to technology adoption and diffusion. Countries that have relied heavily on income from carbon energy resources should prioritize domestic energy substitution, diverting conventional fuels to export markets. This will enable them to mitigate resource income losses in the short term while getting energy prices "right" to promote energy decarbonization and innovation at home. Constraints on technology adoption in developing countries are many, including inadequate information/expertise, limited complementary infrastructure, and capital market failures. Experiences like the agricultural transformation during the Green Revolution, however, show that determined efforts by governments and development partners can facilitate technology diffusion extensively and inclusively.

8.3 Measuring and Modeling Indirect Impacts

In terms of modeling and estimation, empirical study of the direct effect of carbon fuel prices on the balance of payments is relatively straightforward, as long as a country has relatively detailed historical trade data. Armed with this, a variety of standard macroeconometric models can estimate and leverage relevant trade elasticities to develop uncertainty bounds on expected BOP variation subject to historical price volatility. We illustrate this with a typical example from Ireland in box 8.1.

Box 8.1

Impact of a Carbon Tax on the Balance of Payments in Ireland

In this application, Conefrey et al. (2013) used the HERMES macroeconometric model to forecast outcomes for the Irish economy on a medium-term basis. This model was developed for the EU but the authors adapted it to the specificities of Ireland for this study. According to the authors, the model has five key mechanisms: (1) the world demand drives the exposable tradable sector, (2) the energy is imported, (3) goods not tradable internationally (e.g., buildings) are driven by domestic demand, (4) decisions on state tax rates and expenditures are exogenous but not decisions on debt and borrowing, and (5) the labor market takes into account the international labor market in the long run.

A tax on CO_2 is introduced at €20/tonne in 2005 for 15 years. Three scenarios are considered. In the first scenario, the carbon tax is put in place with no scheme for revenue recycling. In the second scenario, the increase in taxation due to the carbon tax is offset by a reduction of the income tax. In the third scenario, households receive a lump sum tax refund to compensate for the introduction of the carbon tax.

In the first scenario, there is a fall of exports due to a loss of competitiveness, but this is largely compensated by a larger fall in imports as the demand for energy decreases. Therefore, the balance of payments deficit is predicted to be reduced by 0.35 percent of GNP, thus improving the country's terms of trade as a result of the carbon price.

In both the second and third scenarios (reduced income tax or lump sum refund), the impact on the trade balance is an increase of the deficit (respectively by -0.33 percent and -0.41 percent of GNP). This occurs because the domestic consumption increases a lot, and therefore so do imports.

Calculating the direct effects of pricing carbon per se is more complicated for several reasons. First, observed price data apply to primary and secondary energies (e.g., gasoline and electricity, respectively), not to their carbon content; yet carbon content is essentially proportional to quantity used, and the resulting price increase will reduce fuel demand and therefore carbon and other emissions. As became apparent in other sections, imputing carbon prices based on carbon content can be (with weak assumptions) straightforward. A second challenge is interpreting demand and supply responses, which will depend on how carbon prices are applied. In the simplest case, a carbon price is levied as an ad valorem tax per unit of energy supply. Domestic consumers then see the tax-inclusive price and reduce demand accordingly, while suppliers see this price net of the carbon premium, reducing domestic supply accordingly. In a closed economy, the direct estimation problem then boils down to applying two elasticities (demand and supply) to one price change induced by the shift of supply from marginal private cost (MPC) to marginal social cost (MSC) by the amount of marginal externality cost (MEC)–i.e., MSC = MPC + MEC.

A third complication is taking account of external markets and border prices. Impact assessment is more complex for an open economy, where demand may decrease from both domestic and foreign sources and supply may be diverted to exports. Identifying BOP impacts in this case begins with decomposing domestic "absorption" between domestic and imported energy, and production between supply delivered to the domestic market and exported to the rest of the world. On the demand side, energy buyers will see domestic and imported goods as substitutes. If both sources of energy bear the same ad valorem carbon premium (over producer prices for domestic and cost, insurance, and freight import prices for imported goods), it is reasonable to assume homogeneity, i.e., that demand for domestic and imported energy decrease in equal proportions. This assumption is generally innocuous because the fuels in question are close substitutes.

On the supply side, domestic energy firms may produce for both the domestic and export markets. What happens now depends on the application of carbon prices to output by destination. First assume that only domestic supply bears the carbon premium. In this case, domestic demand is reduced, driving down domestic prices and increasing the incentive to export. For a small exporting country, producers can divert all their excess supply to external markets, offsetting some of their domestic revenue shortfall. In the small-country case, these producers cannot pass on the carbon premium to international markets, so we assume they will export at producer prices. In any case, a simple elasticity model can be estimated to predict the degree to which relative (export/domestic) prices affect aggregate supply and its targeting to domestic and foreign markets.

In both cases, it should be noted that we also make the so-called small-country assumption, i.e., assume that both import supply to and export demand from our country are perfectly elastic. Demand or supply responses to carbon pricing that affect a country's terms of trade (the purchasing power of exports) could be estimated, but only with relatively intensive data development. The challenge here is to decompose covariance between individual energy trade flows and international prices, and between price effects on imports/exports and import/export effects on world prices. This is beyond the scope of this guide and may not be realistic for many countries.

8.3.1 Indirect Effects

Because energy services pervade the economy, the indirect effects of carbon price changes will always be extensive; the important question for policy making is their direction (cost or benefit) and magnitude. International and domestic prices are linked by detailed trade flows, with their responsiveness subject to the relative sizes of global and domestic markets. In this section we discuss some salient issues about such indirect (linkage) effects as they relate to benefits from carbon pricing.

Although the BOP benefit implicates a county's external economic linkages, the indirect effects can be estimated with modeling tools similar to those used for the other benefits discussed in this guide, and along similar pathways. In particular, supply chain analysis would be a logical first step, especially for goods and services that are carbon-intensive. In these cases, strong price transmission can be expected from a small numbers of inputs, e.g., primary energy fuels or secondary energy carriers like coal-fired electric power. For more complex supply chains, multiplier (input-output) and CGE models can aggregate more extensive income and expenditure chains linking carbon prices across the economy. Multiplier models are easier to use, but their restrictive assumptions render their estimates indicative at best, usually consistent in direction but likely to overestimate both positive and negative impacts. CGE models are more complex and data intensive but are more consistent with modern microeconomic theory and allow for extensive counterfactual scenario analysis. The choice of method for an individual application will depend on the complexity of the indirect effects being estimated, technical capacity, and data resources. The remainder of this section is devoted to a few special topics related to trade and carbon prices, but first an example of CGE assessment of BOP effects is presented (box 8.2). This 1993 study looked at the impact on the UK economy of imposing a carbon tax, employing a method that is still relevant for policy makers interested in doing this kind of assessment.

Box 8.2

Impact of a Carbon Tax on UK Balance of Payments

Barker, Baylis, and Madsen (1993) looked at a $3 carbon tax on a barrel of oil (starting in 1993), which would increase to $10 in 2000, converted to import duty rates and controlling for inflation. They used a CGE, the Cambridge Multisectoral Dynamic Model of the British economy for their assessment. This is a large-scale energy-environment-economy model that treats energy demand by means of aggregate equations for energy users and fuel share by means of equations for electricity and each of the main fossil fuels. It models detailed relationships between industries as behavioral agents, and also models the linkages between supply chains, demand, investment, trade, employment, wages, and prices.

Four scenarios were considered, according to two policy dimensions: the tax can be implemented either on European Community (EC) economies or on OECD economies; and, assuming revenue neutrality, it can be offset by reducing either the VAT or income tax rates (table B8.2.1). The base scenario is simply what is predicted to happen if no carbon tax were implemented.

Table B8.2.1

Selected Macroeconomic Results: Percentage Point Difference in Balance of Payment/GDP from Base Scenario

Year	EC tax with VAT offset	EC tax with income offset	OECD tax with VAT offset	OECD tax with income offset
1995	-0.07	-0.13	-0.22	-0.30
2000	-0.16	-0.38	-0.47	-0.78
2005	-0.23	-0.23	-0.55	-1.02

Source: Barker, Baylis, and Madsen (1993).
Note: EC = European Community; GDP = gross domestic product; OECD = Organisation for Economic Co-operation and Development; VAT = value added tax.

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In all four scenarios, the balance of payments (surplus in the baseline) was predicted to deteriorate. As in most traditional CGE tax experiments, without stipulating economic benefits from the tax, efficiency and competitive effects lead to small negative growth effects without revenue neutrality (recycling) and small positive benefits with revenue offsets. The effect is larger when the tax is applied across all OECD economies because the authors exempted energy-intensive industries for competitiveness reasons in the EC-only scenarios. The impact on the balance of payments is also larger when the carbon tax is offset by a decrease of income tax (stimulating imports) than when it is offset by a decrease of the VAT. The salient drivers of these macroeconomic impacts are indirect, extending from fuel imports to industry-level competitiveness and across complex fiscal linkages.

8.3.1.1. Carbon Prices and Trade Policy

Aggregate impacts of carbon prices are interesting in their own right, but the interaction of carbon prices and sector trade patterns can also be an important issue. This is especially the case for countries whose comparative advantage is sensitive to the energy content of their trade, such as those that are very reliant on carbon-intensive exports or imports. Using a CGE assessment framework, Beghin, Roland-Holst, and Van der Mensbrugghe (1997) argue that coordinating trade and environmental policy can better reconcile efficiency and pollution mitigation goals. For example, substituting carbon taxes for tariffs on imported fossil fuels can remove protectionist barriers without adverse environmental impacts. Alton et al. (2012) model the impact of a national carbon tax in South Africa on trade balance results, including different models of foreign, consumption or production tax (see box 8.3).

Box 8.3

Impact of a Carbon Tax in South Africa

Alton et al. (2012) study the impact of implementing a carbon tax on the South African economy, using a model that allows for endogenous investment responses, such as a firm investing in less energy-intensive technology after the carbon tax. Their CGE approach captures interactions between the government, households, firms, and foreign countries. Their main policy scenarios assess the impacts of a linear schedule of carbon tax levies that begins at \$3 per million metric tons of CO_2 equivalent ($MMTCO_2e$) in 2012 and extends to \$30 per $MMTCO_2e$ in 2022.

The baseline scenario is constructed by running the model without a carbon tax. The authors then consider three dynamic policy regimes. Under the “production” scenario regime (scenario 1), the tax is applied domestically on the net supply of primary fossil fuels. Under the “consumption” scenario (scenario 2), South Africa taxes only products that are consumed on its soil: products exported are rebated, and imports are carbon-taxed on landed import value the same way as goods produced in South Africa. These adjustments are made to preserve “competitive neutrality.” Under the “foreign tax” scenario (scenario 3), trading partners implement a tax such as the one in scenario 2, but South Africa does not (the tax begins at \$1.5 in 2012 and rises to \$15 in 2022). Results are shown in table B8.3.1.

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Table B8.3.1

Selected Trade Balance Results: Imports and Exports 2010–25

	Initial value, 2010	Baseline growth rate (%)	Change in WQI		
			Production carbon tax	Consumption carbon tax	Foreign carbon tax
Exports	24.6	4.11	-0.88	0.24	-0.42
Imports	-26.6	4.19	-0.81	0.22	-3.19

Source *Alton et al. (2012).*

In the first scenario, the balance of trade deteriorates because the competitiveness of firms decreased–a result of the exclusion of foreign-produced goods from the scope of the carbon tax. In the second scenario, balance of trade improves, as the opposite conditions are in place. The third scenario leads to a decrease in both exports and imports, but the fall of imports is much larger, so the trade balance effect is positive.

One important insight from the embodied resource trade perspective is that policy differences (e.g., labor or environmental standards, concessional credit, etc.) can confer comparative advantages on countries. In the context of carbon prices, this would imply the existence of so-called “pollution havens,” where relatively lax environmental standards attract investment for export of pollution-intensive products. Despite many studies, however, the evidence for pollution havens remains quite weak.[51] Having said this, there remain systematic imbalances in the emissions content of trade, and these are susceptible to both carbon pricing and sectoral trade policy. In this context, Lee and Roland-Holst (1997) show how Indonesia’s historical trade orientation has been environmentally asymmetric, resulting in significant transfers of pollution-retention services from its domestic economy to trading partners, particularly Japan. While trade liberalization would improve Indonesian real income, the authors show how it would also raise emissions of major industrial pollutants. In light of this trade-off between outward-oriented industrialization and the environment, they used a general equilibrium framework to assess the relative cost of curtailing pollution with a variety of instruments. Their results indicate that a uniform effluent tax is the most cost-effective instrument in abating GHG emissions.

The most important finding of Lee and Roland-Holst (1997) is that when uniform environmental taxation is combined with trade liberalization, it is possible to navigate the complex interactions between trade and environmental policy and to abate industrial pollution while maintaining or even increasing real output. In other words, trade liberalization should not be discouraged because of its environmental effects, and carbon prices need not lead to macroeconomic losses if distortions can be removed elsewhere. Devising the right combination of such complementary policies requires diligent empirical support, and CGE models are excellent tools for this purpose.

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[51] See Eskeland and Harrison (2003); Cole (2004).

8.3.1.2. Embodied Carbon Trade

A first step beyond estimating direct carbon price effects is to acknowledge that merchandise trade corresponds to trade in the domestic resources and services needed to produce the merchandise. Thus a labor-, energy-, or pollution-intensive exporter is exporting embodied services of the corresponding factor or resource, sparing the importer the need to use domestic resources (and experience attendant externalities) at home. For example, until recently, 30 percent of China's energy consumption, largely coal-fired, was used to produce exports (Kharl and Roland-Holst 2011). This means importers of those goods were essentially importing coal energy services, but outsourcing pollution to China. Through these dynamic linkages, carbon prices have a cost pass-through to affect trade in carbon-intensive goods. A domestic carbon tax will reduce domestic demand for carbon-intensive goods, reduce imports, and divert some supply to exports.

An analogous case of water resources is presented in box 8.4. It shows that if Morocco added a levy to the water content of agri-food products, it would have three impacts: reduced domestic demand (absorption) for water-intensive food products, higher incentives to divert domestic production to export markets, and increased domestic water use efficiency. The first two effects, driven by higher consumer prices and lower producer prices in the domestic market, would have a favorable effect on the BOP. A carbon price would likely have similarly pervasive indirect effects through trade flows across fossil fuel–dependent commodities.

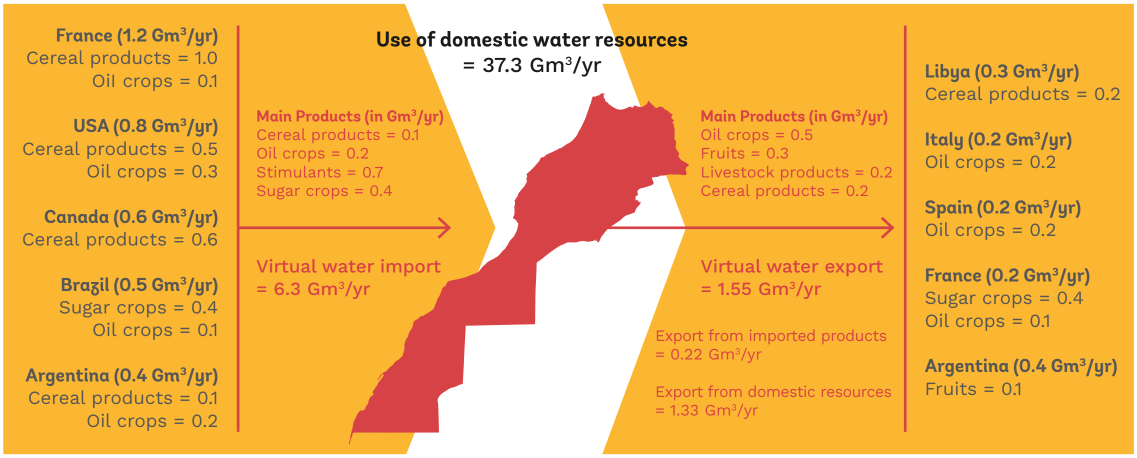
Box 8.4

Global Water Services: Opportunities from Trade in Embodied Resources

An insightful assessment by Hoekstra and Chapagain (2007) demonstrates that Morocco's agricultural trade is much more water-intensive on the import side, leading to a large agri-food surplus combined with a large deficit in embodied water services.

Figure B8.4.1

Virtual Water Balance of Morocco Related to Trade in Agricultural Commodities



Source: *Hoekstra and Chapagain (2007).*
Note: *The water balance is referred to as "virtual" because it involves water imported in the form of food. Gm^3 = billion cubic meters.*

International foreign direct investment and other capital flows appear responsive to more significant cost drivers–like relative wages, direct resource cost, tax treatment, etc.–than to average or marginal environmental compliance costs. That being said, fear of energy cost increases probably does explain some of the early reluctance of newly industrialized economies to consider carbon pricing; their concern is that it would undermine export competitiveness.[52] Today, the plummeting cost of competitive renewables is changing the prospects for low- and no-carbon energy transition completely. Indeed, countries that are early adopters of clean energy can expect the attendant productivity and cost improvements to strengthen their competitiveness, while "green marketing" can offer greater pricing power in higher-income export markets.

As a practical matter, estimating BOP impacts from carbon pricing can be done with a combination of trade and input-output data. These impacts can be derived for a given set of imports and exports by assuming these goods are made with a fixed proportion (Leontief) technology and calculating the cost share of carbon in each.

This calculation can be done on a first-order or general equilibrium basis. The first-order approach looks only at carbon fuels used directly in producing the traded goods, assumes 100 percent pass-through to their respective trade prices, and then calculates the incremental BOP effect.[53] A more comprehensive approach would use either a "dual" price multiplier matrix or CGE model to unpack all the component carbon services used to deliver imports or exports to the border.[54] The multiplier case assumes 100 percent pass-through to calculate the incremental price effect on imports and/or exports and BOP, while the CGE estimate would allow for some price adjustment.

8.3.1.3. Dutch Disease and Other Maladies

In the early 1970s, the so-called energy crisis heralded a tectonic adjustment in global fossil fuel markets. More assertive pricing by a cartel of oil-producing nations could be seen as a natural experiment in carbon pricing. Unfortunately, the ensuing decade of stagflation, wealth transfers, and extensive economic restructuring left a stubborn legacy of concern over energy and economic security. Because prosperity was so undermined by higher fossil fuel prices, many policy makers have retained an instinctive aversion to carbon pricing. Indeed, environmental and growth objectives are still often seen as incompatible, even though the energy crisis took place in a completely different global technology environment, one without credible innovation capacity to rapidly expand production of carbon energy substitutes or more energy-efficient use technologies. We live in a different world now, one where artificially low carbon prices can still retard low-carbon innovation and growth.

While escalation of oil prices did confer short-term and medium-term benefits on some countries, it also increased external dependence. Direct windfalls of higher export earnings made great fortunes for some and generated valuable public resources for many. The long-term benefits of this "new money" depended, of course, on how it was used to support further development, and here experience was very mixed. To a significant extent, differences had to do with long-term per capita reserve capacity (the resource constraint) and the realities of public finance. Some countries invested wisely in human resources, economic diversification, and infrastructure, while others sought shorter-term rewards through transfer payments and even corruption. Although chapter 7 does discuss revenue recycling, many of these issues are otherwise outside the scope of the guidebook.

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[52] For more on this important topic, see CPLC (2019b).
[53] See for example Dietzenbacher and Mukhopadhyay (2007) for detailed examples and methods.
[54] See Roland-Holst and Sancho (1995) for a discussion of price multiplier analysis

One important indirect impact of this and other “resource booms,” however, remains relevant to export-dependent economies and to carbon pricing. This is a structural economic distortion, dubbed Dutch disease because of its application to the context of Holland’s North Sea oil exploitation. Revenues from North Sea carbon fuels had a stunning impact on the Dutch economy, sharply improving its terms of trade. While this improvement had a desirable aggregate wealth effect, it also distorted domestic relative prices, sharply increasing the purchasing power of nontradable goods and services (rising with the income effect) against tradable prices. The latter were stabilized by a global economy much larger than the domestic markets supplying Holland’s own services and other nontradables. Domestically, this shift reduced the relative returns to domestic investment in non-energy tradable sectors, causing Holland to “deindustrialize” and the GDP share of other export sectors to shrink. Since that experience, there have been many efforts to “sterilize” resource windfalls, isolating them in offshore sovereign wealth funds and other vehicles to immunize the beneficiary economies against Dutch disease. Along with other international financial institutions and development partners, the World Bank has for decades counseled developing countries to be wary of “winning the resource lottery” or experiencing booms that entail significant externally driven wealth effects (even including development aid, box 8.5), as these are decidedly mixed blessings.

Technically, Dutch disease is driven by a wealth effect and a relative price effect. While carbon pricing is more purely a relative price effect, it can still induce sectoral relative price distortions. For example, levying a substantial carbon tax will lower the relative (producer) price of carbon-intensive goods and services. For other (noncarbon) goods, relative producer prices will increase, possibly undermining their export competitiveness, thereby the BOP. Hopefully, the same relative price appreciation will encourage investment in these sectors, but some revenue recycling for concessional credit, trade promotion, etc. might be needed to sustain export competitiveness. The same logic applies to domestic noncarbon goods and imported substitutes. Their higher relative prices may lead to increased domestic market penetration by imported substitutes, further shrinking the trade balance.

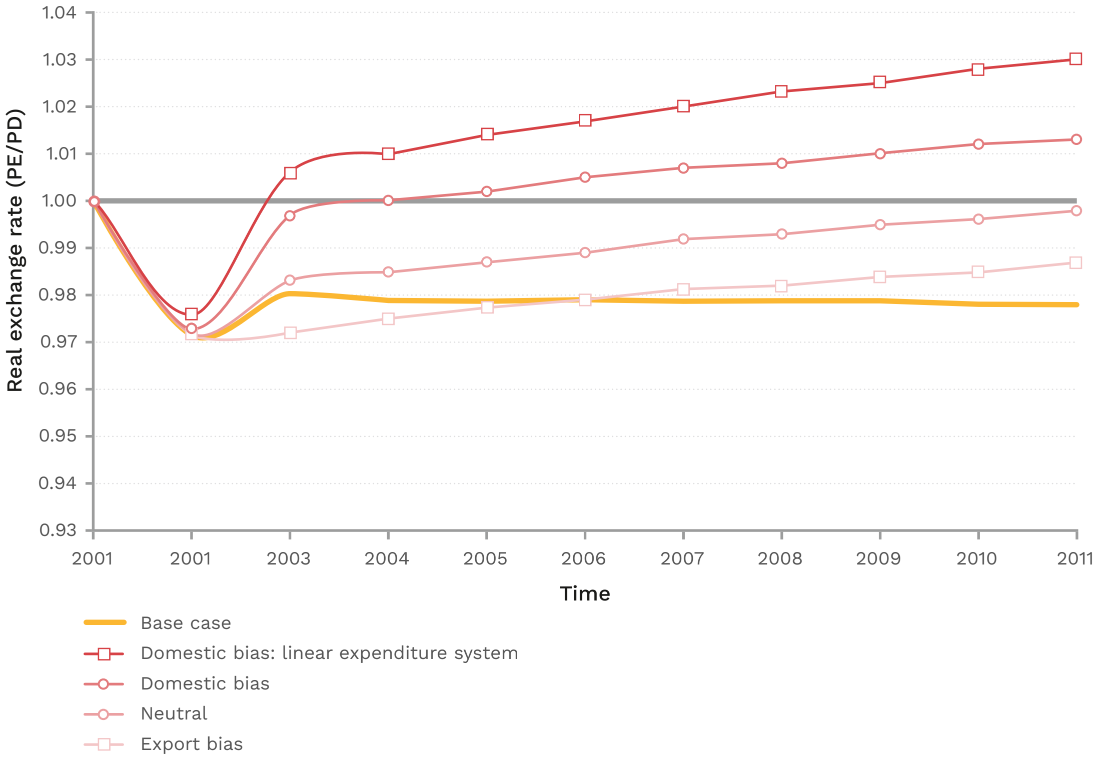
Box 8.5

Dutch Disease and External Assistance

Beginning with a very parsimonious CGE analysis, Devarajan and Go (1995) established a sustained research and policy agenda cautioning developing countries on the structural risks presented by resource booms. These intertemporal models show that longer-term structural effects can significantly offset the windfall benefits of large external inflows, and that even development assistance flows can present Dutch disease risks (figure B8.5.1), undermining export competitiveness with real exchange rate appreciation (Rajan and Subramanian 2011; Adam and Bevan 2006).

Figure B8.5.1

Export-Weighted Real Exchange Rate Response to Aid-Financed Public Investment



Source: Devarajan et al. (1997).

Note: PE/PD = Ratio of trade-weighted export prices (PE) to demand-weighted domestic prices (PD)

9.

Technological Change

At a Glance

- Carbon pricing can provide a dynamic incentive to induce technological change that can lead to low-carbon technology innovations.
- Empirical evidence finds that environmental regulations typically lead to innovations, although the costs do not always offset the gains from innovation (the Porter hypothesis). Research suggests this may also be true for carbon pricing, though with heterogeneity across sectors and firm levels.
- Benefits of technological change can be measured by the following metrics: business performance, innovation, productivity, and export competitiveness.
- To fully reflect the benefits from technological change, CGE models must consider technology as an exogenous parameter.

9. Technological Change

9.1 Introduction

Greater recognition of the social cost of fossil fuel use provides new impetus for putting a price on carbon, but it can also incentivize the adoption of new technology, higher productivity, and low- or zero-carbon innovation. The carbon fuel energy system is an artifact of the Industrial Age, an era of resource-intensive growth accompanied by serious environmental damage and chronic inequality. Today's leading economies have transitioned to postindustrial economic structures, with greater and more equal prosperity fueled by higher productivity, real wage appreciation, and skill-intensive development. Carbon pricing along with supporting policies can facilitate this progress in any economy by promoting resource efficiency, new technology adoption, and more sustainable long-term energy use.

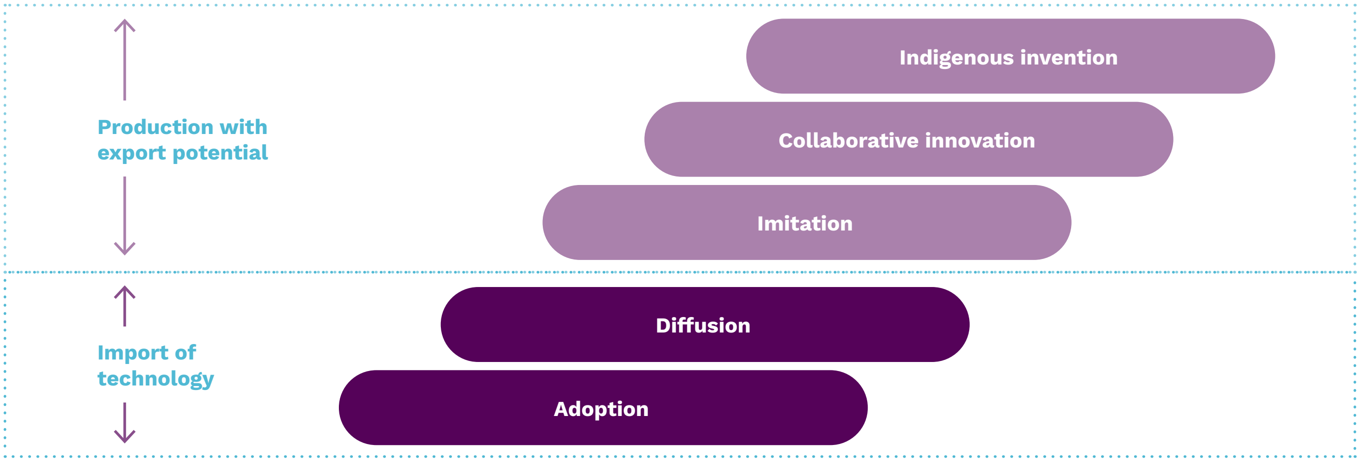
In theory, the higher costs from carbon pricing should provide a dynamic incentive to influence low-carbon technology (LCT) innovation or adoption. This innovation process is typically referred to as induced technological change (ITC). Whether environmental regulations can lead to ITC has been a topic of debate in the research community; the contention that it can is known as the Porter hypothesis. The Porter hypothesis has both weak and strong versions: the weak version posits that more stringent environmental regulation can stimulate innovation, and the strong version posits that innovation will more than compensate for the costs of compliance, leading to increased competitiveness and productivity. In other words, productivity gains through innovation will totally exceed all costs associated with regulation.

While pricing is not a key barrier to innovation across all industries, it is certainly relevant for firms that are reliant on fossil fuel–based technologies. While some firms may elect to absorb the price, for others carbon pricing presents two options: either switch to existing LCT alternatives, or invest in new LCT innovations.

For many low- to middle-income countries, carbon pricing may play a role in speeding up LCT adoption (e.g., through imports) and innovation. Some countries may not have the technological abilities to innovate in this sector initially and may instead rely on the import of technologies. Over time, they may move through the "technology-transfer staircase" (figure 9.1) to become LCT developers.

Figure 9.1

The Technology-Transfer Staircase



Source: Pigato et al. (2020).

9.2 Applying the Porter Hypothesis to Carbon Pricing

There is an extensive literature considering the Porter hypothesis, particularly in the US and the EU. The findings from this research can be applied to carbon pricing. Research suggests that there is evidence to support the weak Porter hypothesis. Aghion et al. (2015) find that increased energy prices appear to alter the mix of research and development (R&D) toward cleaner innovations within firms. Their work found that higher fuel prices induce auto firms to redirect innovation toward clean technologies (e.g., electric and hybrid) and away from dirty technologies (e.g., internal combustion engine). However, the authors also find that a firm's propensity to innovate in clean technologies depends on past exposure to clean technologies, indicative of the path dependency hypothesis.[55]

Other research considers how climate R&D affects spending across sectors rather than within sectors. Popp and Newell (2012) consider whether an increase in climate R&D represents new spending in R&D or is substituted away from other types of R&D spending. Their work finds no evidence of crowding out across sectors. That is, increased spending in climate R&D does not draw resources away from other R&D sectors. Thus innovation through carbon pricing might not be zero sum across sectors.

Evidence is mixed on the strong Porter hypothesis. Lanoie et al. (2011) consider 4,200 facilities across seven OECD countries and find no support for the strong version. Specifically, they find that the direct effect of environmental policy stringency on business performance is negative, although it does appear to induce investment in environmental R&D. Rubashkina, Galeotti and Verdolini (2015) consider the manufacturing sector in 17 EU countries between 1997 and 2009, looking at innovation through the proxy of patents. While the authors find evidence to support the weak Porter hypothesis, they find no evidence of the strong Porter hypothesis (i.e., that environmental regulations lead to increased productivity).

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55 Path dependence is an economic concept that explains how the set of decisions is based on decisions or events in the past, even though the past circumstances may no longer be relevant.

Costantini and Mazzanti (2012) find positive support for the strong Porter hypothesis in the EU. They find that environmental policies in general are not harmful for the export competitiveness of the manufacturing sector, and furthermore, that specific energy tax policies can positively influence exports. Wang and Shen (2016) find support for the strong Porter hypothesis in China. Their work demonstrates that as environmental regulation increases, environmental productivity improves. However, there is heterogeneity across industries, and for pollution-intensive industries productivity declines. Xie, Yuan, and Huang (2017) also find support for the strong Porter hypothesis in China. The authors consider both formal and informal environmental regulations and find varying degrees of support.[56] For formal regulations they find a positive, nonlinear relationship between regulations and productivity, while findings for informal regulation are inconclusive.

The work in China suggests the Porter hypothesis is valid in developing countries, but other research presents a more nuanced explanation. For example, Albrizio, Kozluk, and Zipperer (2017) find that environmental regulation has a positive short-term productivity effect only in the most technologically advanced countries. The effect decreases with the distance from the global technology frontier, and for the least productive countries no effect was found; thus the results from China are likely unique and may not extend to developing countries in general. The authors also find heterogeneity at the firm level: only the top fifth of firms experienced productivity gains, whereas productivity in other firms decreased. This finding would suggest that positive effects on productivity may be smaller in developing countries. Other work, however, suggests that firm strategies, rather than locations, drive the heterogeneity. Ramanathan et al. (2017) also consider China and find that results depend on the specific firms' resources and capabilities. Firms that are able to adopt a more dynamic approach to environmental regulations are better able to reap the benefits. Thus even technologically advanced firms in less developed countries may see productivity gains from stricter environmental regulation.

Other work has attempted to quantify the benefits of ITC through environmental policy. For example, Popp (2004) has shown that ITC can reduce mitigation costs by 6 percent to 12 percent. More recent work has found similar benefits, specifically that ITC through carbon pricing can lower mitigation costs by 12 percent. However, this effect is highly dependent on the sectors that benefit from ITC. If ITC is focused on the energy sector, the mitigation costs can be reduced to 30–40 percent (Liu and Yamagami 2018).

Although much of the research focuses on environmental policies and regulations generally, direct links can be made to carbon pricing from the environmental policies that cause fossil fuel prices to increase (Aghion et al. 2015).

As the literature cited demonstrates, the potential innovation and productivity benefits of corrective carbon prices are substantial. Although these gains will likely be heterogeneous across countries and sectors, technologically advanced firms in low- to middle-income countries will very likely see ITC benefits from a carbon price.

Even countries and firms that are not at the front of the global technology frontier have the potential to benefit from carbon pricing through LCT transfers. Although this relationship is less studied, imports of LCT can lead to innovations over time as the technologies are adapted and operated in local settings. Under the right circumstances, this knowledge transfer can lead to original innovations (Pigato et al. 2020). The quantifiable benefits of technological change are summarized in figure 9.2.

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[56] *Formal environmental regulations refer to command-and-control and market-based regulations, while informal regulations refer to public environmental awareness and pressure.*

Figure 9.2

Metrics for Technological Change Benefits

- R&D
- Business performance
- Innovation (patents)
- Productivity
- Export competitiveness

Source: World Bank.

9.2.1 Carbon Prices for Long-Term Productivity, Competitiveness, and Growth

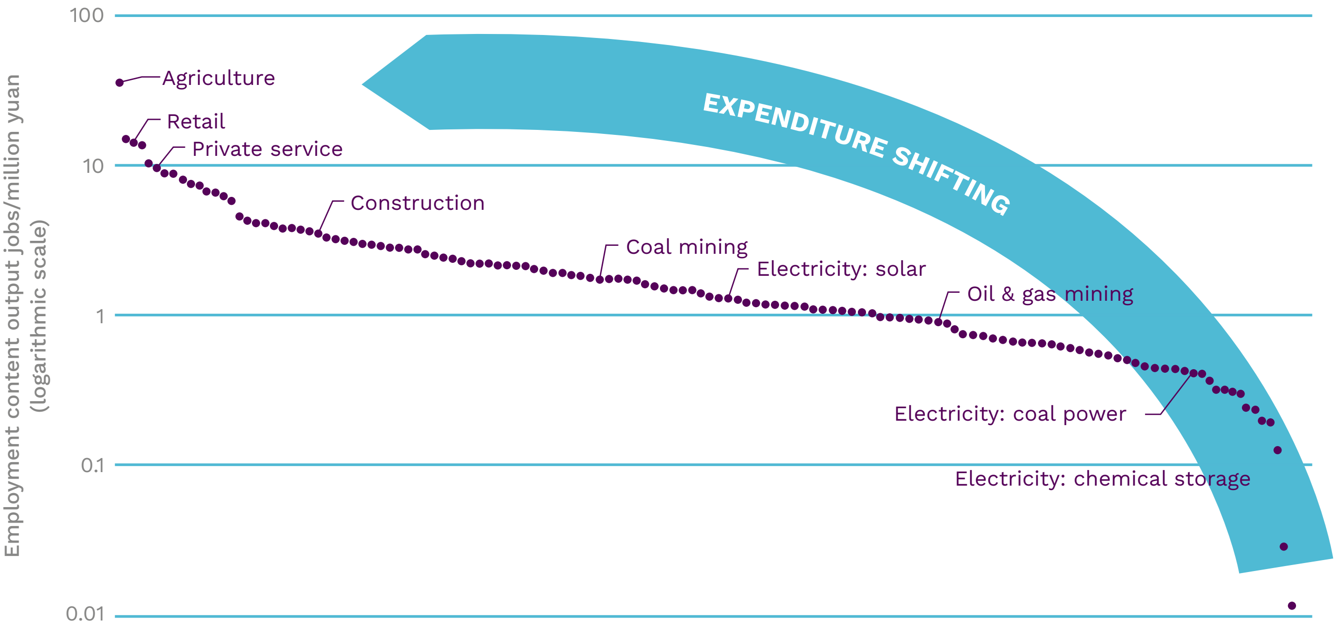
The discussion in chapter 6 (on transportation) emphasized the importance of removing carbon fuel technology biases in the price system. This is important for steering energy use toward long-term sustainability, but today a legacy of energy assets, production, and use practices may also require correction with direct investments. These "stranded" carbon fuel assets exist at all scales and across an entire economy, from coal-fired power plants to smallholder diesel water pumps; and carbon tax revenues can be used, at least in part, to facilitate their retirement and replacement with low- and no-carbon substitutes through subsidies and direct investments. The complete transition from these carbon fuel assets is beyond the scope of this guide, but further discussion can be found in Fay et al. (2015).

Facilitating more efficient diffusion of new energy use technologies has the potential to contribute significant dynamic growth benefits to the economy. First, accelerating the transfer of new technologies has the potential to stimulate domestic modernization, investment, and skill development (Pigato et al. 2020). Doing so for more energy-efficient technologies can also drive stimulus for broad-based demand, output, and job growth–representing expenditure diversion from the carbon fuel supply chain. Promoting energy efficiency (in vehicles, appliances, or any durable goods) can save money for households and enterprises. These savings would be diverted toward other expenditures, the majority of which (in developing countries) go to domestic services and small enterprises that (1) employ workers from all skill levels and demographics, and (2) are nontradable, meaning these new jobs cannot be outsourced (figure 9.3).

Even if the use technologies are imported, the energy savings and most of the multiplier impacts of expenditure shifting will be domestic.[57] As figure 9.3 makes clear, the carbon fuel supply chain is among the least employment-intensive, and this is already after deducting a significant import cost share. Jobs per million of revenue in the service sector are over 100 times more labor-intensive than the same metric in the carbon energy supply chain, and the difference is far too large to be offset by wage inequality. Simply put, the majority of a dollar saved at the gas pump is spent on the dominant constituents of household spending (food, retail, services), stimulating much stronger and more diverse job growth.

Figure 9.3

How Revenue Reallocation and Energy Efficiency Create Jobs



Source: *Chen et al. 2021, using data from Chinese National Bureau of Statistics, "Input-Output Table 2017"; and Chinese National Bureau of Statistics, China Labor Statistical Yearbook 2018.*

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[57] *So much so that a logarithmic (vertical) scale is needed to span the disparities.*

9.3 Measuring and Modeling Impacts

9.3.1 Direct Effects

There are two main approaches to estimating the effect of a carbon price on technological change. The first is modeling technological adoption and simulating different carbon pricing scenarios to learn about technological investment behavior. The second is to use an empirical model that estimates the statistical relationship between a carbon price and a metric that characterizes technological change (e.g., the number of patents). Because data are limited and the empirical approach requires that the carbon price already be in place, the modeling approach is more common. We discuss both approaches here.

The effects of a carbon price on technological change result from induced investments in R&D and technology deployment (typically referred to as ITC). When a carbon price is implemented, firms must balance the trade-off between the "long-term fee" that comes from persistent carbon fuel use and the "short-term upgrade fee" associated with deploying a cleaner technology (He et al. 2018). The investment response that firms choose depends on the carbon price, production costs, carbon emissions, and upgrade costs they face. A number of studies have used theoretical economic models to study this choice (e.g., Shittu and Baker 2010; Khalilpour 2014; Zhou et al. 2014). They highlight important factors that influence the extent of technological investment under a carbon price, including expectations about future carbon prices, available technological options, and the strength of the patent system, among others (see box 9.1 for a more detailed example of this modeling approach). Akin to CGE frameworks, these models use economic theory to develop representations of the firm decision-making process and then introduce a carbon price into the system and examine how the model predicts changes to investment in technology.

This approach has strengths and weaknesses. On the one hand, it does not require detailed data, does not require a preexisting carbon pricing instrument, and is "micro-founded," i.e., based on theoretical understanding of technology investment decisions at the firm level. On the other hand, the models are not well suited for validation with observed data, they can be less transparent than empirical models, and they are difficult for non-experts to implement. Nonetheless, modeling technological investment decisions can provide useful insight into how a carbon price will affect the rate of technological change.

Turning to econometric models, there are empirical models that consider generally how productivity growth depends on a firm's ability to adopt existing technologies (technological catch-up) and on its ability to innovate (technological pass-through). The general modeling technique—known as the Neo-Schumpeterian model of multifactor productivity growth—has shown that regulations have a heterogenous effect on productivity growth depending on the level of technological advancement at the firm or country level (Bourlès et al. 2013). This model has been refined to account for environmental policies (Albrizio, Kozluk, and Zipperer 2017).

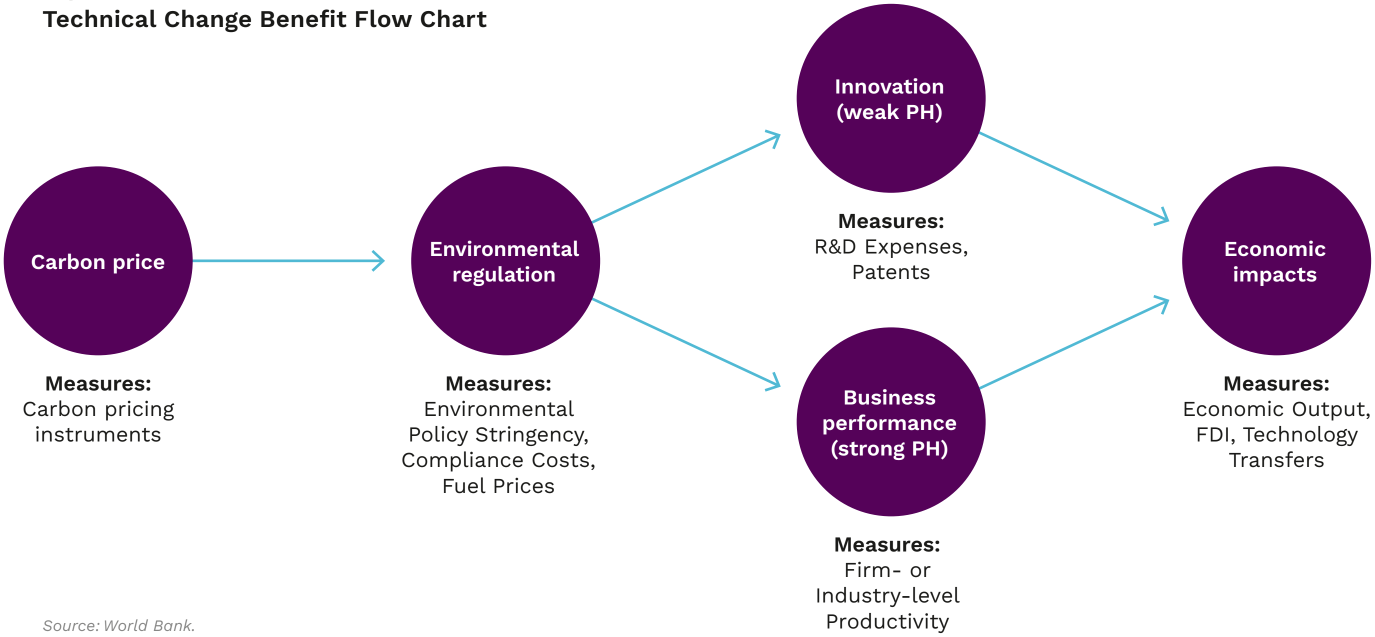
More generally, historical comparisons of profitability show that primary energy producers in OECD countries (e.g., oil majors and national oil companies) have consistently high markups, tax deferrals, or some combination of these that yield returns to equity consistently exceeding market averages. This suggests that pricing carbon and reducing carbon fuel dependence could improve energy sector competitiveness.

Econometric models are frequently used to study the Porter hypothesis and can be used for carbon pricing. For the weak version, innovation is commonly measured through R&D expense or through the number of patents (a proxy for the product of R&D activity). For the strong version, business performance is measured through firm- or industry-level productivity. Using a metric for environmental regulations (typically measured as compliance costs), econometric analysis can establish the link between regulations and innovation or productivity. A similar strategy can be applied for carbon pricing either through a direct policy such as a carbon price or an indirect metric such as fuel prices. Strengths of this approach are the flexibility to include a range of variables and the ability to capture general equilibrium effects through historical outcomes. Limitations are the more extensive data requirements and the need for a carbon price (or related metric) to be in place.

A simplified overview of the econometric modeling approach is displayed in Figure 9.4.

Figure 9.4

Technical Change Benefit Flow Chart



Source: World Bank.

Note: PH = Porter hypothesis; FDI = foreign direct investment.

The first step in the benefit modeling approach is relating the specific carbon pricing instrument to environmental regulations. This relationship could be as simple as fuel prices, or it could fall into an index of environmental policy stringency if compared across countries. For example, one such index developed by the OECD covers 24 countries over the period 1990–2015 and indexes environmental policy across selected instruments (Botta and Kozluk 2014). Changes in carbon pricing would affect various metrics in the index (such as taxes or trading systems).

Environmental policy can then be related to innovation or productivity as discussed above. Although these are benefits in their own right, they can be quantified further. For example, improved innovation or productivity can increase economic output or lead to technology transfers from high-income countries to low- and middle-income countries. This latter point is of particular interest, as the widespread deployment and mass-scale transfer of LCT can significantly reduce global emissions (Pigato et al. 2020).

Box 9.1

Modeling Evidence: The Effect of a Carbon Tax on R&D

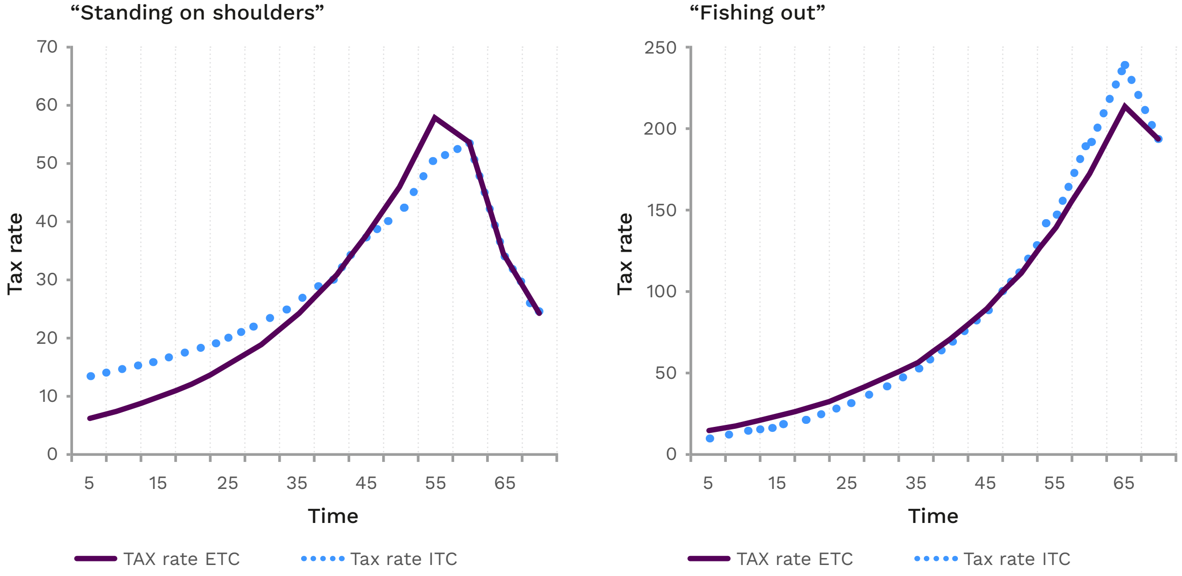
A potential benefit of introducing a carbon price is that by taxing emissions-heavy fuels, it incentivizes investment in clean technologies. Whether these investments in R&D, technology deployment, etc. are realized depends on a number of factors. Greaker and Pade (2009) highlight the important role played by knowledge and learning externalities, like other market failures such as low levels of patent protection and intertemporal knowledge spillovers.

One important factor is whether technological change is endogenous (ITC case) or exogenous (ETC case). Models with endogenous change treat technological processes as R&D-driven knowledge accumulation or learning by doing, while models with exogenous change treat technological progress as something that comes from external sources. A second important factor is how much it costs to adopt new ideas as they spread. As shown in figure B9.1.1, the “standing on shoulders” scenario models a setting where new technologies become cheaper to adopt over time, while in the “fishing out” scenario they become more expensive. A key part of these scenarios is the carbon price level required to induce the technical change to meet an emission target; whether the price is higher or lower in the early stages influences how technological ideas evolve.

The primary finding of this work is that policy makers could have reasons to set a higher carbon tax today if there is technological change driven by R&D as opposed to pure exogenous technological change. This result is dependent on both the direction and size of the knowledge externality and the extent to which there is a learning externality. Specifically, if there is a “standing on shoulders” knowledge externality or weak patent protection or both, then a higher carbon price from the start may be warranted.

Figure B91.1.1

Cost of Adopting New Ideas: Model Showing Falling Costs (left) vs. Model Showing Rising Costs (right)



Source: Greaker and Pade (2009).
Note: ITC = endogenous technological change; ETC = exogenous technological change.

9.3.2 Indirect Effects and CGE Modeling

Many of the economic impacts of technological change induced by a carbon price are indirect and best modeled in a CGE framework. In fact, modeling technological change is an important component of CGE modeling, and so the approach is well suited to capturing the indirect linkages.

Typically, technology is considered exogenous in CGE models. Some models account for technology as a mixture of endogenous substitution of other production factors and consumer goods for energy, induced changes in the energy mix, assumed autonomous total factor productivity growth, and factor-specific productivity progress, including autonomous energy efficiency improvement. These changes fail to reflect how changes to technology through a policy decision would affect outcomes. This is particularly relevant for carbon pricing, as technological change generates benefits that likely will not be captured if technology is exogenous. Therefore, to capture the full benefits of carbon pricing, technology must be endogenous and determined by the model.

Two examples are included in the boxes below to highlight new modeling approaches to technology. Box 9.2 provides an overview of some of the techniques being used across 17 CGE models. Box 9.3 takes a more focused look at a specific modeling approach. Interested modelers can incorporate the techniques discussed below to better reflect how carbon pricing can create benefits through ITC. As the examples demonstrate, failing to account for technological innovation can misrepresent the total costs and benefits of carbon pricing.

Box 9.2

Capturing Energy and Emission Trends in CGE Models

Faehn et al. (2019) offer fairly up-to-date and extensive model comparisons that provide a useful though incomplete general reference for practitioners. The authors review 17 state-of-the-art recursive-dynamic CGE models and assess the key methodologies and applied modules each uses for representing sectoral energy and emission characteristics and dynamics. One of the main virtues of CGE models in a carbon-pricing context is the information they provide on the interaction of energy supply, energy demand, and emissions across various sectors and regions in an economy-wide context. Furthermore, given the long time horizon of both climate change impacts and technological change, long-term projections are vital. Yet treating technology as endogenous is at odds with how climate pricing will affect technological change and presents an inaccurate forecast of benefits.

In their paper, Faehn et al. seek to provide technical insight into recent advances in the modeling of current and future energy and abatement technologies and in the use of these technologies to estimate baselines and project scenarios 20 to 80 years ahead. Three different approaches to baseline quantification are distinguished: (1) exploiting bottom-up model characteristics to endogenize responses of technology investment and utilization; (2) relying on external information sources to feed the exogenous parameters and variables of the model; and (3) linking the model with more technology-rich, partial models to obtain bottom-up-and pathway-consistent parameters.

Looking at technology projections specifically, there are some common features. Technology representations have gotten more detailed in response to extraction processes of fossil fuels and new renewable energy sources. Some models have included ITC directly, usually in the form of learning-by-doing curves (e.g., the REMIND or DART models). Others consider a “semi-endogenous” approach that splits capital use into industry-specific extant capital and new capital. Finally, some models represent technological progress within emission abatement by including marginal abatement cost curves. This allows for endogenous emission coefficients and investment cost.

Box 9.3

Bottom-Up Abatement Technologies in a Global CGE Model

Weitzel, Saveyn, and Vandyck (2019) present a framework for integrating bottom-up information for end-of-pipe abatement technologies. The traditional approach to marginal abatement cost curves is to fit an aggregate curve to point estimates from bottom-up data that are assumed to be monotonically increasing and have a continuous derivative. However, abatement options can be heterogenous across different pollutants and sectors. Some have inexpensive abatement potential (such as chemicals that can be easily substituted), while others have expensive abatement options (such as production processes that cannot be changed or substituted). For example, the chemical sector is typically a single industrial sector in CGE models, while the abatement potential can vary significantly. Thus, these discrete abatement options are often not accurately reflected by a smooth abatement cost curve.

Rather than using bottom-up estimates to fit a marginal abatement cost curve, Weitzel, Saveyn, and Vandyck (2019) preserve bottom-up information and integrate directly into the CGE model. This structure has several benefits for modelers. First, shocks to the model influence the abatement costs of individual technologies and affect the shape of the abatement curve endogenously. Second, the model covers the effects on upstream and downstream sectors and trade flows, including the intermediate goods and services needed for the relevant abatement technologies. Third, the model allows specifying conditional inequalities, such that a technology is active only when the pollution costs are sufficiently high.

The authors compare the integrated approach to the classical marginal abatement cost strategy. Their primary finding is that aggregating bottom-up data into a smooth abatement cost curve leads to either an over- or underestimation of costs and to loss of information; it also implies that the modeler cannot pinpoint the specific abatement technology that is adopted in a scenario. Their finding has direct implications for the modeling of technology benefits from carbon pricing. Carbon pricing will push firms to either abate or innovate, and the accurate modeling of abatement costs is necessary to demonstrate the benefits of ITC.

A Appendix A: Partial Equilibrium and General Equilibrium Models

Partial Equilibrium Models

Partial equilibrium models can be used to evaluate the effect of a carbon-pricing instrument on a limited segment of the economy, usually considered to be the market for a generic type of good or service (e.g., power, vehicles, manufacturing, etc.). Partial equilibrium or "single market" assessments can provide a detailed picture of that economic segment; however, they do not give any indication of potential indirect effects, including linkages up and down supply chains or effects in related goods markets, across consumer expenditure patterns, or within tax systems. Despite this narrow focus, partial equilibrium models can be extremely useful for evaluating a specific impact of interest. Because they do not attempt to model the entire economy, partial equilibrium models can provide very detailed representations of the part of the economy they are designed to examine in a way that is typically not possible with a general equilibrium approach. Modeling the impact of a carbon price using partial equilibrium models can show more granular data, technology processes, and market regulation representations than a CGE model. This type of approach can be used to model simplified two-variable relationships, such as the effect of a carbon tax on the number of road fatalities or number of pollution deaths; and understanding these impacts is critical in weighing costs against potential benefits.

Partial equilibrium models typically use historical data linking prices and demand to model how policy tools affecting energy prices will affect the economy. A common concept utilized by these types of models is the price elasticity of demand (box A.1), which measures, in percentage terms, how much a given price change will affect demand. For example, the price elasticity of demand for gasoline could be used to estimate how much gasoline demand decreases in response to a 5 percent rise in gasoline prices.

Box A.1

Price Elasticities of Demand

Price elasticity measures how demand changes in response to a change in price. Specifically, price elasticity is expressed as

$$E = (\Delta Q/Q)/(\Delta P/P).$$

The equation shows that price elasticity (E) is equal to the ratio of percentage change in quantity ($\Delta Q/Q$) to percentage change in price ($\Delta P/P$) (Δ is the symbol for "change" or "difference").

In general, when the price of a market good rises, the quantity demanded drops. Thus, price elasticities are expected to be negative. When E is between 0 and -1, demand is referred to as "inelastic," meaning that the percentage decline in quantity is smaller than the percentage increase in price. When E is equal to -1, demand is referred to as "unit elastic," meaning the percentage change in quantity perfectly matches the percentage change in price. And when E is more sensitive, i.e., when E is less than -1, demand is called "elastic," indicating that the (opposite) percentage change in quantity is relatively greater than the percentage change in price.

The main strength of partial equilibrium models as compared to general equilibrium approaches is simplicity, meaning there are relatively low data requirements to implement representations of detailed industries or sectors, and that results are communicated with relative transparency. By emphasizing direct linkages, these models are well suited for applications like understanding how specific fuels will respond to a carbon price or how emissions will respond to fuel prices.

A primary limitation of partial equilibrium models is also their simplicity, in particular their inability to capture indirect and induced effects. Indirect effects follow first-order linkages between the market being considered and its direct suppliers and buyers. These include cost-price transmission up and down supply chains, with respect to factors used in direct production, and fiscal effects linked to the sector's own production and commercial activity. Induced economic effects take these linkages to the rest of the economy, following effects of price and quantity changes on other agents (competitors, consumers, etc.) and economic decisions they make. Taken together, indirect and induced effects can be substantial, in some cases exceeding the direct effects. Moreover, these impacts are generally dispersed broadly and affect stakeholders outside of the modeled sector. This situation obtains for many environmental policies. For instance, air quality standards for power plants impose financial costs on one specific sector but provide public health benefits for the entire community. In such cases, only a full accounting of significant costs and benefits–which a partial equilibrium model cannot do, regardless of its complexity or extent–can effectively reconcile private agency with the public interest.

Because of the complexity of indirect and induced linkages, measuring them may require detailed elasticity data that are difficult or costly to obtain. This means that available elasticities must sometimes be extrapolated from comparison cases, often in very different places and contexts. Even when elasticity estimates are available, they are based on historical relationships that can be extrapolated outside their sample only with care. Additionally, in holding the rest of the economy fixed, partial equilibrium models are generally too focused to permit assessment of simultaneous and/or complementary policies. Nonetheless, when applied appropriately, partial equilibrium models can be useful tools for understanding benefits from a carbon price.

Multi-Market Models

An intermediate stage between single-market partial equilibrium models and economy-wide general equilibrium are models that specify the inner workings of and interconnections between a few markets with core linkages to each other. These multi-market models can be useful in cases where a few indirect effects are very prominent, but data and other constraints don't permit a full CGE analysis. Examples in a developing country context include agri-food supply chains that combine rural farm production with intermediate processing, logistics, and trade with urban markets, and where there are interactions between energy production, distribution, and leading use categories like electric power and mobility. Only a fraction of assessments use this approach, but those who are interested can find learning materials and examples across the development literature.[58]

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[58] A good entry point is Sadoulet and de Janvry (1995).

General Equilibrium Models

The complexity of today's economic reality is such that policy makers relying on intuition or rules of thumb alone are unlikely to achieve anything approaching optimality. The same risk extends to single-market partial equilibrium analysis, where indirect effects can outweigh the direct impacts being measured. A more inclusive class of models, including multi-market, CGE, and dynamic stochastic general equilibrium (DSGE) or macrostructural models, uses more elaborate economic theory to characterize the larger economy and its interconnections. This increased scope enables such models to explain linkages and the indirect and induced effects that extend across sectors and economic agents. Models are "micro-founded," that is, they are empirical simulation tools calibrating behavioral models of changing conditions, along with producer responses to these changes. Because of this design, CGE models are highly flexible and well suited for more comprehensive impact assessments, e.g., comparing total economic effects of different prospective policy instruments, estimating government revenue from a tax, or estimating changes in economy-wide emissions in response to a carbon price. Some so-called integrated assessment models take the CGE approach a few steps further and include links between emissions and public health, public health and the economy, etc., to close the economy-environment link. Meanwhile, some integrated assessment models have also coupled CGE, partial equilibrium, and physics models to better understand the policy implications on these benefits.

The three essential components for successful CGE modeling are theory, data, and software. These are reviewed below.

Theory and Methodology

In terms of economic theory, the core of any CGE model reflects the neoclassical paradigm. Models are often extended with more exotic theory, but most standard CGE models are built upon a simple macro accounting framework and theoretical canons of constant elasticity of substitution (CES) or Cobb-Douglas production theory (including Leontief intermediates), Stone-Geary demand, and international trade modeled as CES and constant elasticity of transformation (CET) aggregations of imports and exports, respectively, that are imperfect substitutes. The prescription for learning all this includes the basic national income and product accounting, microeconomic theory, and some intermediate trade theory. For those already past this threshold, there are now several good reference books on building CGE models. These began to appear as by-products of the World Bank's early commitments to development planning, typified by Dervis, de Melo, and Robinson's (1989) mainstay. More up-to-date methods, issues, and cases are presented in (for example) Burfisher (2017) and Roland-Holst and Van der Mensbrugghe (2017).[59]

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[59] *The latter work is also available in Chinese.*

Data Resources

The main advantage of CGE models is that they capture detailed interactions across the economy. However, this comes at the price of intensive and extensive data development. The core data requirement is a set of inter-industry transactions accounts, preferably embedded in a social accounting matrix (SAM) that tabulates transactions between the other leading actors in the economy, households, and public institutions. The essential importance of this kind of data has been recognized by Nobel prizes for both Leontief and Richard Stone, and the World Bank has been a very prominent contributor to both input-output and SAM data resources for at least a generation.[60]

In addition to the SAM, CGE models can require detailed information on labor and other resources and on emissions and other economy-environment linkages; it can also require large quantities of technical coefficients estimated from primary, secondary, or comparison sources. Fortunately for today's modelers, there is a very large reserve of these information resources, and they are shared relatively openly across the profession. The best entry point for these resources by far is the GTAP, which maintains a multi-year, multi-region input-output database. This is further supplemented by national macroeconomic data and extensive satellite data sets that cover other measures linked to the economic flows in the core database, including trade policies, greenhouse gas emissions, energy use, migration flows, and land use patterns.[61]

GTAP should be the first data stop for anyone wanting to calibrate a national CGE model. With 141 countries and regions in the current version (10) and details on domestic production and trade in 57 sectors, GTAP offers strong support for basic model construction and calibration. Many countries have multiple years of input-output tables from previous GTAP versions, and all contributed data have detailed documentation that directs users to appropriate domestic source material.

Programming and Data Science

The main data science technique applied to CGE modeling is classical coding.[62] The heart of these models is a system of (usually nonlinear) equations simulating economic activity. These equations (often thousands of them) need to be solved with input data and structural parameters, producing output that can be interpreted and rendered for communication. If we think of a CGE model as itself a production function, what links the inputs and outputs is a relatively large and complex computer program. Building, maintaining, and (most importantly) interpreting the findings of such a model is an ambitious task, but fortunately many have accomplished this and are happy to share their experience. GTAP and various other institutions, including the World Bank, offer open source models that can be adopted as prototypes for new CGEs. While care is needed to use these tools responsibly and effectively, we strongly recommend leveraging them for the sake of expedience and more coherent and inclusive research dialogue.[63]

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[60] See for example King (1981); Pyatt and Roe (1978).

[61] See Purdue University, "GTAP Data Bases: GTAP Satellite Data and Utilities," www.gtap.agecon.purdue.edu/.

[62] CGE models have been written in most major source-level programming languages, but the more popular medium by far is a higher-level language called the Generalized Algebraic Modeling System (www.gams.com). For an advanced introduction, see McCarl et al. (2012).

[63] Many modeling and data management tools are available on the GTAP site (www.gtap.agecon.purdue.edu/) or through individual members. For open source CGE models, two prominent sponsors are the International Food Policy Research Institute (https://www.ifpri.org/publication/standard-computable-general-equilibrium-cge-model-gams-0) and the University of Laval (http://www.pep-net.org).

Conclusion

While CGE models have many strengths, they also have limitations. They are substantially more difficult to build and run than partial equilibrium results models, and the longer and more complex linkages require more careful interpretation. Because of this increased complexity, their workings become less transparent to nontechnical audiences. Of course, this has no necessary implication for their reliability, but communicating results can be challenging. Responsible stakeholder engagement with this kind of policy research has two fundamental requirements: diligent effort to explain results and their assumptions intuitively, and interval estimation that explicitly recognizes the role of uncertainty. Fortunately, modern computing resources also offer more efficient methods of uncertainty analysis to evaluate the robustness of model results.

With the publication of hundreds of CGE-based environmental policy assessments over the last two decades, we have ample evidence to support best practice applications for carbon pricing throughout the world. That having been said, secondary data will often be necessary, and sometimes even those data will be inadequate. As a general rule, we recommend that practitioners approach their policy issue with the simplest tool first, then use more comprehensive assessment methods as justified by data and findings.

Early applications of CGE models in most cases are highly aggregated, which can “wash out” detailed interactions and impacts. Aggregation should be part of a stepwise analysis that begins with a tractable aggregation, then disaggregates strategically important agents and activities as time and data allow and findings justify. In summary, while partial and general equilibrium models each have strengths and weaknesses, they should be considered as complements. Used together, they can help provide a richer understanding of the benefits of carbon-pricing policies. Ultimately, the specific issue, data availability, and technical capacity will dictate the best choice.

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