An Integrated Assessment of the Economic Costs and Environmental Benefits of Carbon Taxes in China

Chris P. Nielsen, Mun S. Ho, Yu Zhao, Yuxuan Wang, Yu Lei, and Jing Cao

April 2013

Abstract

The rapid economic growth in China has brought a parallel degradation of the environment that is of great concern to policy makers. A more recent policy concern is the international pressure for controlling carbon emissions. We analyze the costs and benefits of various carbon tax policies. The complex links between economic activity, energy use, emissions, air quality and human health requires an integrated approach. In collaboration with researchers in several fields of environmental sciences, we tie together a multi-sector economic model, a detailed emissions inventory, an advanced atmospheric model (GEOS-CHEM), and health assessment tools (BenMAP model). We find that a modest carbon tax would not only reduce CO_2 emissions substantially, but also achieving a sizable ancillary benefits by reducing local air pollution, and the likely negative economic costs are modest. Then we compared six carbon tax proposals to shed some light on future carbon tax reform in China.

JEL Classification Codes: C68; D58; H23; Q28

Keywords: China, Carbon Tax, SO_2 Policy

1. Introduction

The Chinese government asserts that its contribution to greenhouse gas (GHG) control should be based on the principle of "common but differentiated responsibilities" agreed to under the 1992 United Nations Framework on Climate Change (UNFCCC), by which wealthier nations are to take the lead. It recognizes that some level of explicit GHG control is inevitable, however, and that China must move toward controls that can be credited in any international regime that succeeds the Kyoto Protocol.

Indeed, at the 2011 UNFCCC negotiations in South Africa, China signed on to the Durban Platform, in which all nations agreed to establish a common legal regime in GHG control for both developing and industrialized countries. China's position at Durban built on its unilateral commitment in 2009 to reduce the carbon intensity of its economy—carbon dioxide emissions divided by GDP—by 40–45% in 2020, compared to 2005 levels.

In this paper, we examine a number of carbon policy options for China, applying the integrated research framework that ties together a multi-sector economic CGE model, a detailed emissions inventory, an advanced atmospheric model (GEOS-CHEM), and health assessment tools (BenMAP model). This integrated framework allows us to assess the effects of future policies not only on carbon emissions, but also on China's economy, energy use, air pollution emissions, domestic air quality, and the damages to public health and agricultural productivity that result.

Many observers would agree, at least in theory, that the most straightforward approach to limit emissions of carbon is to place a price on it. The rationale is simple, that introducing economic disincentives to activities that emit carbon, notably combustion of fossil fuels, would encourage lower emissions. The policy imposes a higher financial penalty if the emission intensity of the activity is higher; burning coal, for instance, generates roughly twice as much CO_2 per unit of delivered energy as burning natural gas. By putting a price on each kilogram of CO_2 emitted, the use of coal would incur an additional cost that is twice that imposed on use of gas. This will shift energy consumption at the margin toward gas, and even more so toward noncarbon energy sources, and incentivize improved energy efficiency. Over the longer run, it will raise investment in lower-carbon infrastructure and gradually restructure the energy system as a whole.

Harnessing the tax system for CO_2 control may be the simplest and most direct approach to pricing carbon. New revenues are also generated that the government can use in a variety of ways, such as compensating those disproportionately impacted by the tax, or reducing existing taxes that may distort the economy. In political terms, a carbon tax would be instantly credible to the international community, even envied in some nations where carbon taxes are rejected chiefly on the grounds of political infeasibility. A tax-based approach could have an additional advantage over command-and-control mandates like those of the 11th and 12th Five-Year Plans (FYPs): moving from unpredictable, sequential, and piecemeal emission controls to a consistent mechanism that can be adjusted incrementally over time, thus reducing the costs of policy uncertainty. Such desirable properties of carbon taxes have been discussed in many studies, including Nordhaus (2010) and Aldy et al. (2010).

Carbon tax options have been much discussed by Chinese officials, and the fiscal title of the 12th FYP includes a mandate to initiate environmental taxes on pollutants that many experts indicate was designed for possible extension to carbon. High-level Chinese officials have since indicated that some form of tax on carbon is possible by 2015 (Wei 2012). There have been many analyses of carbon taxes by Chinese researchers, such as Su et al. (2009), a study by the Research Institute for Fiscal Science, a center affiliated with the Ministry of Finance, which pushes for carbon taxes within government deliberations on carbon policy, and other more academic studies including Liang, Fan, and Wei (2007), Wang, Li, and Zhang (2011), Yi et al. (2011), and Lu, Tong, and Liu (2011). While these analyses have their individual strengths, they are not integrated with a comprehensive accounting of emissions and simulation of local air quality that our research program provides. They are therefore unable to quantify potentially large ancillary benefits of the tax policies to China's domestic environment, public health, and agriculture. Instead in this paper we consider in some detail various carbon price options using an integrated assessment framework to examine the costs and benefits of such policies comprehensively.

Many other analysts have noted that there is no best option to implement a carbon tax; different policy packages have different impacts on the various segments of society (e.g., Fischer and Fox 2011; Liang, Fan, and Wei 2007). The size of the tax obviously matters, as well as the timing. Given the broad-based nature of most carbon tax proposals, substantial new revenues can be generated, and their use is a key area of emphasis and contention. A well-designed policy to compensate affected taxpayers may substantially improve the political feasibility of the tax while reducing the economic costs. Another area of concern in countries that have considered carbon price policies is the protection of energy-intensive industries that are exposed to international competition.

To illustrate the main issues China faces in placing a price on carbon emissions, in this paper we examine six different carbon tax options from 2013 to 2020, using our integrated assessment framework. The choice of 2020 as the final year of the modeled policy term is not arbitrary. Our reasons relate both to the policy context and our research needs. First, as noted at the outset, 2020 is the target year of China's domestic commitment to improve the overall carbon intensity of its economy by 40–45%, measured against the 2005 level. Second, 2020 is also the target year of the Durban Platform when, in principle, all countries will become subject to a common legal regime in GHG control. China's anticipated CO_2 emissions in the period leading up to 2020 could influence its negotiating positions, and China's carbon path under different policy scenarios is of interest.

Third, 2020 is a primary target year used in China's recent energy planning, including, for instance, capacity targets in hydroelectric, nuclear, wind, and solar power generation. These plans serves our analytical needs because they help to inform our understanding of what would happen in China in a "business-as-usual" base case—that is, a scenario assuming no additional policy—against which we estimate the effects of an added carbon tax.[1] The choice of 2013 as the first year of the tax term is less critical. In any case our goal is not to recommend a specific policy for actual implementation during specific years, but rather to investigate the general effects of the policy options, whenever they might be implemented.

Our paper is structured as follows. We describe the structure of our integrated assessment framework that ties together an economic CGE model, a detailed emissions inventory, an advanced atmospheric model (GEOS-CHEM), and health assessment tools (BenMAP model) in section 2. Then in section 3 we introduce the base case and various carbon tax options utilizing the proposed integrated assessment framework. Section 4 concludes with policy recommendations.

[1] This is not to say that we simply accept that all of those capacity targets and other energy plans will be realized. In fact we follow the capacity projections of the International Energy Agency, which makes expert judgments of the feasibility of the plans given China's recent energy trends, international market factors, and other considerations (IEA 2010).

2. An Integrated Assessment Framework

The pollution causal chain that is used in the Harvard–Tsinghua study builds on the analytical framework described in detail in Ho and Nielsen (2007). Here we highlight some new elements to improve this framework by applying a comprehensive integrated framework for assessing costs and benefits. The system is illustrated in Figure 1 and has four major components:

i) A model of the economy that estimates the energy consumption for each of 34 sectors, for each year, tracking how GDP and technologies might evolve.

ii) An emissions inventory covering all the main pollutants, with special detail for the most polluting sectors, estimated at a fairly fine spatial resolution.

iii) An atmospheric chemistry and transport model covering the whole globe with the same detailed resolution as the emissions inventory for China.

iv) A health risk model that estimates the health impact using population distribution data over the same grid, and estimates the value of such impacts.

We discuss these main elements in turn beginning with the energy use of the 33 economic sectors and residential sector identified.

[Figure 1 about here]

2.1 Industry output and energy use

The economic model is based on the input–output table for 2007 that gives the inter-industry flow of commodities. In particular, it gives the yuan value of each fossil fuel and electricity input for each industry.

Of the 33 industries identified, Construction has the highest level of gross output in 2007 at 6,272 billion RMB, followed by chemical with 6,200 billion and Metals Smelting with 6,110 billion. This reflects the unusual nature of the 2007 economy with the huge investment boom. The biggest user of coal is Electricity, Steam and Hot Water followed by Metals Smelting and Nonmetal Mineral Products. The biggest users of oil for combustion are Transportation, Chemicals, electricity and Metals Smelting. The biggest users of natural gas by far are Chemicals and Electricity, Steam and Hot Water.

The big coal users are the largest contributors to SO_2 emissions, with the Nonmetal Mineral Products (mostly cement) responsible for the majority of process (non-combustion) emissions.

By our estimates the Electricity, Steam and Hot Water sector alone was responsible for 14,099 kilotons of the total 26,596 kilotons of SO_2 emissions in 2007. Unlike SO_2 emissions, TSP emissions are not simply linked to fossil fuel use; the emission factors depend on the boiler types and control equipment. The biggest emitter of TSP is the Nonmetal Mineral Products industry followed by Electricity.

2.2 Emissions inventory

The emissions inventory for this integrated assessment, developed by collaborating environmental engineers, covers both detailed point source information (coal-fired power plants, cement plants and iron and steel smelting plants), and area sources, including both mobile and stationary source types in China (Zhao et al. 2011).

Emission factors were determined for each of the pollutant species, for each of the above-mentioned industries, and for each fuel type; for example, the tons of PM_{10} emitted per ton of coal used when a particular control technology is used in the iron and steel industry. An array of both published studies and unpublished field measurements are used, including information about the shares of the different control technologies and the coal quality in each location. The emissions of pollutant *x*, in location *j* in year *t*, is then given by these emission factors and the estimates of output and fuel use in year t by grid cell location. The spatial resolution of the emissions inventory is $0.5^{o}\times0.667^{o}$, matched to the nested grid of the GEOS-Chem atmospheric model used.

2.3 Estimating pollutant concentrations with GEOS-CHEM-CHINA model

Collaborating atmospheric scientists in the larger study use an updated version of the nested-grid capability in the global GEOS-Chem model, which allows for a higher spatial resolution (0.5°x 0.667°, with 15 layers below 2km) for the nested window over East Asia (Wang et al. 2004; 2009). This is nested within the global GEOS-Chem model, which has a 4°×5° resolution. The model takes the gridded emissions inventory and assimilated meteorological fields for a given time period, simulating atmospheric chemistry and transport to yield concentrations for a full complement of trace gases and aerosols at each grid cell. Altogether 80 chemical species and more than 120 reactions are considered.

GEOS-Chem China may be more refined than other regional models now used for several reasons: (a) inclusion of background and boundary concentrations through nesting in a global model; (b) validation of simulations against observations of ground stations, aircraft monitors and satellites; and (c) analyzing unexpected results with a thorough knowledge of the chemical and physical processes behind both observations and model results.

2.4 Assessing damages on health and agriculture

From the simulated air quality improvement, additional collaborators estimate the health benefits and their valuation using the US EPA's Benefit Mapping and Analysis Program (BenMAP). This is a population risk assessment model that takes the changes in pollutant concentration estimated by the atmospheric model and estimates the effect on human health across the country. It also calculates an economic valuation of this health risk; in this case, the *yuan* valuations of reductions in mortality and morbidity due to air pollution control. The key elements of BenMAP are: (a) population by age in each grid cell corresponding to the grid of the GEOS-Chem China model; (b) concentration-response functions for various endpoints and pollutants, e.g. the change in the incidence of chronic bronchitis due to an increase in the concentration of $PM_{2.5}$ by 1 $\mu g/m^3$; (c) valuation of each health endpoint derived from surveys of "willingness to pay" for health risk reduction.

We incorporate the most recent concentration-response estimates in World Bank and SEPA (2007), Levy and Greco (2007), Aunan and Pan (2004) and HEI (2004). Acute mortality coefficients are estimated by studies of population exposures over days and weeks, while chronic mortality is estimated by studying a cohort of people over years. The chronic effect is much higher than the acute effect, but no Chinese cohort studies have been completed. We report the chronic estimates based on Western studies to give a sense of the possible magnitudes, but note that epidemiologists warn against this.

Next we incorporate an update of the 2000 Census population distribution based on 2003 surveys by the Chinese Academy of Sciences. This work generated a population map at a fine 1km x 1km scale. Then we examined the most recent willingness-to-pay studies in China to monetize the health damages (Zhou and Hammitt 2007; Guo and Hammitt 2006; and Guo, Hammitt, and Haab 2009; Krupnick et al. 2006). These studies show the typical wide range of estimates in CV studies, but do show some similarity in their VSL- to- income ratio.

2.5 Assessing economic effects with economic growth model

We construct a multi-sector dynamic model of the Chinese economy to assess the impact of environmental policies. This model is described in detail in Ho and Nielsen (2007, Chapter 10). In our model, growth is driven by labor force growth, capital accumulation, productivity growth and improvements in the quality of aggregate labor and capital. The main agents are the household, producers, government and the rest of the world. Household savings and government-funded investment are the main sources of investment; unlike most developed economies the government role in China is much larger. The model recognizes that the central plan plays a role in setting some prices and quantities.

The household sector maximizes a utility function that uses all 33 commodities as arguments. The demand parameters change over time to represent the income effect: the share of total expenditures allocated to income-inelastic goods such as food falls as income rises. Household income is derived from labor, capital and land, supplemented by transfers from the government. Labor is supplied inelastically by households and is mobile across sectors.

This is a Solow growth model where the private savings rate is set exogenously. Total national private savings is made up of household savings and retained earnings of enterprises. These savings, together with allocations from the central plan, finance national investment. They also finance the government deficit and the current account surplus. Investment in period *t* increases the stock of capital that is used for production in future periods. The plan part of the capital stock is assumed immobile in any given period, while the market part responds to relative returns. Over time, plan capital is depreciated and the total stock becomes mobile across sectors.

The government imposes taxes on value added, sales and imports. On the expenditure side, it buys commodities, makes transfers to households, pays for plan investment, makes interest payments on the public debt and provides various subsidies. Expenditures on interest and transfers are exogenous, and the exogenous deficit target is met by making government spending on goods endogenous.

Finally, the rest of the world supplies imports and demands exports. World relative prices and the current account balance are set exogenously in this one-country model, and an endogenous variable for terms of trade clears this equation.

On the supply side, 33 industries are identified; each producer uses capital, labor and intermediate goods to produce output, and a constant returns-to-scale cost function is used to determine the choice of inputs. The production technology changes over time; there is a term for autonomous productivity growth, and other terms to represent “biased” technical change. Biased technical change for energy refers to changes in energy use that are not due to price changes (often referred to as the autonomous energy efficiency improvement, AEEI).

There are 33 markets for the commodities; that is, there are 33 endogenously determined prices that equate supply with demand for the domestic commodities identified in the model. The total supply consists of domestically produced goods and imported varieties; these are assumed to be imperfect substitutes. There are three markets for the factors of production – land, capital and labor, and three prices to clear them. The model is a standard constant returns-to-scale model and is homogenous in prices.

3. Carbon Tax Options and the Base Case

3.1 Base Case

The base case is the foundation of all of our economic modeling, which, in this paper, is based on the 2007 official input-output tables of China (NBS 2009). We are implementing each policy over the period 2013–2020, but we start our projections in 2007. We report the projections in the table and figure both to 2020 and beyond, to 2032, to give the reader a full sense of the underlying economic trajectory. The GDP growth between 2007 and 2020 is projected in the base case at a rapid 8.4% per year. The population growth, while slowing, averages 0.54% for this period, but the working-age population is essentially flat. Coal consumption is projected to grow at 3.3% per year, while oil, and especially gas, use are expected to grow faster. This rise in oil use is expected even as we include the projection of rising world oil prices from EIA (2009, table 12), shown in figure 2 (gray line marked with squares). As a result, total fossil energy use is projected to grow at 3.9% per year. Given the rapid GDP growth, however, this figure corresponds to a substantial decline in the energy-to-GDP ratio. In figure 2 we can see the much less steep profile of energy consumption compared to the GDP line. The emissions of CO_2 are also rising at less than half the rate of GDP growth, at 3.8% per year.

[Table 1 here]

[Figure 2 here]

We also project a rapid growth of electricity consumption, 6.9% per annum, and gas consumption at 8.1% per year over the period 2007–2020. These rates are close to forecasts of the International Energy Agency well known to researchers (IEA 2010, Annex A). This rapid growth of electricity output and the much slower growth of coal consumption mean that we (and IEA) are projecting a substitution toward other fuels and renewable energy sources, and an improvement in productivity in electricity production. Thus in the base case we are already projecting a steady reduction, for instance, in the amount of coal used to generate a kilowatt-hour of electricity. A carbon price would accelerate these trends in productivity and fuel substitution.

During this period of rapid income growth and structural change, the composition of the economy is expected to change substantially. The share of consumption in GDP rises from 37% in 2007 to 47% in 2020.[2] The structure of output shifts toward services, which are less energy-intensive than manufacturing. We emphasize that this shift only means that the share of resources devoted to services is higher; the absolute quantity of steel and other manufactures produced continues to rise with capital accumulation and productivity growth.

3.2 Carbon Tax Options

As noted previously, a carbon tax policy is a package of related but distinct rules: the magnitude of the carbon price, the date of implementation, the use of revenues, and sometimes the protection of vulnerable sectors. In total we examine six policy scenarios, summarized in table 2, to explore these issues.

[Table 2 here]

The size and timing of a carbon tax are important because economic actors need time to adjust to the policy. Firms need to change production processes and capital equipment to use less carbon-intensive fuels and other intermediate inputs, and households also need to acquire new equipment that uses less energy. A tax that is announced in advance and implemented gradually will ease these costs of adjustment. A delay in implementing the carbon price, of course, means a delay in achieving emission reductions. It is less valuable to compare a tax of 10 yuan per ton of CO_2 starting today with the same tax starting in ten years' time, than to compare two different time profiles of tax rates that will generate the same cumulative reduction in emissions at some

[2] While this may seem like a rapid change in consumption, it is based on the intense discussions to rebalance the Chinese economy away from exports to domestic consumption. This rise in consumption parallels the assumption of a much smaller trade surplus. The consumption share fell from 46% in 2000 to 36% in 2007. That is, we saw rapid changes in the recent past, and thus it is reasonable to project a quick return to more typical patterns.

date. Given the nature of the climate risks of GHG concentrations and the long atmospheric lifetime of CO_2, the cumulative reduction is the most relevant point of comparison; the emissions in any particular year do not have a large impact on the climate risks in, say, 2100. For further discussion of this issue, see Newell and Pizer (2003).

Before we introduce our tax scenarios, note that unless otherwise noted, all values in this chapter are expressed in constant 2007 yuan, meaning in terms of prices that prevailed in the 2007 base year. This practice allows us to ignore the effects of inflation and eases comparison of economic effects across years.

Scenario F1: In the first scenario, we begin with a simple tax of 30 yuan per ton of CO_2 for all years in the policy period 2013–2020. Thirty yuan was roughly equivalent to US$3.90 in 2007. At this price, we project that the cumulative emissions of fossil fuel CO_2 from 2013 to 2020 would be 64.79 gigatons (Gt), a substantial reduction compared to the 74.23 Gt projected for the base case with no additional policy to those already announced.

Scenario F2: In our second scenario, we choose a different profile of carbon prices that achieves the same level of cumulative reductions: we start with a low tax of 10 yuan per ton of CO_2 in 2013 and increase it steadily to roughly 50 yuan per ton by 2020. The exact tax rate in 2020 and thus the profile of taxes are calculated such that the cumulative CO_2 emissions from fossil fuel combustion from 2013 to the end of 2020 are identical to those of F1, 64.79 Gt. Holding total CO_2 emissions constant over the two cases will allow us to explore the effect on the economy of implementing a tax gradually over time compared to setting a static rate from the outset.

Scenario F3: We have chosen the preceding carbon tax levels even if they seem low compared to prices in international carbon markets. These are imaginable rates that are not excessive relative to prevailing energy prices in China, but that still would generate significant emission reductions. Note, however, that carbon prices in the EU Emission Trading System (EU ETS) were about US$25–30 per ton of CO_2 in our base year of 2007, although they were under US$9 at the end of 2011 (in 2011 currency). When the U.S. House of Representatives passed a cap-and-trade bill in 2009 (which later died in the U.S. Senate), a U.S. Environmental Protection Agency analysis projected an initial carbon price of US$13–17 per ton of CO_2, equivalent to more than 100% of the price of coal at the mine mouth. To show the effect of higher carbon prices, in F3 we begin with the same 10 yuan per ton of CO_2 in 2013 as in F2, but increase it instead to 100 yuan per ton by 2020. This is much closer to recent prices in international carbon markets and will show the effects on China's economy, carbon emissions, and air quality of such a price convergence.

Importantly, in these first three scenarios, the carbon tax revenues are given back to households in a lump-sum fashion. By this, economists mean that households receive a transfer from the government, the size of which does not depend on any household decision such as the expenditures on fuels. The revenue use assumption is changed in our next scenario.

Scenario F4: This scenario has the same path of tax rates as in F2—rising from 10 yuan per ton of CO_2 to roughly 50 yuan per ton—but the new revenues are now used to cut the enterprise income tax rate. The result is that the proportion of profits that enterprises keep after taxes is higher, and this changes the incentive to invest. It is expected to lead to slightly higher growth in GDP compared to the lump-sum transfer of revenues to households, as in F2.

Scenario F5: Considering energy-intensive industries (EITE) -- such as thermal power generation, iron and steel production, and cement manufacturing – will be hurt for the increased costs after carbon tax, so policies like the US Waxman-Markey cap-and-trade bill contained subsidies to these EITE industries. Similarly, we assume F5 will follow follow the same path of carbon prices as in F2, but use a part of the new revenues to subsidize the EITE manufacturing industries, calculating output subsidy rates similar to the Waxman-Markey mechanism. The most energy-intensive, trade-exposed sector in China is production of nonmetal mineral products (including cement), which would receive a 0.25% subsidy rate, followed by the primary metal and chemical industries, as shown in the table below. At these rates, the subsidies do not recycle all of the carbon tax revenue, and the remaining revenue is transferred in lump sums back to households.

Scenario F6: In the first five scenarios, we assume that the carbon price is imposed unilaterally by China. This makes the prices of energy-intensive Chinese goods rise relative to their world prices. In the best case, however, carbon prices would be imposed within a multilateral framework, in which a number of countries would act in concert. Countries need not necessarily impose the same price on emissions, but to give a simple illustration of the impact of international carbon pricing, in F6 we raise the prices of goods traded between China and the rest of the world by the same amount that we estimate for the domestic prices. F6 follows F2 in other respects, including the path of carbon prices and the recycling of revenues directly to households.

4. Effects on the Economy and Energy Use

We implement all scenarios by imposing a tax on the three fossil fuels (coal, oil, and natural gas) in proportion to their carbon content. The setting of tax rates ignores CO_2 emissions from other sources such as process emissions and combustion of biofuels and agricultural wastes, to keep implementation as simple as possible. We also recycle the new revenues completely so that aggregate government consumption of goods and services remains unchanged at base case levels. At this stage we can estimate emissions of CO_2 under the scenarios because they are generated directly from consumption of fossil fuels projected in the economic model and, because CO_2 is a global pollutant, we are unconcerned with its spatial distribution; this characteristic is in contrast to all of the other species, which affect air quality and must be estimated bottom-up.[3]

The results for the first carbon tax year of 2013 are given in table 3 and for 2020 in table 4. We will focus especially on F2 but describe the outcomes in order from F1 to F6.

[Table 3 here]

[Table 4 here]

4.1 Effects of Tax Rates and Time Paths: Scenarios F1, F2, and F3

In F1, with the same 30 yuan per ton tax in all years, the annual reduction in CO_2 emissions compared to the base case is about 12–13% in each year of the period, as plotted by the plain black line in figure 3. In the first year, coal use falls by 15.6% while oil use falls only 1.6%, leading to a 12.1% fall in total energy use. This causes a reduction in output of the energy-intensive industries and a small 0.09% reduction in aggregate GDP. With the transfer of carbon tax revenues to households their consumption does not fall. The important change is in the terms of trade, which appreciates by 0.1% as a result of a fall in import demand, especially for oil imports.[4] This appreciation is accompanied by a fall in total exports of 0.69%. Thus the reduction in GDP falls mainly on net exports, cushioning the shock to domestic investment. Over time, the lower investment results in a smaller capital stock and lower consumption. The fall in capital would have normally lowered GDP; the continued (small) appreciation of the terms of trade, however, keeps the GDP loss to 0.09% even in 2020 (see table 4).

[3] The projections are scaled to a rigorous estimate of CO_2 emissions for 2007 that is in fact calculated bottom-up. In this case the bottom-up approach is to validate the base year estimate against instrumental measurements and to estimate uncertainty, but is not needed to judge the effects of the tax policies on carbon emissions.

[4] Methodological note: The terms of trade may be regarded as the number of units of exportable goods that are needed to exchange for one unit of imports. That is, it is the price of imports divided by the price of exports. An appreciation of the terms of trade means that the country needs to export less for the same ton of imports.

[Figure 3 here]

Scenario F2 allows a more gradual adjustment, with the price of carbon rising from 10 yuan per ton in 2013 to around 50 yuan per ton in 2020. As noted, the exact path of carbon tax rates is chosen such that the cumulative emissions over the period 2013–2020 are the same 64.79 Gt achieved in F1. The cumulative emissions are plotted in figure 4 for all scenarios. In this scenario, the small initial tax leads to a modest 4.5% reduction in fossil energy use in 2013, and a corresponding 4.8% reduction in CO_2 emissions (table 3). In comparison, the CO_2 reduction versus the base case is 13.0% under the static 30-yuan tax of F1; the reductions are not proportional given the nonlinearities in the system. The first-year fall in GDP is a tiny 0.02%, with a slight increase in consumption, a slight decrease in investment, and a bigger decrease in exports. The relative contributions of these factors to the change in GDP—consumption, investment and net exports—are the same as in F1.

[Figure 4 here]

Over time, as the carbon tax rate rises, the reduction in fossil fuel CO_2 emissions versus the base case grows, as plotted in figure 3.3 (the line of large dashes, representing F2, F4, and F6); by 2020, fossil CO_2 emissions are 18.9% lower. The paths of carbon intensity (fossil fuel CO_2 emissions per unit GDP) of the two cases are shown in figure 5. In F1 (the plain black line), there is a big initial drop, followed by a path that is almost parallel to the base case. In F2 (light gray line), there is a smaller initial fall in carbon intensity, but by 2020 it is lower than that of F1.

[Figure 5 here]

The changes in the macroeconomic variables over time for F2 are plotted in figure 6. The lower investment in all years result in a smaller capital stock and the reduction in GDP, compared to the base case, grows year by year. As the tax rate rises, the increasing carbon tax revenues imply an increasing transfer to households and increasing consumption. This significant fall in GDP and rise in consumption is accompanied by a small reduction in investment; these patterns are again due to the appreciation in the terms of trade, leading to a large 1.1% reduction in exports by 2020 (table 4). With the high tax of 50 yuan per ton in 2020, coal use is 23% lower than in the base case in 2020 and oil use is 2.1% lower, resulting in a total fossil fuel reduction of 17.7%.

[Figure 6 here]

Behind these small changes in the aggregate economy are bigger changes at the industry level, as a result of the diverse range of fossil fuel and electricity use. In figure 7 we show the ten largest percentage changes in commodity prices versus the base case, and figure 8 gives the ten largest percentage changes in industry output. The light bars are for the first-year effects in 2013, and the dark bars are for 2020. With a first-year tax of 10 yuan per ton of CO_2, the after-tax price of coal (at the mine mouth) naturally rises more than any other commodity, a 5.7% increase. Electricity is fossil-fuel-intensive, and its price rises by 0.96%, while the energy-intensive manufacturing industries (nonmetal mineral products, chemicals, and primary metals) show price increases of about half a percent. These higher prices lead to a fall in sales, and the industry outputs fall by corresponding percentages: coal (−5.8%), electricity (−0.98%), and nonmetal mineral products (−0.43%).

[Figure 7 here]

[Figure 8 here]

By 2020, when the tax has risen to about 50 yuan per ton, the price shocks are much bigger. The price of coal rises by 28%, of electricity by 4.0%, of petroleum refining by 2.0%, and of the products of the three energy-intensive manufacturing industries by almost 2%. These price changes lead to a big reduction in output of coal (−23%), electricity (−3.9%) and petroleum refining (−2.4%). Our model takes a long-run view of market adjustment, which means that the labor and capital markets have time to clear and any workers initially laid off are reallocated to other industries. Capital resources also move from these shrunken industries to others. Which sectors expand depends on two factors: their energy intensity and the recycling of tax revenue. In F1 and F2, the lump sum transfer of the new revenues results in higher household consumption, so sectors producing consumption goods expand, particularly the less energy-intensive ones. By 2020, the output of finance grows by 0.22%, food manufacturing by 0.13%, and real estate and agriculture by 0.12%.

The last topic we examine in this section is the effect of more ambitious reduction targets. In F3, we adjust the profile of tax rates so that they rise from 10 yuan per ton of CO_2 in 2013, as in F2, to 100 yuan per ton by 2020, twice the level in F2 and closer to international carbon prices. As shown in figure 3.4, the cumulative fossil CO_2 emissions in this case are 59.35 Gt, or a 20.0% reduction from the base case, compared to the 12.7% reduction in F1 and F2. From table 3.4, we see that aggregate GDP in 2020 is 0.33% lower than the base case, compared with 0.14% in F2.

The decline in 2020 coal use is 37% (versus 23% in F2), in oil use is 4.0% (2.1% in F2), and in electricity use is 6.8% (3.9% in F2). The reduction in annual fossil fuel CO_2 emissions is 31% in 2020, compared to 19% in F2.

These comparisons show that the economy does respond to higher carbon prices, but at a somewhat diminishing rate; doubling the tax rate does not double the emission reduction. There is a rising marginal cost in reducing CO_2 emissions, as shown in other analysis of carbon prices. (See, for example, the analyses of U.S. GHG control proposals in U.S. EPA 2010.) We should caution, however, that we have not yet considered attendant increases in health and crop benefits from ancillary reduction of air pollution. Clearly the choice of an emissions target, realized through a tax rate, must consider local environmental benefits as well as benefits of reducing climate change risks.

4.2 Effects of Alternative Revenue Uses: Scenario F4

Many analysts have emphasized the desirability of using new revenues to reduce the distortions caused by existing taxes. (See, for instance, Bovenberg 1999; Parry, Goulder, and Williams 1999.) Taxes introduce a wedge between the buyer and seller: a seller willing to sell for at least one yuan and a buyer willing to pay up to one yuan cannot complete a mutually beneficial transaction if there is also a sales tax. More specific to our analyses, economics recognizes distortions due to taxes in the largest markets, in labor and capital. The income tax on labor and capital introduces a sizable wedge between firms and workers, and between firms and capital owners.

To explore the prospect for a carbon tax to reduce preexisting distortions, in F4 we use the new tax revenues not for lump-sum transfers, but to cut all existing tax rates at a proportional manner. The path of carbon prices in this case is the same as that in F2, 10 yuan per ton of CO_2 rising to 50 yuan per ton. Looking at the 2020 effects in table 4, we see that this alternative use of revenues yields a big change in the composition of aggregate GDP. On one hand, households no longer receive a large transfer, and consumption is essentially unchanged from the base case, compared to the 0.27% increase in F2. On the other hand, enterprises receive a large cut in the tax on profits. With higher retained earnings, investment is 0.57% higher than in the base case, compared to no change in F2.

GDP falls slightly in the first year compared to the base case (−0.02%, table 3), but with the higher investment, GDP by 2020 is slightly higher (+0.02%, table 4). That is, the higher capital stock offsets the negative impact of the carbon tax. Given that the GDP in F4 is slightly higher than in F2, the energy use and emissions are slightly higher; the change in coal use in 2020 is −22.9% compared to−23.0% in F2, and the change in total fossil energy use is −17.5% versus −17.7%. While we might have expected larger differences in energy use, keep in mind that prices are not identical in the two scenarios. With a higher demand for oil than in F2, the price of oil is higher and the terms-of-trade effect is milder: exports decline 0.81% in F4 versus 1.12% in F2. These higher energy prices help to curb demand for energy, even as the composition of activity switches away from consumption toward investment, which has a higher proportion of energy-intensive goods such as cement and steel.

4.3 Effects on Emissions

The economic simulations of carbon tax policies in the prior section generate for each policy not only the costs, but also the consumption of energy, including fossil fuels, that are the starting point for evaluating the environmental benefits. The first step is estimating the emissions that result in each scenario (as illustrated in figure 1).

We focus on emissions of CO_2—any reduction of which is regarded as a benefit by itself—and of key air pollutant species: sulfur dioxide (SO_2), nitrogen oxides (NO_X), and particle matter less than 10 microns and 2.5 microns in diameter (PM_{10} and $PM_{2.5}$). We first recapitulate how we estimate emissions in general. Emissions are calculated "bottom-up," combining information on (1) fuel consumption and industrial production by sector and region; (2) unabated emission factors, expressed in the mass of pollutant per unit fuel combusted or per unit output; and (3) removal efficiencies of relevant emission control technologies. This information must be compiled from the literature on all emitting processes, covering diverse industries, transportation modes, and household, commercial, and agricultural practices. All emission processes, additionally, must be geographically located so that they can serve as inputs in the atmospheric simulations.

1) 2007 Base Year and 2020 Base Case

The estimated emissions of CO_2 from combustion of fossil fuels are 6,703 million tons (Mt) in the 2007 base year. For reference, total CO_2—including process emissions from cement and aluminum production, and combustion emissions from household biofuels and agricultural biomass—is estimated at 8,476 Mt in 2007. In the tax simulations we only consider fossil fuel emissions.

The total SO_2 emissions in our base year of 2007 are estimated at 30.6 Mt, 5.9 Mt higher than the official estimate (NBS and MEP 2010). Estimated emissions of PM_{10} are 18.8 Mt, $PM_{2.5}$ 13.3 Mt, and NO_X 23.8 Mt. Specifically, SO_2 emissions from coal-fired power plants are estimated to have declined from 16.1 Mt in 2005 to 14.2 Mt in 2007, and PM_{10} emissions from 1.8 to 1.6 Mt. These declines are attributed to national policies in energy saving and emission controls during the 11th FYP. NO_X emissions from power plants, which were not targeted in the 11th FYP, are estimated to have increased from 7.0 to 8.2 Mt.

For the base case in 2020, the estimated emissions of all species are shown in table 5. National CO_2 emissions from fossil fuel combustion are projected to increase 63.6% to 10,966 Mt, from 6,703 Mt in 2007. A notable but cautionary[5] result is that in terms of fossil fuel carbon intensity (CO_2 emissions divided by GDP), this projection translates to a 44.8% reduction compared to the base year of 2007, or a 49.7% reduction compared to 2005.[6] Recall that in 2009, China committed domestically to reduce its carbon intensity 40–45% by 2020, relative to 2005. While we only consider carbon emissions from fossil fuel combustion, this is the dominant source of CO_2, and it suggests, caveats duly noted, that existing policy as represented in the base case—without any additional policy such as a carbon tax—may be sufficient to achieve China's target.

[Table 5 here]

Sulfur dioxide emissions are projected to decline 19% compared to 2007, driven by extension of policies to control SO_2 to additional power plants and new applications of flue gas desulfurization in other industrial sectors such as iron and steel. The national share of emissions from coal-fired electric power will decline to 33%. Moreover, national emissions of primary PM_{10} and $PM_{2.5}$ will decline by 25% and 26%, respectively, chiefly because of the continued transition in the cement industry from shaft kilns to precalciner kilns (see Lei et al. 2011).

Despite the proposed NO_X emission control policies that we incorporate (mainly in the electric power sector), national NO_X emissions are projected to increase by 10% in the base case as a result of the growth in energy consumption in industrial sectors. Specifically, NO_X

---

[5] See endnote 3.

[6] Because our base year is 2007, the intensity back to 2005 is extrapolated using CO_2 emissions estimated by CDIAC (2010) from 2005–2007 and GDP from the *China Statistical Yearbook*.

emissions will decrease by 9% for coal-fired power plants but increase by 37% in other industries. The effects of the swift increase in fuel consumption in transportation will likely be counteracted by the falling emission factors that result from the implementation of stricter emission regulation for both on-road and nonroad sources. The shares of NO_X emissions from coal-fired electric power plants, industry, transportation, and residential and commercial combustion (including open burning of biomass) are projected at 28%, 42%, 21%, and 9%, respectively.

2) 2020 Carbon Tax Cases

The imposition of carbon taxes would lead to major reductions compared to the base case in emissions not only of CO_2—the primary aim of any carbon tax—but also of all other key species of interest. To show the effects of the carbon tax policies on emissions of the key species, figure 9 gives the total emissions in the 2007 base year and in 2020 for the base case and four main tax scenarios, and also for the intervening years for fossil fuel CO_2.[7]

[Figure 9a, b, c, d here]

In figure 9*a* we see the continued growth in fossil fuel CO_2 emissions already described for the base case, even as carbon intensity declines. Beginning in 2013, the first year of tax imposition in all of our main policy scenarios (F1 to F4), the effect of the tax on CO_2 is obvious. While the sudden 30 yuan per ton tax in F1 would immediately drive annual emissions down in 2013, in subsequent years the growth rate would return almost back to the base-case rate. By 2020, CO_2 emissions would be 11% higher than the 2012 level, but 12% lower compared to the base case 2020 level. The initially small, but rising, taxes of F2 and F4 would elicit sustained reductions of growth in annual fossil CO_2 emissions, leading to a 19% reduction compared to the base case in 2020, though still a 3% increase over the 2012 level. Only in F4, where the tax begins small and then approaches international carbon prices by 2020, would the policy drive total emissions down year on year, achieving a 12% reduction over 2012 emissions in 2020 and 31% reduction relative to the base case. Indeed in this case, 2012 would be China's peak year of fossil CO_2 emissions.

---

[7] National emissions are much easier for us to estimate for fossil CO_2 than for the other species, because the economic model directly projects energy use and CO_2 emissions after scaling to the aforementioned CO_2 inventory (Zhao, Nielsen, and McElroy 2012). Although we could estimate bottom-up emissions of the other species for any given intervening year—2012, for instance, to spotlight how a carbon tax first imposed in 2013 would shift the emission trajectories—this step would require a large research effort that is otherwise unnecessary to draw our key conclusions about the 2013–2020 policy cases.

As for emissions of PM_{10} and SO_2 (figures 9***b*,and 9*c***), the effectiveness of existing policies on energy efficiency and emissions is reflected in the reduction of PM_{10} and SO_2 in the base case for 2020 versus 2007 discussed earlier, while figure 9*d* shows the difficulty reining in emissions of NO_X. Importantly, however, each of the carbon tax policies would sharply improve these pollutant trajectories by 2020. The expected declines in emissions of SO_2 and PM_{10} in the base case would be enhanced: F1 would reduce 2020 SO_2 emissions 14% and PM_{10} emissions 10% relative to the base case, F2 and F4 would reduce them 21% and 16%, respectively, and F4 would reduce them 34% and 25%. In the case of NO_X, moreover, the carbon taxes would arrest the anticipated growth in annual emissions: F1 would lead to a slight decline by 2020 compared to 2007 levels (−0.3 Mt) and an 11% reduction relative to the base case, F2 and F4 would generate a somewhat greater reduction from 2007 (−1.8 Mt) and 17% lower than the base case, and F3 a very significant reduction from 2007 (−4.5 Mt), 27% less than the base case.

4.4 Effects on Pollution Concentrations

To briefly recapitulate the next step in the benefit research, as represented in figure 1, we must translate gridded emission estimates to atmospheric concentrations, including both physical transport and chemical transformation in the air. Recall that we are interested not only in primary pollutants such as particles and SO_2, emitted directly from smokestacks and tailpipes, but also secondary pollutants formed chemically in the air from precursor species, such as sulfate particulates and ozone.

To conduct these analyses, we use a model of Chinese regional air quality that was developed by our program over more than a decade, nested within a global chemical transport model, GEOS-Chem. The China model has been tested against observations by ground stations, aircraft, and satellites, and employed in a number of studies of atmospheric chemistry in China. Our focus is simulating the concentrations of SO_2, NO_X, $PM_{2.5}$, and ozone (O_3), the latter two causing the dominant damages to public health and crop productivity.

Both the simulation of air quality and analysis of health and crop benefits of reduced pollution exposures are time-consuming research endeavors, and we do not aim to complete these steps for all our scenarios. Instead, we consider the value of different comparisons, concluding that the best set for full atmospheric assessment is the base case and F2, F3, and F4. As shown in table 5, however, our bottom-up emission assessment unexpectedly resulted in very similar emission profiles for F2 and F4 for all the concerned species, because these two scenarios yield similar paths in energy consumption. Indeed the emissions are far too close to merit separate atmospheric simulations for these two scenarios, and we can simply treat them as equivalent in this section and the next one.

1) Effects of Scenarios F2 and F4 on Pollution Concentrations

Figure 10 summarizes monthly mean changes in surface concentrations of (a) NO_X, (b) SO_2, (c) O_3, and (d) $PM_{2.5}$ for four months, representing the four seasons in 2020, between the 2020 policy cases F2 and F4 versus the base case. The changes are expressed as the level of the policy case minus the level of the base case.[8] Negative values indicate that the policy measures in the F2/F4 scenarios reduce pollutant levels at the surface compared to the base case.

[Figure 3.10a, b, c, d here]

The model results in figures 10a and 10b show that concentrations of both NO_X and SO_2 are reduced over all regions of China and in all seasons in F2/F4 compared to the base case, which is to be expected as total national emissions of NO_X and SO_2 are estimated to decrease by 17% and 21%, respectively. The changes in NO_X and SO_2 are significant in absolute terms over east China;[9] the annual mean decrease over this region is about 1.2 parts per billion by volume (ppbv, a standard concentration metric for pollutant gases) for NO_X and 1.5 ppbv for SO_2.

Emissions of primary $PM_{2.5}$ are lower by 14% in the F2/F4 cases than in the base case. As a result of reductions of both primary and secondary $PM_{2.5}$ levels (the latter from lowered emissions of NO_X and SO_2, the chemical precursors of $PM_{2.5}$), $PM_{2.5}$ declines throughout China and in all seasons compared to the base case, shown in figure 10d. Relatively large reductions are simulated for all of east China extending from the North China Plain to the Pearl River Delta, where the annual mean reduction of $PM_{2.5}$ is 4.2 $\mu g/m^3$ (micrograms per cubic meter) in F2 or F4 compared to the base case. The seasonal variations in these differences are again driven by atmospheric dynamics and chemistry affecting secondary $PM_{2.5}$ formation. The maximum reduction in absolute levels of $PM_{2.5}$ occurs in January, reaching a quite large 6.1 $\mu g/m^3$ average over east China.

The carbon tax policies F2 and F4 do not always lead to reductions in ozone concentrations. Over east China, concentrations of O_3 rise in January and decline in July, as shown in figure 10c.

---

[8] More precisely, these are denoted and defined as $\Delta NO_{x,F2/F4} = NO_{x,F2/F4} - NO_{x,base}$, $\Delta SO_{2,F2/F4} = SO_{2,F2/F4} - SO_{2,base}$, $\Delta O_{3,F2/F4} = O_{3,\ F2/F4} - O_{3,\ base}$, and $\Delta PM_{2.5,F2/F4} = PM_{2.5,F2/F4} - PM_{2.5,base}$.

[9] East China is defined in these analyses as 100°E–120°E, 22°N–42°N.

The mean changes in ozone in F2/F4 over east China are +0.8 ppbv in January and −1.7 ppbv in July, about +2% and −3.5% of the base case level, respectively. The largest decrease in monthly mean ozone occurs around 30°N in east China in July, with a maximum of 3–4 ppbv reduction, or about 7.5% of the base case level. In both April and October, changes in ozone transition from increases over the North China Plain to decreases south of the Yangtze River.

2) Effects of Scenario F3 on Pollution Concentrations

The stronger atmospheric effects of the higher tax rates of F3 are revealed in figure 11, again summarizing monthly mean changes from the base case in surface concentrations of (a) NO_X, (b) SO_2, (c) O_3, and (d) $PM_{2.5}$ for the seasonally representative months of 2020.[10] Negative values indicate that the policy measures in the F3 scenario reduce pollutant levels at the surface compared to the base case.

[Figure 11a,b,c,d here]

Figures 11a and 11b show that both NO_X and SO_2 are again lower over all regions of China and in all seasons in F3, compared to the base case, decreasing nationally by 27% and 34.5%, respectively. The annual mean decrease over east China is 2 ppbv for NO_X and 2.4 ppbv for SO_2. The largest reductions of NO_X and SO_2 due to F3 occur in the winter, and the lowest in the summer.

Emissions of primary $PM_{2.5}$ are lower, by 22%, in F3 compared to the base case, and there is a decrease in concentrations of $PM_{2.5}$ throughout China and in all seasons (figure 11d). Relatively large reductions are simulated for all of east China extending from the North China Plain to the Pearl River Delta, where the annual mean reduction of $PM_{2.5}$ can reach a very significant 7.2 $\mu g/m^3$, 69% larger than the reduction in the F2 case. The maximum reduction in absolute levels of $PM_{2.5}$ occurs in January, reaching an average of 10.3 $\mu g/m^3$ over east China.

As in other carbon tax cases, F3 does not always induce a decline in ozone concentrations. Over east China, ozone rises in January and declines in July compared to the base case, shown in figure 11c. The mean changes in F3 over east China are +1.3 ppbv in January and −3 ppbv in July, about +3.2% and −6% of the base case levels, respectively. The largest decrease in monthly mean ozone occurs around 30°N in east China in July, with a 6–7 ppbv reduction, or about 13% of the base case level. F3 shows the same geographical characteristics as F2/F4 in both April and

[10] The differences are defined similarly to those for F2F4, as $\Delta NO_{x,F3} = NO_{x,F3} - NO_{x,base}$, $\Delta SO_{2,F3} = SO_{2,F3} - SO_{2,base}$, $\Delta O_{3,F3} = O_{3,F3} - O_{3,base}$, and $\Delta PM_{2.5,F3} = PM_{2.5,F3} - PM_{2.5,base}$.

October, where it transitions from increases over the North China Plain to decreases south of the Yangtze River.

3) Comparison of Scenarios F2 and F4 versus Scenario F3

Comparing the changes in annual mean SO_2 concentrations in F2/F4 versus F3, we find that the reduction corresponds almost linearly to emission reductions. The same linearity holds also for NO_X. The reason is that primary emissions are dominant contributors to the two species. The reductions in annual mean $PM_{2.5}$ over east China, however, are difficult to analyze similarly with respect to emissions because they result from reduced emissions not only of primary $PM_{2.5}$ but, to a much larger extent, of SO_2 and NO_X (precursors to sulfate and nitrate forms of $PM_{2.5}$).

Concentrations of ozone similarly do not vary linearly with reductions of O_3-precursors, because of the chemical mechanisms presented in chapter 7. However, as only the emissions of NO_x are reduced in the 2020 policy cases from the base case levels, and not other O_3 precursors including volatile organic compounds (VOCs),[11] the change in ozone in F2/F4 or F3 can be used to indicate the chemical regimes of ozone production (specifically, whether they are NO_X-limited or VOC-limited). The simulations indicate that under the 2020 emission scenarios (including the emission levels of VOCs in the 2007 base year), the North China Plain region lies in a VOC-limited regime except in summer, and the Pearl River Delta region in a NO_X-limited regime except in winter.

4.5 Effects on Health and Agricultural Damages of Air Pollution

In this section we estimate the net effect of the changes in the $PM_{2.5}$ and ozone concentrations due to the carbon tax policies on public health and productivity of major grain crops. A U.S. EPA assessment tool called BenMAP is used for evaluating the health impacts. In a nutshell, health damages—in terms of both premature mortalities and morbidity (disease) endpoints—are estimated taking account of (1) the simulated pollution concentrations; (2) the population distribution in China, updated to 2020; (3) the base incidence rates of nonaccident mortality and other health endpoints; and (4) concentration-response (C-R) relationships from the epidemiological literature. The same conclusions about applicable C-R functions drawn in chapter 8 are directly applied here. This is one of the most important steps in determining our estimates of the ancillary benefits of the policies.

[11] It may be reasonable to assume increasing stability of VOC in 2013–2020 compared to the growth in 2006–2010 given the attention VOCs are beginning to gain in air pollution control communities in China, and the model of VOC control in cities in more developed countries that have helped to drive down photochemical smog.

The crop impact assessment focuses on ozone effects on three primary grains—wheat, rice, and maize—and uses a framework that is analytically similar to that of the health assessment. One important distinction is the need to consider greater temporal resolution in both pollutant concentrations (because ozone exhibits such strong daily and seasonal variations) and crop growth (which is, naturally, highly seasonal).

1) Health Benefits

The estimated health benefits for each endpoint are summarized in table 6, with lower and upper bounds reflecting uncertainties in the underlying epidemiological studies. Compared with the base case, improvement of air quality in the carbon tax policy scenarios (F2/F4 and F3) would lead to 13,800 and 23,200 avoided premature deaths from acute effects of $PM_{2.5}$ exposures in 2020, respectively, and 5,500 and 9,900 premature deaths from acute effects of ozone exposures in 2020. The estimates of avoided deaths from chronic effects of $PM_{2.5}$ exposures are 83,200 and 139,000 for the emission reductions of F2/F4 and F3, respectively. The avoided premature deaths from acute effects of $PM_{2.5}$ and O_3 reductions due to the F2/F4 and F3 carbon taxes would account for 0.25% and 0.42%, respectively, of all-cause deaths; the percentages due to estimated chronic effects of $PM_{2.5}$ exposures are 1.06% and 1.78%.

[Table 6 here]

The benefits of the policies in terms of population risks of morbidity are also significant, although not as striking. The reduced pollution levels due to the carbon taxes of F2 or F4 would lead to an estimated average of 123,000 avoided cases of hospital admissions and 5.3 million cases of outpatient visits, and those due to F3 would avoid 213,000 cases of hospital admissions and 8.9 million cases of outpatient visits.

We also represent the geographical distributions of avoided acute mortality due to changes in $PM_{2.5}$ exposures for F2/F4 and F3 in figure 12, and those due to changes in ozone exposures in figure 13. Compared to the base case, acute mortality due to $PM_{2.5}$ and ozone exposures is reduced in most inhabited areas of China. This statement is true even for ozone exposures, except for a few megacities including Beijing, Tianjin, and Shanghai, and the smaller city of Dalian, despite increases in ozone that result from the policies in some regions and seasons, as shown in figures 10 and 11, to be explained in the following paragraphs.

[Figure 12a, b, c, d here]

As shown in table 6, the health benefit of avoided acute mortality is mainly due to the decline of $PM_{2.5}$ exposures. The areas with the largest such benefits are unsurprisingly located in densely populated metropolitan areas such as Beijing, Tianjin, Shanghai, Guangzhou, and Chengdu. Regionally, the benefits of reduced $PM_{2.5}$ are very significant in areas centered on Henan-Hebei-Shandong, southern Jiangsu, and the Sichuan basin.

2) Crop Benefits

Estimates of the benefits to rice, wheat, and maize production due to the carbon tax policies are summarized in table 7. The estimates are based on averaging the effects calculated using several ozone exposure indexes (M12, SUM06, W126, and AOT40) and corresponding exposure-relative yield relationships. We also present the geographical distributions of the benefits to rice, wheat, and maize production in figures 14–16.

[Table 7 here]

[Figure 14 here]

[Figure 15a, b, c, d here]

The estimates of benefits to wheat production of the carbon tax, depending on the exposure index, vary from 0.13 to 2.17 Mt in F2/F4 and 0.33 to 4.44 Mt in F3. The estimates for rice vary from 1.00 to 2.81 Mt in F2/F4 and 1.68 to 4.80 Mt in F3, and for maize from 2.50 to 5.36 Mt F2/F4 and 4.28 to 9.36 Mt in F3. Increased grain production would occur throughout most of China in both F2/F4 and F3 compared with the base case, noting that there would be reduced production of wheat in the Hebei-Henan-Shandong area. This interesting effect results from a coincidence of elevated ozone levels in this area and the growing season of winter wheat, namely, March through May.

We compare our estimates to China's total grain production in 2007. We find that the carbon tax would increase wheat, rice, and maize production in China by around 0.8%, 1.0%, and 2.7%, respectively, in F2/F4, and around 2.0%, 1.7%, and 4.7% in F3. These increases appear moderate but notable compared to total national production; in some regions the effect could exceed 10%, which would be very significant locally.

Finally, we also calculate the monetary value of the agricultural benefits from the carbon tax by multiplying the increased yields by projected prices for the grains. To estimate these prices, we use the projection of the average price for national agricultural production from the economic model. The total estimated value of the grain yield benefits is 15.7 billion yuan in F2/F4 and 28.3 billion yuan in F3.

5. Comparison of the Effects of the Carbon Tax Scenarios

To summarize our results, we compare key effects in 2020 of the carbon tax policy options in table 8.

[Table 8 here]

Scenario F1, the static 30 yuan per ton tax with revenues rebated to consumers in lump sums, shows moderate economic effects compared to the base case in 2020, with a 0.09% reduction in GDP, a 0.17% increase in consumption, and a negligible effect on investment. Its impacts in 2020 on coal use and emissions would be modest compared to the other cases, with reductions from base-case levels of 10% to 15%. However, the unique challenges posed by this carbon tax structure are somewhat lost viewing it from a 2020 perspective, because it is the most abrupt policy analyzed. In this case readers should also revisit table 3 and figure 5, showing the effects in the first tax year of 2013. The table indicates impacts of F1 on the economy, energy use, and emissions that would be two- to fourfold larger than those of all the other cases. Because Chinese decision makers would seek to avoid a sudden disruption to GDP and notably export volumes, given an option of a smoother policy transition as shown in our other cases, we consider it unlikely that a carbon tax would be imposed with such a static time profile.

Scenario F2, a 10 yuan per ton tax that climbs to around 50 yuan in 2020, with lump-sum rebates to consumers, is a likelier carbon-tax policy. It would achieve the exact same cumulative CO_2 reduction as F1 over the eight-year policy term, but would do so by easing a policy into place incrementally. Its negative impact on GDP in 2020 would be somewhat larger than that of F1 (and somewhat smaller in 2013), but its benefit to consumption would also be larger. By 2020, the effect on coal use and annual emissions of CO_2, PM_{10}, SO_2, and NO_X compared to the base case would be substantial, with reductions ranging from 16% to 23%. Importantly, this scenario would result in sharp improvements in regional air quality, judged especially by concentrations of $PM_{2.5}$ and ozone. These in turn would translate into very substantial public health benefits, with an estimated 13,800 or as many as 83,200 premature deaths avoided from exposure to $PM_{2.5}$, depending on epidemiological assumptions. Another 5,500 premature deaths from acute ozone exposure would also be avoided. In addition, the net ozone reductions would raise production of wheat, rice, and especially maize, with an estimated total economic value of

15.7 billion in constant 2007 yuan. Scenario F2 thus illustrates the large direct and indirect benefits that could be gained, at modest cost, if a carbon tax policy were implemented at rates similar to those discussed previously in Chinese policy-making circles.

Scenario F3, identical to F2 except with tax rates that accelerate more quickly to 100 yuan in 2020, naturally shows even larger effects by that year. The negative impact on GDP compared to the base case, −0.33%, would be sizable, though growth in consumption would also be large, +0.39%. Some might consider these economic impacts justified, however, given the enormous reductions in coal use and emissions and benefits to air quality, public health, and crop productivity that would result. Annual Chinese fossil CO_2 emissions would be hugely reduced under F3 compared to the base case, 30.8%, noting again that this is the only scenario analyzed that results in emissions falling over time from a peak in 2012. Emissions of domestic pollutants would also be sharply reduced, from 25% for PM_{10} to 34% for SO_2. This reduction would lead to 23,200 estimated avoided premature deaths from acute $PM_{2.5}$ exposures, or an enormous 139,000 avoided from chronic $PM_{2.5}$ exposures. Net reductions in ozone compared to the base case would lead to an additional 9,900 premature deaths avoided, and 28.3 billion yuan of increased grain production. While comparing F3 to F2 indicates that a doubling of carbon tax rates would bring somewhat diminishing gains in terms of benefits, it also suggests that remarkable improvements in both carbon emissions and China's degraded air quality might be achievable at relatively manageable costs to its economy.

Scenario F4, identical again to F2 except that the tax revenues would instead be used to reduce existing taxes, illustrates an important option in carbon tax policy design. The effect on emissions compared to the base case (and therefore the benefits to air quality, health, and agriculture) would be effectively identical to those of F2, but the impacts on the economy of this alternative revenue recycling would differ significantly. The policy does not compensate households and thus does not raise consumption but would lead to higher retained earnings of enterprises, raising investment by 0.57% in 2020 compared to the base case. This higher capital stock would reduce distortions of the carbon tax, and could eventually leave GDP unaffected or even improved slightly over a business-as-usual case. In other countries, it has proven politically infeasible to use revenues of carbon pricing purely to offset more distortionary existing taxes in this way, because industries forced to pay most under new carbon pricing advocate forcefully to be compensated from the new revenues.[12] Scenario F4, however, suggests that if this sort of revenue-neutral policy design were politically feasible in China, it might offer the broad and substantial environmental benefits common to all our scenarios, but at costs to the economy that would be even smaller than in the other cases.

In Scenario F5 we follow the same path of carbon prices as in F2, but use a part of the new revenues to subsidize the EITE manufacturing industries, calculating output subsidy rates similar to the Waxman-Markey mechanism. The most energy-intensive, trade-exposed sector in China is production of nonmetal mineral products (including cement), which would receive a 0.25% subsidy rate, followed by the primary metal and chemical industries, as shown in the table. At these rates, the subsidies do not recycle all the carbon tax revenue, and the remaining revenue is transferred in lump sums back to households.

[Table 9 here]

The subsidy rates look modest, but the impact compared to F2 is noticeable in table 5. The carbon-intensive industries do not need to raise prices to the extent shown in figure 6, and thus experience a much smaller output loss. Coal consumption falls by less (−21.3% in 2020 versus −23.0% in F2), and total energy consumption falls by only 16.2% compared to 17.7% without the subsidy. Annual CO_2 emissions are thus only 17.4% lower than the base case, compared to 18.9% in F2; cumulative fossil CO_2 emissions are 65.67 gigatons, versus 64.79 without the subsidy.

The smaller amount of transfers to households means that the change in consumption is smaller (0.15% versus 0.27%). The net effect of this smaller change in prices of energy-intensive goods and smaller consumption is a smaller loss in GDP; by 2020, GDP is only 0.07% smaller than the base case, compared to the 0.14% loss without the subsidies in F2. Other effects of the smaller change in prices are a weaker appreciation of the terms of trade and a fall in exports that is much less than that in F2.

The results of Senario F6 for the first year, 2013, are shown in the last column of table 3. When the prices of energy-intensive goods in the rest of the world are high, the impact of the Chinese carbon tax on their net exports is smaller; in F2 the higher prices of Chinese goods

[12] This observation refers to actual or proposed use of revenues generated by auctions of carbon allowances in such programs as the EU Emission Trading System, the northeastern U.S. cap-and-trade program (the Regional Greenhouse Gas Initiative, RGGI), and the failed 2009 Waxman-Markey bill in the U.S. Congress. The EITE subsidies examined in scenario F5 represent an example of such compensation.

reduces net exports of those goods significantly, while this effect is dampened in the multilateral tax case. This case is complicated by the assumption that the trade balance is held fixed between the base case and policy case; this implies that any reduction in net exports of energy-intensive goods has to be offset by changes in the terms of trade and changes in the net exports of the non-energy-intensive goods. A simple scenario where only world prices are raised will generate an appreciation of the terms of trade and thus lower net exports.

The following figure shows the changes in industry output as a result of these interactions in the two scenarios; we show them only for the manufacturing and utility sectors to avoid a cluttered plot. The changes for F2 (white bars) for the energy-intensive industries—refining, chemicals, nonmetallic mineral products, primary metals—are bigger than those for the multilateral tax scenario, F6 (dark bars). The changes for the less energy-intensive industries (e.g., apparel, machinery, electrical machinery) are smaller in F2. The nontraded industries such as electric and gas utilities show only tiny differences between the two scenarios.

[Figure 17 here]

In the aggregate the effects are small, as shown in table 3: GDP, consumption and investment in 2013 in F6 are very similar to those of the unilateral carbon tax in F2. With the smaller reduction in the energy-intensive sectors, the fall in energy consumption is smaller in F6: 4.38% versus 4.51%. As a result carbon emissions are also a little smaller, 4.69% versus 4.82%. The key point of this simple case is that the industries affected most by a carbon price will suffer less in a multilateral tax system than under a unilaterally imposed tax.

The results that we have estimated, like all such modeling exercises, are driven by the methodological assumptions and parameter values. The estimated avoided damage depends on the emission factors, activity levels, and concentration-response coefficients, among many other factors, and these are subject to substantial uncertainty. The economic impacts depend on the assumptions regarding the base-case growth and elasticities of substitution, many of which have degrees of uncertainty that are difficult to quantify. One should keep this caution in mind.

6. Conclusion

We draw two overarching conclusions about prospective carbon taxes in China.

First, any negative economic effects of taxes at the rates considered here would be modest at the aggregate level given the scale of recent developments in the Chinese economy that are already under way. In all but one of our cases (F4 in 2020), there would be small trade-offs between consumption, investment, and GDP in both the first and eighth year of introducing a carbon tax. For the most part, smaller reductions in investment could be gained by trading off increased consumption, and vice versa. This trade-off would mainly be driven by the choice of how the resulting tax revenues would be used: rebating them directly to consumers in lump sums (F1–F3, and F6) would increase consumption versus the base case, unsurprisingly, at the cost of slightly diminished GDP growth. Recycling the revenues to enterprises through a reduction of existing taxes (F4) would raise investment in the capital stock and diminish (or even reverse) the negative impact on GDP. Recycling through subsidies to vulnerable industries (F5) would diminish the biggest shocks and the impact on aggregate GDP.

In any case, nearly all these effects would be modest compared to the current and projected growth rates of aggregate GDP and other economic indicators. The estimated reductions in GDP in 2020 compared to the base case would be in the range of zero to three-tenths of a percent; that is, in the most aggressive case, F3, the annual growth rate would change from 8.07% during 2012–2020 in the base case to 8.03%. In our main scenario F2, the reduction in 2020 GDP is only one-tenth of a percent. While the size of these aggregate impacts depends on various technical assumptions of enterprise behavior in the economic model and assumptions in the base case, more pessimistic assumptions would raise these estimates only somewhat.[13] At the same time, gains to consumption in the near term under our consumer rebate scenarios would even be positive: from two- to four-tenths of a percent in 2020. In all cases the carbon tax would reduce exports by 2020, however, ranging from 0.7% (F1) to 2.1% (F3). This effect would be significant, enhancing a structural shift toward consumption-driven growth. This happens to align with the belief of many policy advisers that, ignoring carbon entirely, China's long-term economic prospects would be strengthened by a transition from export-led to consumption-driven growth.

Our second overall conclusion is that not only do carbon taxes efficiently limit China's carbon emissions, but they are also a powerful tool to address China's severely degraded

[13] One of the key features driving costs is the ability to substitute low-carbon inputs for high-carbon ones, the elasticity of substitution in the economic model used. Our model assumes an elasticity of one for industry inputs. More inelastic parameters are used in other models that do estimate higher costs, but not extraordinarily high costs. For example, Adkins et al. (2010) estimate a −0.1% impact on U.S. GDP with a $15/ton CO_2 price, and the Intertemporal General Equilibrium Model (IGEM) estimates that the Waxman-Markey plan would have reduced the growth rate in the United States from 2.67% to 2.63% (U.S. EPA 2009).

domestic air quality, and associated damages, at the same time. The fortuitous fact that the same fossil energy sources that emit carbon are also the primary sources of key air pollutants provides China with a remarkably convenient opportunity to align some of its most pressing domestic and global environmental aims.

All our tax policies would reduce cumulative CO_2 emissions from 2013 to 2020 compared to the base case, around 11%–13% for most of our scenarios (F1-F2, F4-F6) and 20% under the higher tax rates of F3 (see figure 3.4). In annual terms, F1 would reduce 2020 CO_2 emissions by 12% compared to the base case, F2 and F4 by 19%, and F3 by 31%.
Such carbon benefits alone might justify incurring the economic impacts of the tax policies, and yet the policies would also bring ancillary reductions of PM_{10}, SO_2, and NO_X emissions at similar scales. These in turn would produce benefits to public health from reduced $PM_{2.5}$ and ozone concentrations that could be immense: from 28,300 avoided premature deaths to as many as 87,700 under F2 and F4 in 2020 alone, depending on epidemiological assumptions; and from 32,100 to as many as 148,900 under the higher tax rates of F3. Additional effects from net national reductions in ozone levels could boost grain production as much as 15.7 billion yuan under F2 and F4 in 2020, and 28.3 billion yuan under F3.

While our advanced atmospheric model allows us to trace the complex chemistry generating higher ozone levels and thus higher ozone risks to health in a few cities and to wheat production in several provinces due to the taxes, the increased acute ozone mortality in those regions would be more than offset by reductions in $PM_{2.5}$ mortality resulting from the same policy. Wheat farmers in the North China Plain would experience lower yields as a result, but they too would benefit from the lower health damages. We should note that these ozone increases could potentially be mitigated by a complementary policy targeting emissions of volatile organic compounds, the precursor pollutant that chapter 7 indicates governs the chemical formation of ozone in this region of China. The costs of such complementary policies could be spread across the entire population that benefits from the main carbon control policy, leaving no one worse off.

The debates over whether and how to implement a carbon reduction policy in wealthier countries have been contentious and acrimonious at times. In part this response may be due to the immediate and certain costs compared to the distant and uncertain benefits of climate risk mitigation. The pollution levels in the rich countries are comparatively low today, and the ancillary benefits of lower fossil fuel use are estimated at lower levels. The situation in China, and many other developing countries, however, is quite different. Here the air quality is often severely degraded, causing very high levels of health and other environmental damages. The Chinese government recognizes the urgent need to reduce air pollution, or at minimum to slow the growth of pollutant emissions.

Given this goal to reduce local emissions, which are mostly due to fossil fuel combustion, a natural question to consider is whether a policy that recognizes both local pollutants and carbon dioxide is preferable to policies dealing with these problems as though they are unrelated. Our consideration of carbon tax options here show that they can substantially reduce CO_2 and local pollutants at the same time, with a cost that is modest, especially compared to the reduced health damages.

This observation is true from a unilateral Chinese perspective, ignoring the benefits to the rest of the world of reducing its emissions of CO_2, SO_2, and other pollutants. The rest of the world derives substantial benefits from these reductions, however, including improvements in regional air quality across East Asia and well beyond, even across the Pacific Ocean. The reduction in climate risks for the world would be substantial given the large estimated tonnage of CO_2 reduced from the highest emitting country.

This effect indicates that the rest of the world should work with China to implement such emission reduction policies. There are many ways to cooperate internationally. We have already noted that establishment of a multilateral system of carbon prices, even if it took shape gradually, would reduce the effects on trade flows and ease the disruptions of implementing carbon prices in all countries. While China's availability as a source of offsets for carbon markets in other countries, such as under the Clean Development Mechanism of the Kyoto Protocol, appears to be declining for a variety of reasons, other modes of cooperation with wealthier nations are much discussed in the policy arena. These include technical assistance in the development of low-carbon policies, joint development of clean energy technologies and strategies, and scientific cooperation to build capacities and knowledge concerning the physical risks that underpin effective climate policy design. Given our results, we cannot but give our strongest encouragement for such coordinated international action.

Table 1. Base case projection

Variable	2007	2013	2020	2032	2007-20 Growth Rate	25-year Growth Rate
Population (million)	1,316	1,360	1,411	1,437	0.54%	0.35%
Effective labor supply (billion 2007 yuan)	10,019	10,387	10,043	9,423	0.02%	-0.24%
GDP (billion 2007 yuan)	27,260	45,985	80,777	150,894	8.4%	7.1%
Consumption/GDP	0.37	0.41	0.47	0.55		
Fossil energy use (million tons of standard coal equivalent)	2,523	3,386	4,195	5,096	3.9%	2.9%
Coal use (million tons)	1,013	1,295	1,554	1,784	3.3%	2.3%
Oil use (million tons)	845	1,139	1,348	1,669	3.6%	2.8%
Gas use (billion cubic meters)	89	154	255	445	8.1%	6.6%
Electricity use (TWh)	2,246	3,399	5,500	9,749	6.9%	6.0%
CO_2 emissions (fossil fuel combustion, million tons)	6,703	8,915	10,966	13,136	3.8%	2.7%
PM_{10} (million tons)	19.05		13.96		-2.4%	
SO_2 emissions (million tons)	30.53		24.66		-1.6%	
NO_X emissions (million tons)	23.63		26.21		0.80%	

Note: There is 0.714 ton standard coal equivalent (sce) in 1 ton of coal.

Table 2. Carbon tax options examined

Scenario	Time Path of Carbon Tax	Use of Revenues
F1	Tax of 30 yuan/ton of CO_2 (in 2007 yuan) applied for all years during 2013-2020	Rebated lump-sum to households
F2	Tax of 10 yuan/ton in 2013 rising to 50 yuan/ton in 2020; same cumulative CO_2 reduction as scenario F1.	Rebated lump-sum to households
F3	Tax of 10 yuan/ton in 2013 rising to 100 yuan/ton in 2020	Rebated lump-sum to households
F4	Same as F2, 10 yuan/ton in 2013 rising to 50 yuan/ton in 2020	Cut tax rates on enterprise income
F5	Same as F2, 10 yuan/ton in 2013 rising to 50 yuan/ton in 2020	Subsidies to EITE industries; rest rebated lump-sum to households
F6	Same as F2, 10 yuan/ton in 2013 rising to 50 yuan/ton in 2020, assuming action by the rest of the world	Rebated lump-sum to households

Table 3. The effects of a carbon tax in the first year, 2013

Variable	Base Case 2013	Scenario F1: 30Y/ton all years	Scenario F2: 10Y rising to 50Y/ton	Scenario F3: 10Y rising to 100Y/ton	Scenario F4: 10Y rising to 50Y/ton	Scenario F5: 10Y rising to 50Y/ton	Scenario F6: 10Y rising to 50Y/ton
		Lump sum offset	Lump sum offset	Lump sum offset	Tax cut offset	Subsidies to EITE	Lump sum; Multilateral
	(levels)	(percent change from base base)					
GDP (billion yuan 2007)	45,985	-0.09	-0.02	-0.02	-0.02	-0.01	-0.01
Consumption (billion yuan 2007)	18,148	0.29	0.11	0.11	-0.03	0.05	0.11
Investment (billion yuan 2007)	21,455	-0.08	-0.02	-0.02	0.10	0.01	0.00
Government consumption (billion yuan 2007)	5,171	0.00	0.00	0.00	0.00	0.00	0.00
Exports (billion yuan 2007)	14,308	-0.69	-0.28	-0.28	-0.22	-0.19	-0.42
Fossil energy use (million tons of standard coal equivalent)	3.386	-12.1	-4.51	-4.51	-4.44	-3.96	-4.38
Coal use (million tons)	1,378	-15.6	-5.81	-5.81	-5.74	-5.13	-5.68
Oil use (million tons)	1,942	-1.6	-0.54	-0.54	-0.48	-0.34	-0.36
Gas use (billion cubic meters)	153	-4.5	-1.54	-1.54	-1.48	-1.20	-1.49
Electricity (billion kWh)	3,399	-2.8	-0.98	-0.98	-0.95	-0.82	-0.98
CO_2 emissions (fossil fuel; million tons)	8,915	-13.0	-4.82	-4.82	-4.74	-4.25	-4.69
Carbon tax as percent of total tax revenue		2.4	0.89	0.89	0.89	0.89	0.89

Table 4. The effects of a carbon tax in 2020

Variable	Base Case 2020	Scenario F1: 30Y/ton all years	Scenario F2: 10Y rising to 50Y/ton	Scenario F3: 10Y rising to 100Y/ton	Scenario F4: 10Y rising to 50Y/ton	Scenario F5: 10Y rising to 50Y/ton	Scenario F6: 10Y rising to 50Y/ton
		Lump sum offset	Lump sum offset	Lump sum offset	Tax cut offset	Subsidies to EITE	Lump sum; Multilateral
	(levels)	(percent change from base base)					
GDP (billion yuan 2007)	80,777	-0.09	-0.14	-0.33	0.02	-0.07	-0.11
Consumption (billion yuan 2007)	34,906	0.17	0.27	0.39	0.00	0.15	0.27
Investment (billion yuan 2007)	33,343	0.01	0.01	-0.04	0.57	0.10	0.05
Government consumption (billion yuan 2007)	8,267	0.00	0.00	0.00	0.00	0.00	0.00
Exports (billion yuan 2007)	26,655	-0.69	-1.12	-2.11	-0.81	-0.75	-1.27
Fossil energy use (million tons of standard coal equivalent)	4.195	-11.6	-17.7	-28.8	-17.5	-16.2	-17.5
Coal use (million tons)	1,653	-15.2	-23.0	-37.2	-22.9	-21.3	-22.9
Oil use (million tons)	2,297	-1.3	-2.11	-4.01	-1.91	-1.37	-1.94
Gas use (billion cubic meters)	252	-4.5	-7.37	-13.65	-7.13	-6.11	-7.32
Electricity (billion kWh)	5,500	-2.4	-3.86	-6.82	-3.66	-3.40	-3.85
CO_2 emissions (fossil fuel; million tons)	10,966	-12.4	-18.9	-30.8	-18.6	-17.4	-18.8
Carbon tax as percent of total tax revenue		1.9	2.91	5.03	2.93	2.89	2.91

Table 5. Emissions in the base case and scenarios F1-F4 for 2020 (million metric tons/year)

	Base	F1	F2	F3	F4
CO_2	10966	9601	8888	7590	8908
SO_2	24.7	21.2	19.4	16.1	19.4
NO_X	26.2	23.3	21.9	19.2	21.9
$PM_{2.5}$	9.94	9.04	8.57	7.73	8.58
PM_{10}	14.0	12.5	11.8	10.4	11.8

Table 6. Health benefits of carbon taxes in Scenarios F2/F4 and F3.

Pollutant	Health endpoints	F2/F4			F3		
		Mean	Lower	Upper	Mean	Lower	Upper
$PM_{2.5}$	Acute mortality	13,800	8,500	19,100	23,200	14,300	32,100
	Chronic mortality	83,200	23,700	142,300	139,000	39,800	237,200
	Hospital admissions (cardiovascular)	24,100	5,900	42,200	40,500	10,000	70,800
	Hospital admissions (respiratory)	43,200	29,800	56,600	72,400	49,900	94,800
	Outpatient visits, all-cause	5,320,000	2,120,000	8,520,000	8,930,000	3,560,000	14,310,000
Ozone	Acute mortality	5,500	1,500	9,500	9,900	2,700	17,100
	Hospital admissions (cardiovascular)	25,900	18,400	33,500	46,800	33,200	60,300
	Hospital admissions (respiratory)	29,600	24,000	35,200	53,200	43,200	63,300

Units: Number of cases avoided compared to the base case in 2020. In addition to the mean estimates, lower and upper bounds representing the 95% confidence intervals (CIs), are also calculated based on the published CIs for relative risk in the corresponding literature

Table 7. Grain production benefits of carbon taxes in Scenarios F2/F4 and F3.

	F2/F4					F3				
	M12	SUM06	W126	AOT40	Average	M12	SUM06	W126	AOT40	Average
Wheat	133.0	708.8	2165.4	573.3	895.1	325.5	2529.5	4437.4	1303.7	2149.0
Rice	995.8			2808.1	1902.0	1682.4			4796.4	3239.4
Maize	2495.0	5362.3	4516.9		4124.7	4277.5	9363.9	7697.6		7113.0

Units: Increase of crop yields (thousand tons) compared to the base case in 2020, calculated for four different ozone exposure indices (M12, SUM06, W126, and AOT40).

Table 8. Comparative summary of major effects in 2020 of four carbon tax policies versus the base case.

Variable	Scenario F1: 30Y/ton all years	Scenario F2: 10Y rising to 50Y/ton	Scenario F3: 10Y rising to 100Y/ton	Scenario F4: 10Y rising to 50Y/ton
	Lump sum offset	Lump sum offset	Lump sum offset	Tax cut offset
	percent change			
GDP	-0.09%	-0.14%	-0.33%	0.02%
Consumption	0.17%	0.27%	0.39%	0.00%
Investment	0.01%	0.01%	-0.04%	0.57%
Coal Use	-15.2%	-23.0%	-37.2%	-22.9%
CO_2 Emissions	-12.4%	-18.9%	-30.8%	-18.8%
PM_{10} Emissions	-10.3%	-15.7%	-25.3%	-15.6%
SO_2 Emissions	-14.1%	-21.4%	-34.5%	-21.3%
NO_X Emissions	-10.9%	-16.6%	-26.9%	-16.4%
Avoided Premature Deaths	cases			
Acute Effect $PM_{2.5}$ (PRC epidemiology)	-	13,800	23,200	13,800
Acute Effect Ozone (PRC epidemiology)	-	5,500	9,900	5,500
Chronic Effect $PM_{2.5}$ (US epidemiology)	-	83,200	139,000	83,200
Increased Grain Production	million tons or billion yuan			
Wheat (Mt)	-	0.895	2.149	0.895
Rice (Mt)	-	1.902	3.239	1.902
Maize (Mt)	-	4.125	7.113	4.125
Total Value (billion yuan)	-	15.7	28.3	15.7

Table 9. Subsidies given to energy-intensive industries in Scenario F5 in year 1

	Industry	CO_2 Embodied in Fuels and Electricity Used (million tons carbon)	Output in 2007 (billion yuan)	EITE Subsidy Rate
6	Food products and tobacco	34.47	4179	0.03%
7	Textile goods	33.27	2520	0.05%
8	Apparel and leather	7.44	1807	0.01%
9	Sawmills and furniture	10.63	1099	0.04%
10	Paper products and printing	31.09	1493	0.08%
11	Petroleum refining and coking	66.87	2107	0.12%
12	Chemicals	240.40	6200	0.14%
13	Nonmetal mineral products	155.65	2280	0.25%
14	Primary metals	276.52	6110	0.16%
15	Metal products	30.48	1771	0.06%
16	Machinery and equipment	40.62	3949	0.04%
17	Transport equipment	18.26	3298	0.02%
18	Electrical machinery	11.17	2716	0.01%
19	Electronic and telecom equipment	14.95	4119	0.01%
20	Instruments	1.49	488	0.01%
21	Other manufacturing	7.56	1055	0.03%

Figure 1. Framework to Analyze Costs and Benefits of Alternative Emission Control Policies

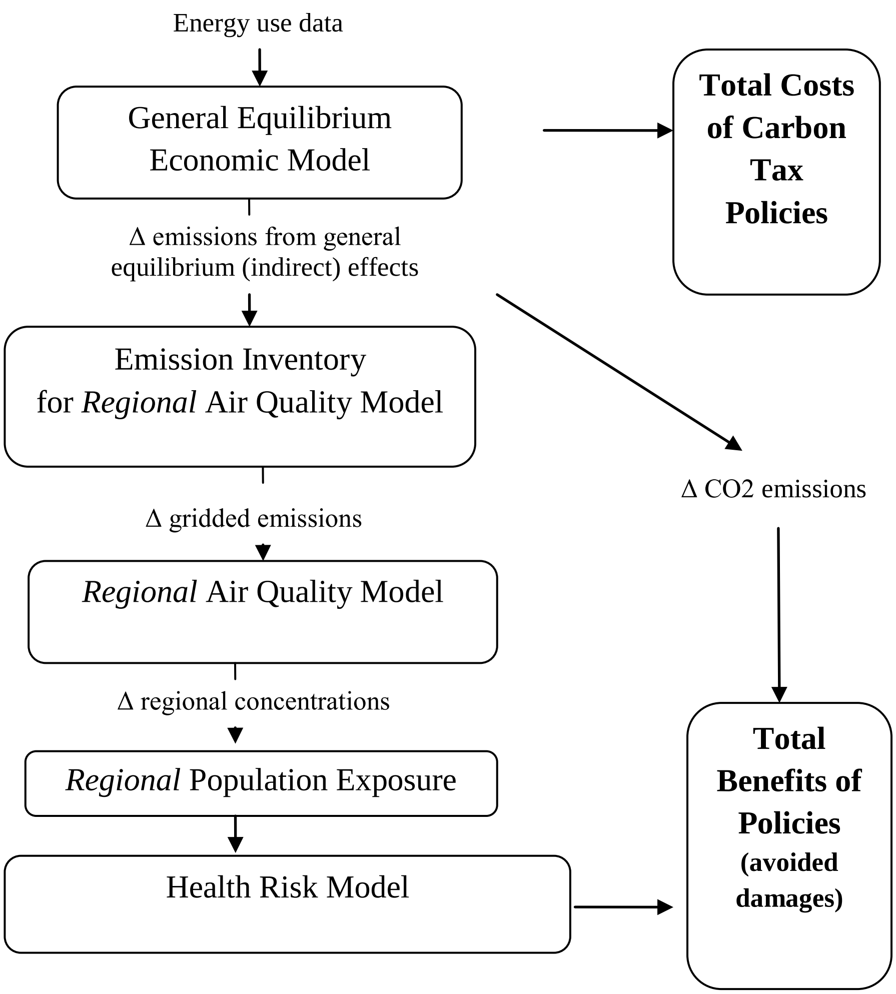


Figure 2. Base case projection of GDP, energy consumption, oil price, and CO_2 emissions

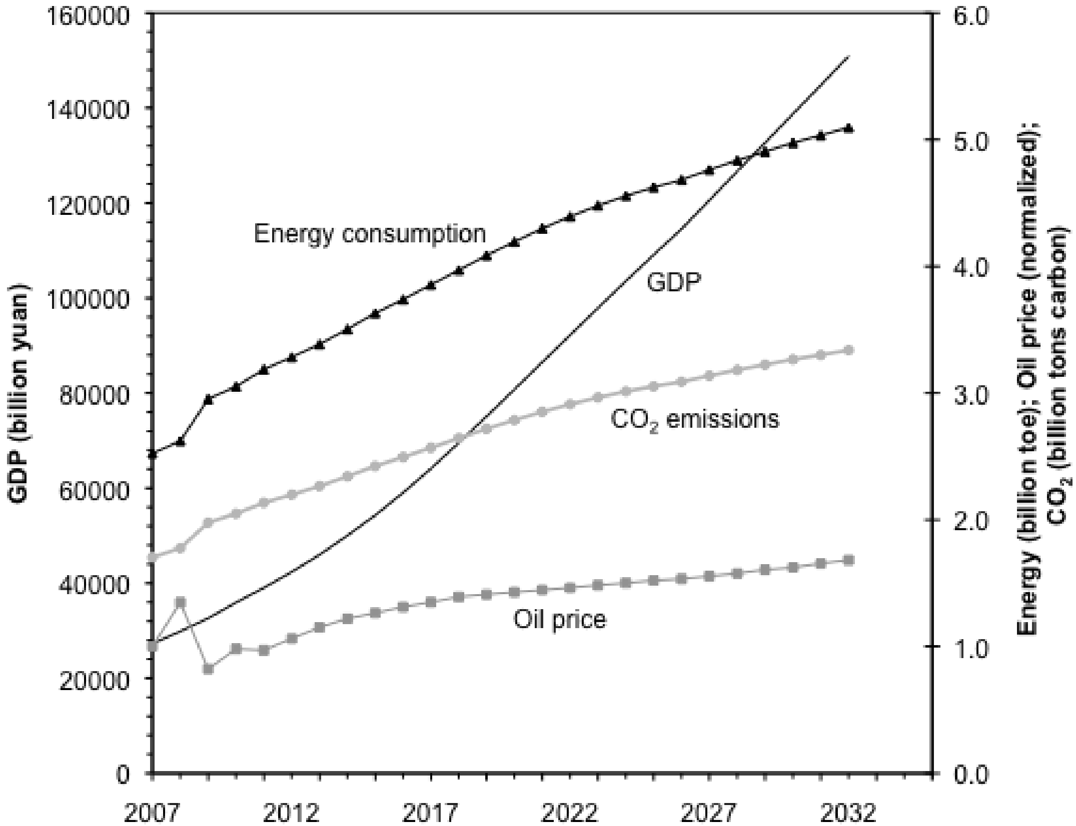
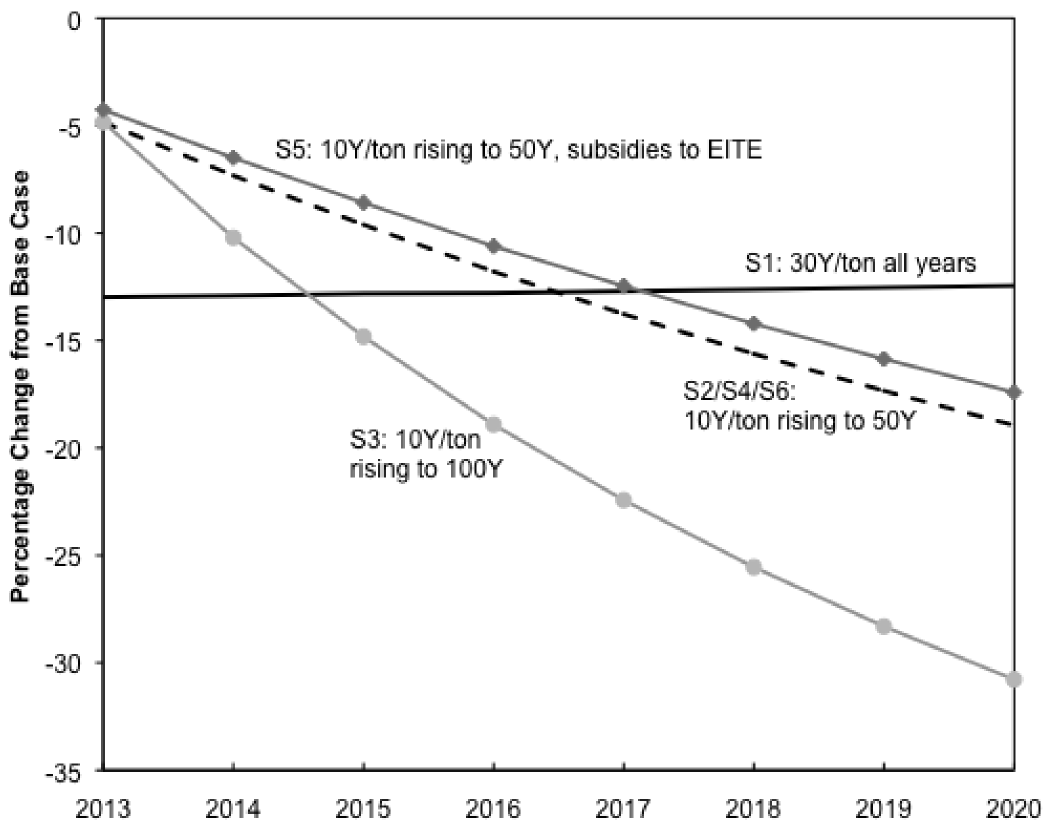


Figure 3. Change in CO_2 emissions due to different carbon tax options, compared to the



base case

Note: F2 (lump sum rebate), F4 (tax cut offset), and F6 (multilateral tax) have the same tax rate profile and nearly identical emission paths. F5 (subsidies to EITE) has the same tax rate profile as F2/F4/F6, but a somewhat different emission path.

Figure 4. Cumulative 2013-2020 CO_2 emissions for different carbon tax scenarios

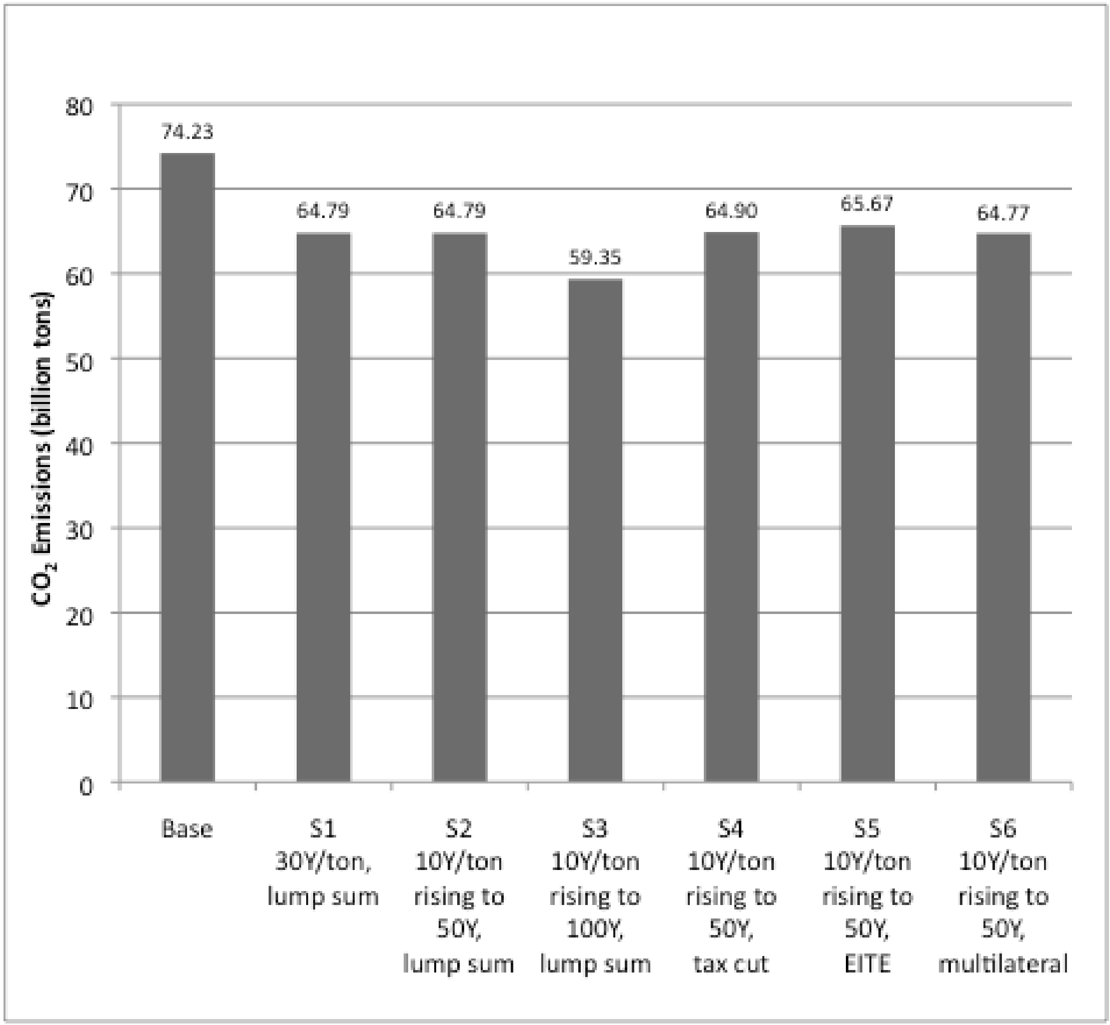
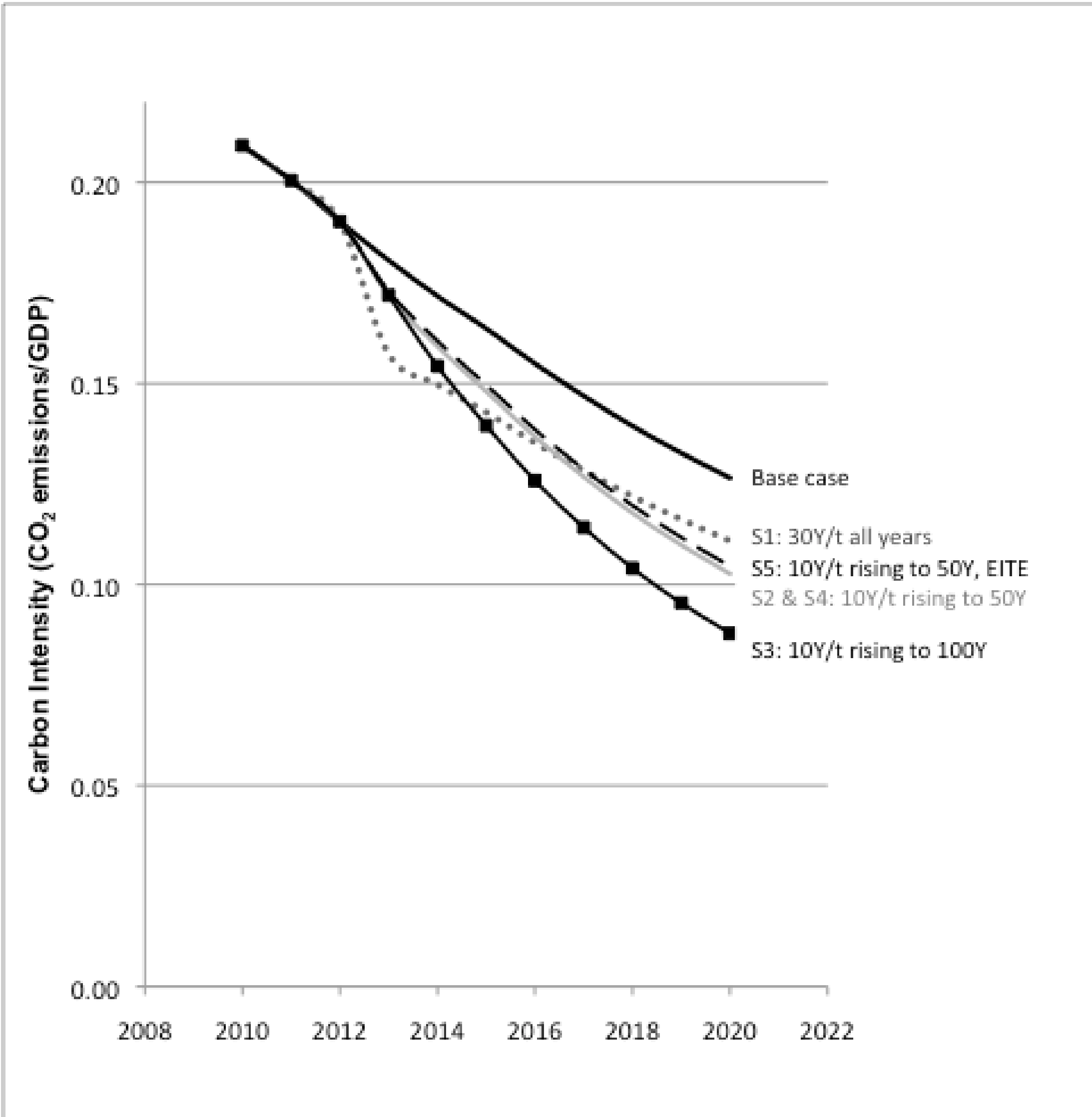


Figure 5. Fossil fuel carbon intensities of the base case and carbon tax scenarios



Note: Carbon intensity here is defined as the emissions of CO_2 from fossil fuel combustion per unit of GDP. The carbon intensities of F2 (lump sum rebate) and F4 (tax cut offset) are indistinguishable, because the effects of the policies on both emissions and GDP are very similar.

Figure 6. Change in GDP, consumption, and investment due to a rising carbon tax (Scenario F2: 10Y/ton rising to 50Y)

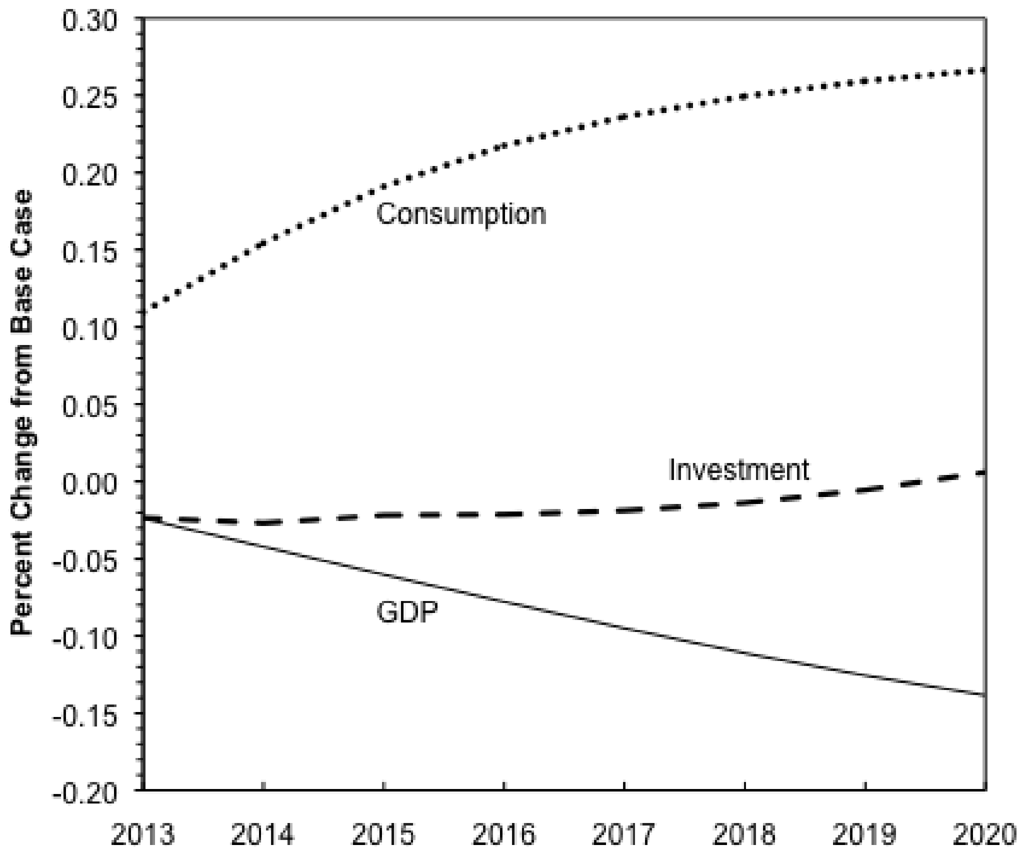


Figure 7. Effect of a carbon tax (Scenario F2) on commodity prices, 2013 and 2020: Top ten percentage changes from base case

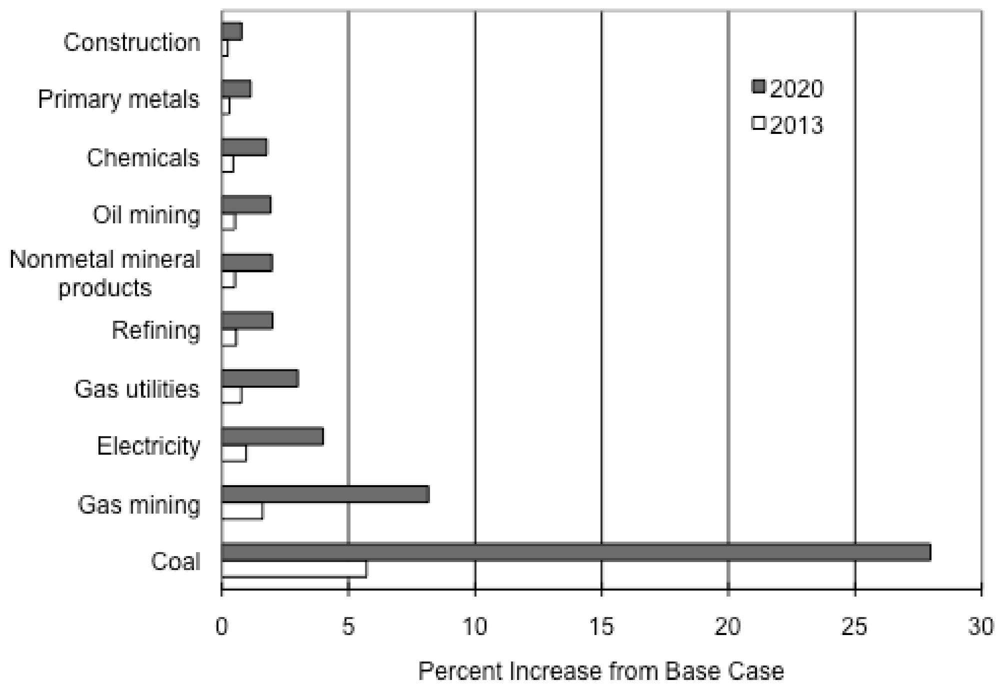


Figure 8. Effect of a carbon tax (Scenario F2) on industry output, 2013 and 2020: Top ten percentage changes from base case

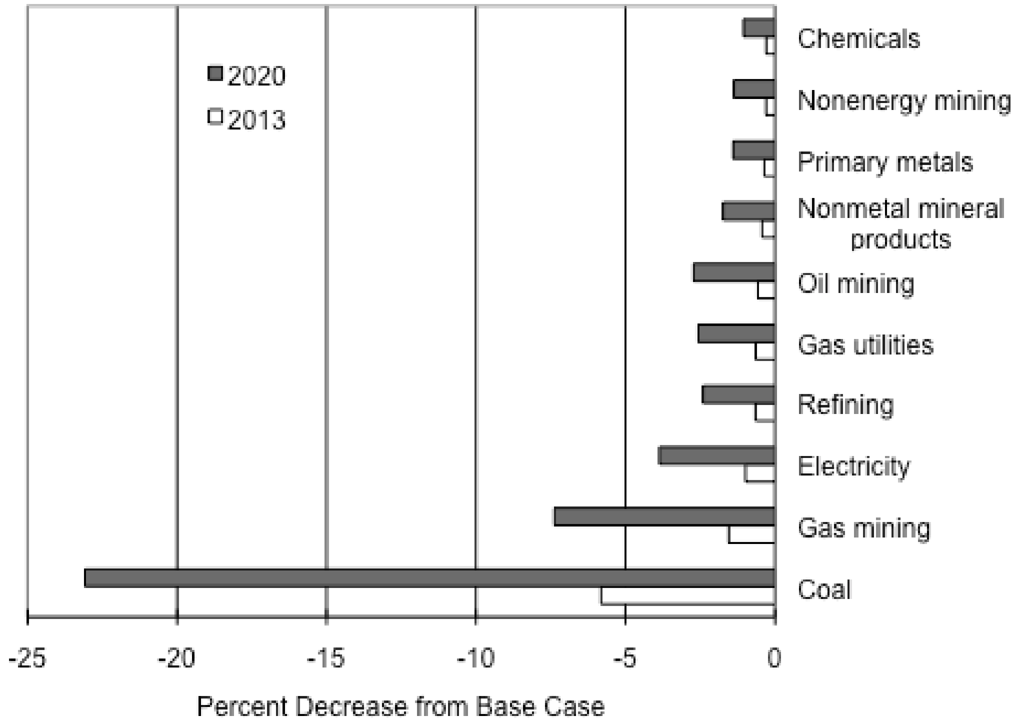
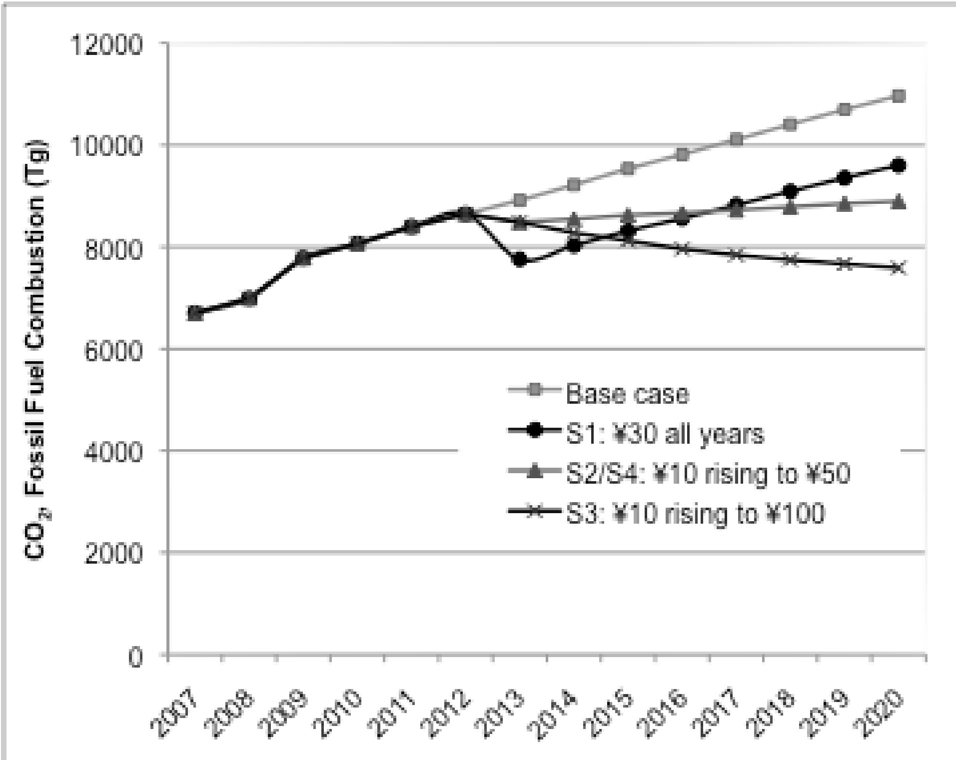
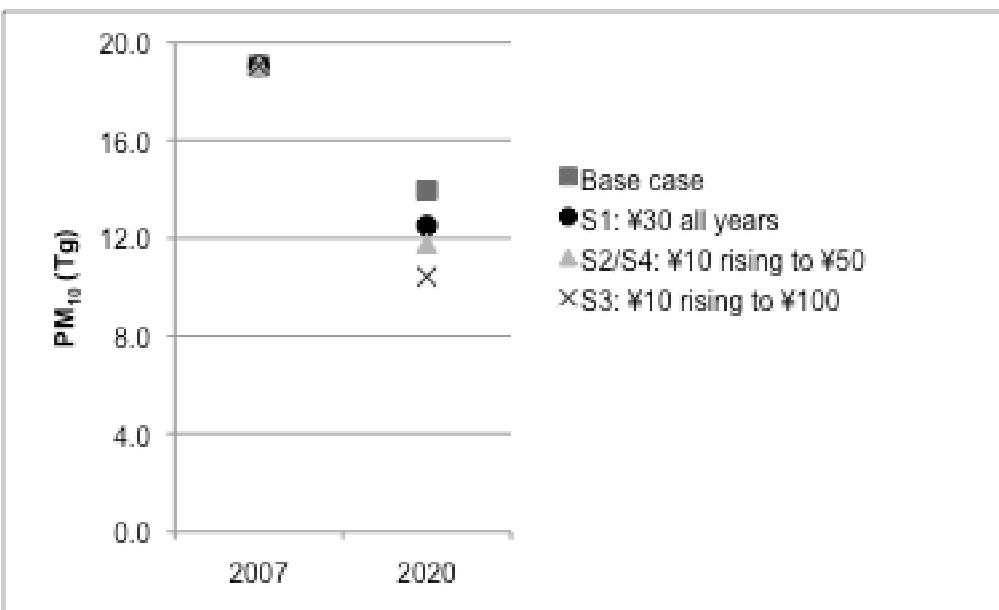


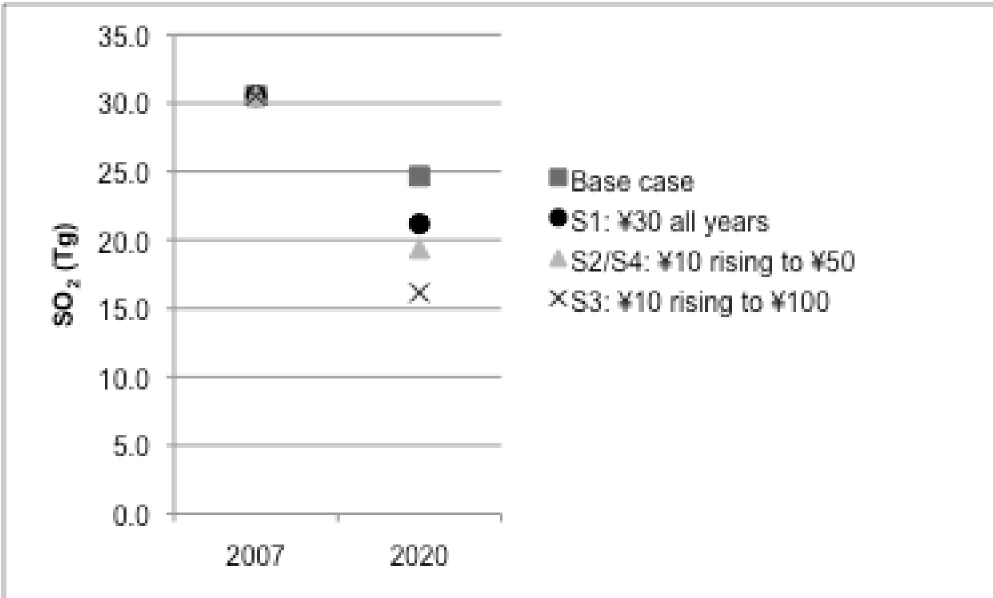
Figure 9. Total estimated emissions of CO_2 and key air pollutants under the base case and Scenarios F1-F4



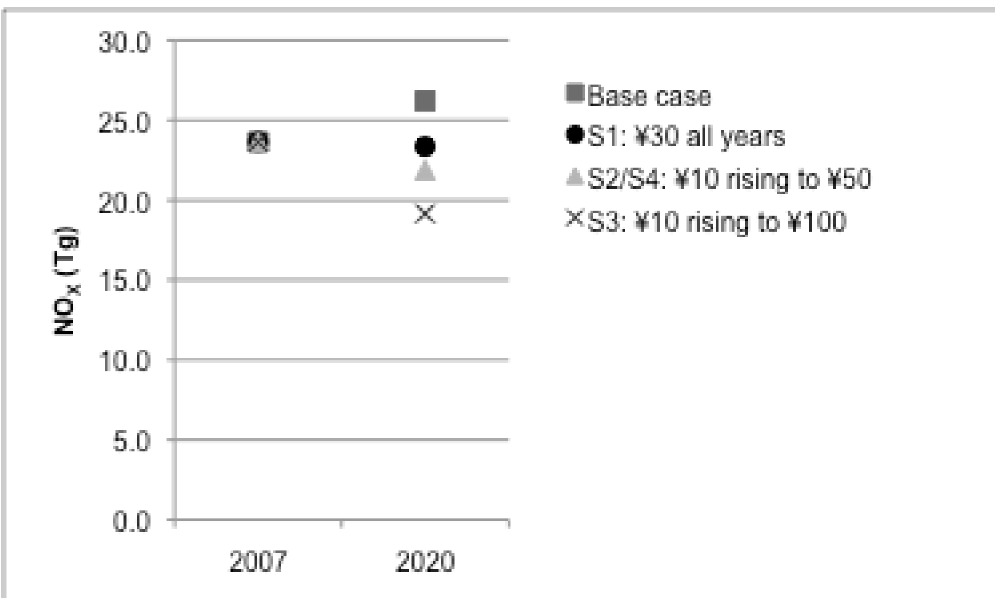
a) CO_2



b) PM_{10}

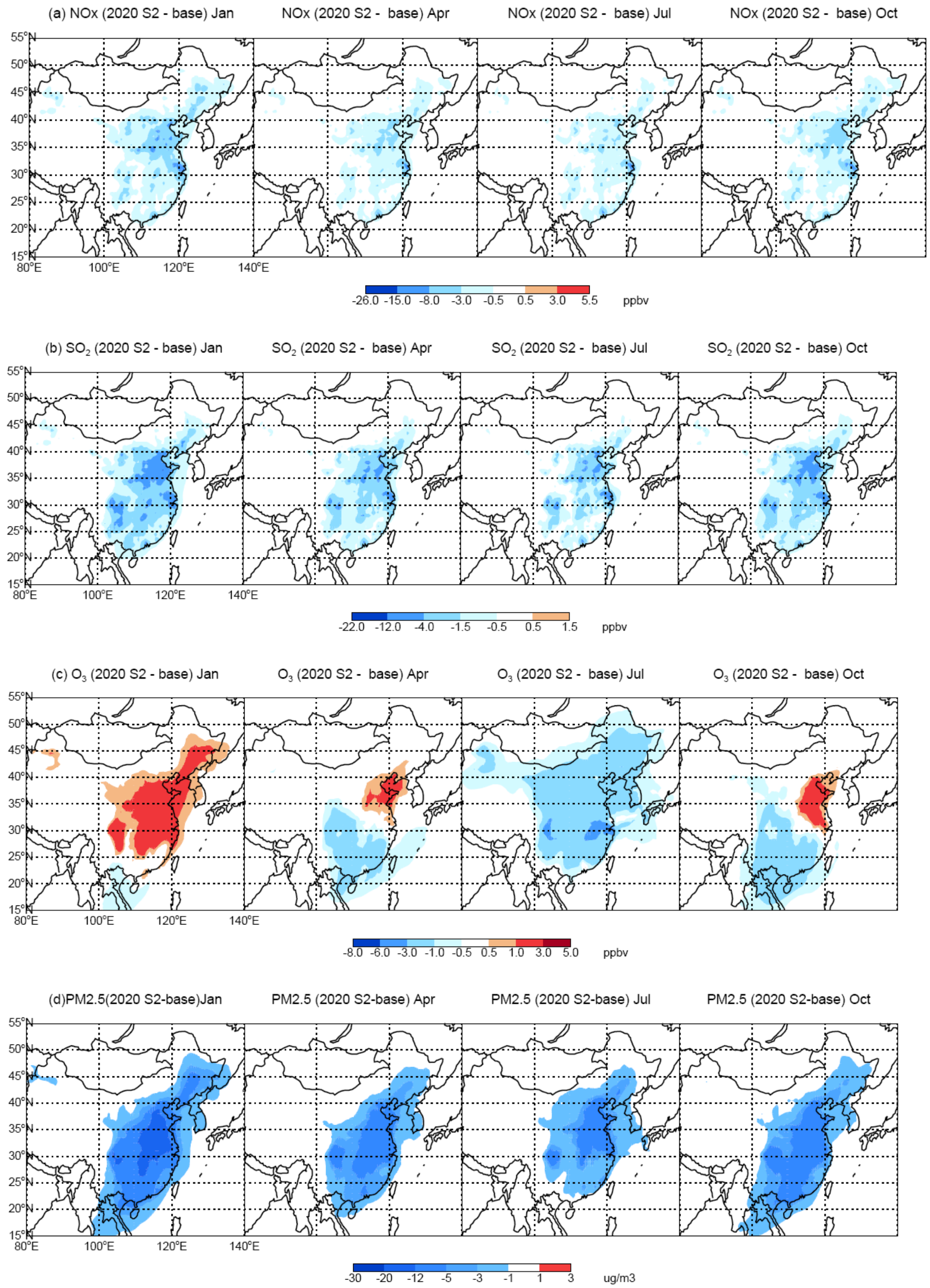

35.0
30.0
25.0
20.0
15.0
10.0
5.0
0.0
SO2 (Tg)
2007
2020
Base case
S1: ¥30 all years
S2/S4: ¥10 rising to ¥50
S3: ¥10 rising to ¥100

c) SO_2


30.0
25.0
20.0
15.0
10.0
5.0
0.0
NOX (Tg)
2007
2020
Base case
S1: ¥30 all years
S2/S4: ¥10 rising to ¥50
S3: ¥10 rising to ¥100

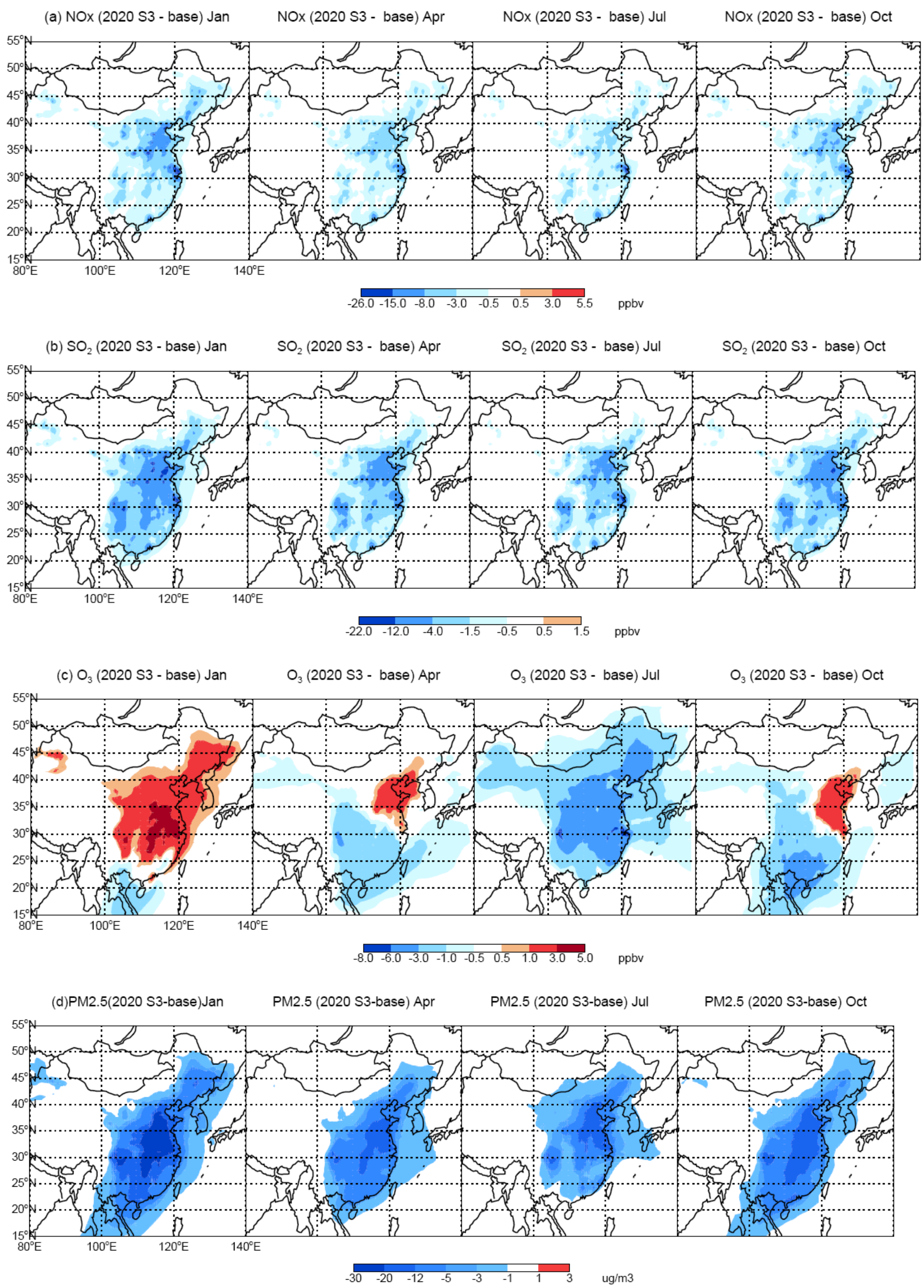
d) NO_X

Figure 10. Simulated changes in surface concentrations of air pollutants due to carbon tax Scenarios F2 and F4



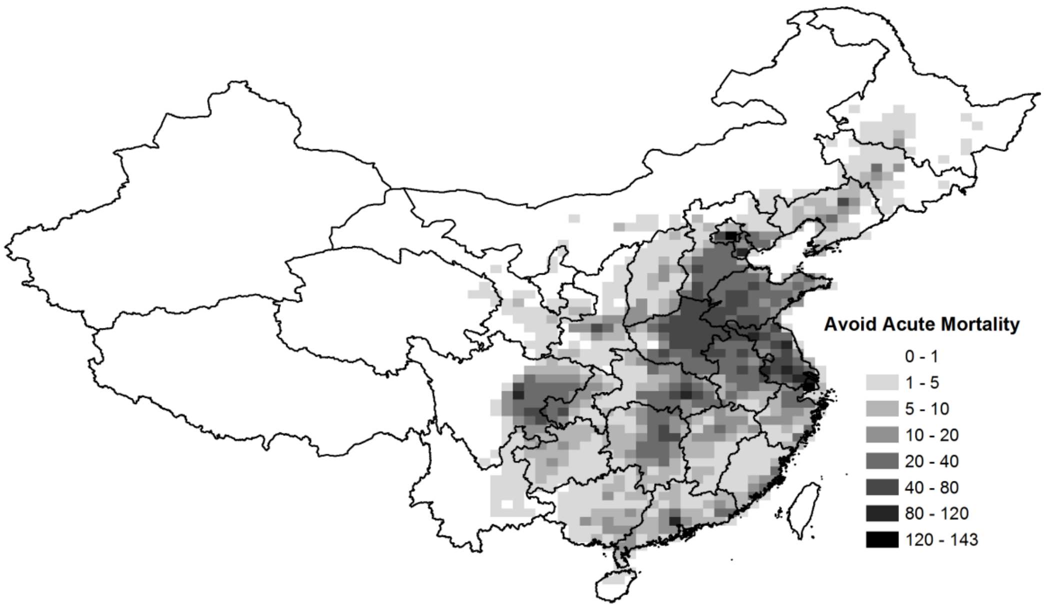
Note: Concentrations in 2020 of (a) NO_x, (b) SO_2, (c) O_3 in ppbv and (d) $PM_{2.5}$ in $\mu g/m^3$, resulting from Scenarios F2 or F4 versus the base case, in January, April, July, and October. Negative values are reductions.

Figure 11. Simulated changes in surface concentrations of air pollutants due to carbon tax Scenario F3

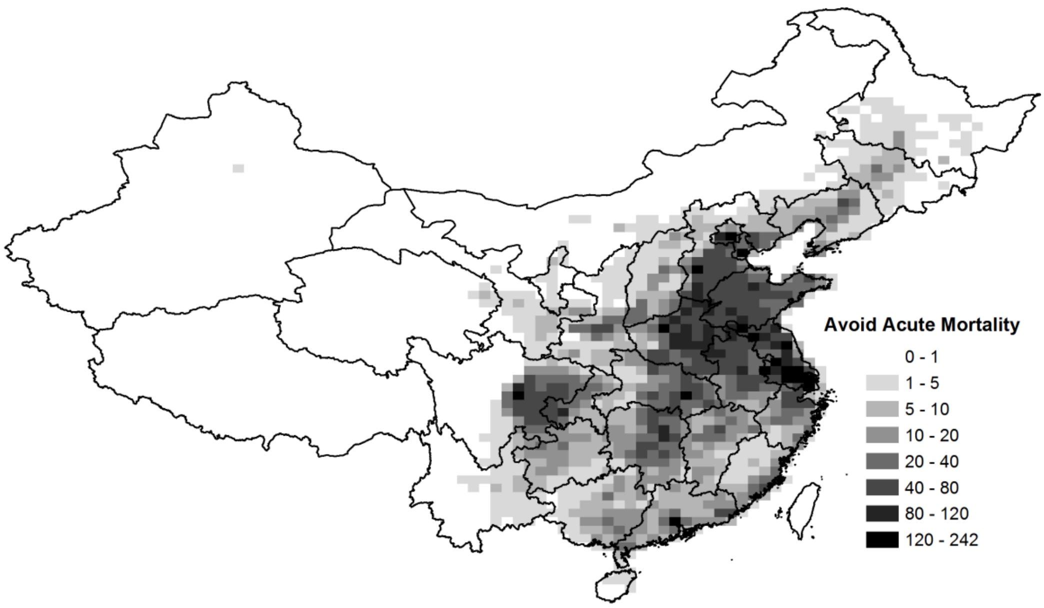


Note: Concentrations in 2020 of (a) NO_x, (b) SO_2, (c) O_3 in ppbv, and (d) $PM_{2.5}$ in μg/m^3, resulting from Scenario F3 versus the base case, in January, April, July, and October. Negative values are reductions.

Figure 12. Cases of acute mortality avoided from changes in $PM_{2.5}$ exposure under F2/F4 and F3 compared to the base case

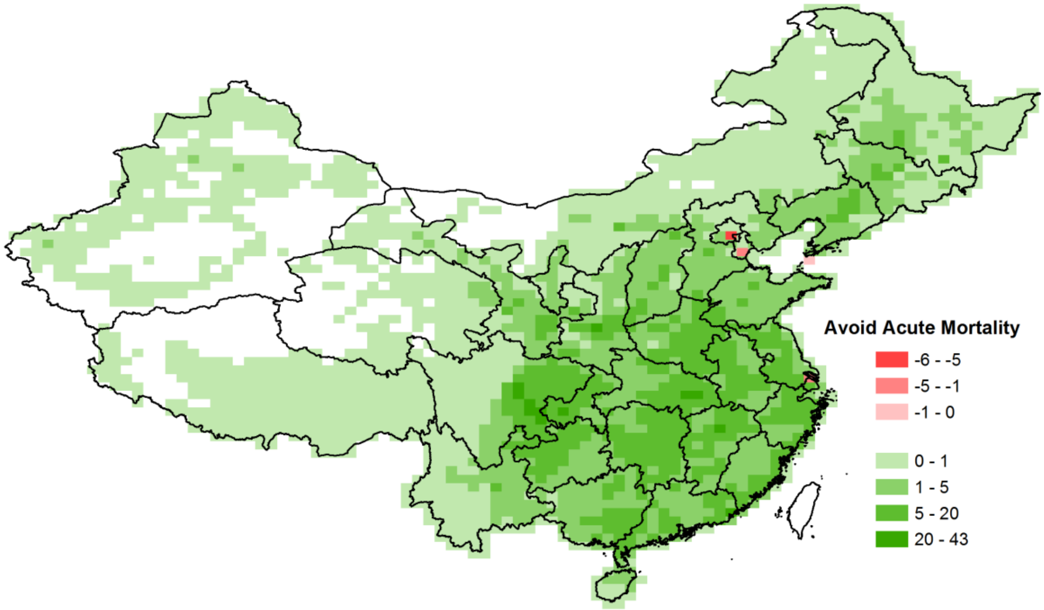


a) Scenarios F2/F4

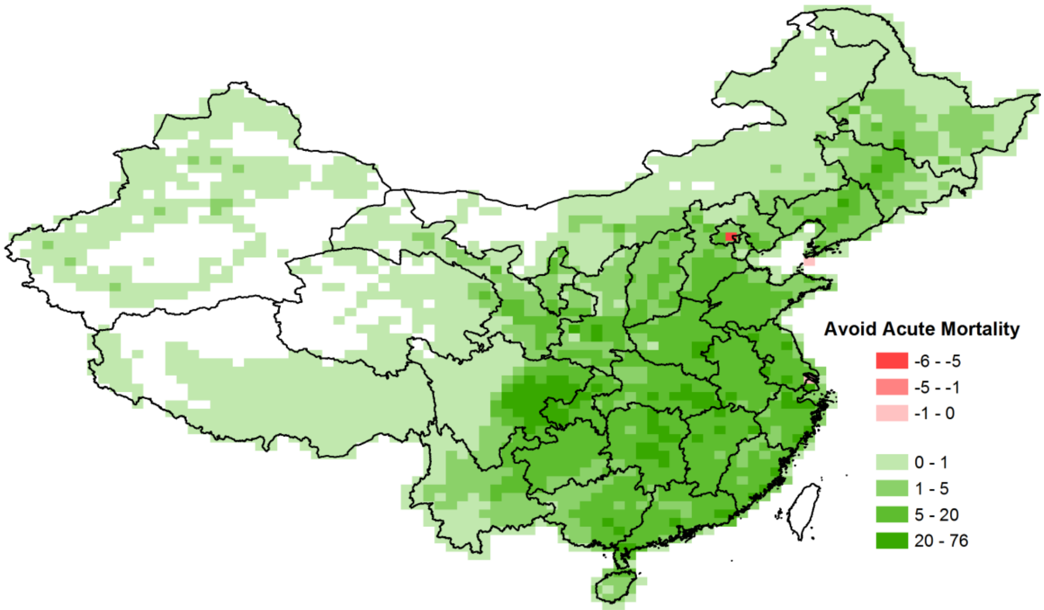


b) Scenario F3

Figure 13. Cases of acute mortality avoided from changes in $PM_{2.5}$ exposure under F2/F4 and F3 compared to the base case

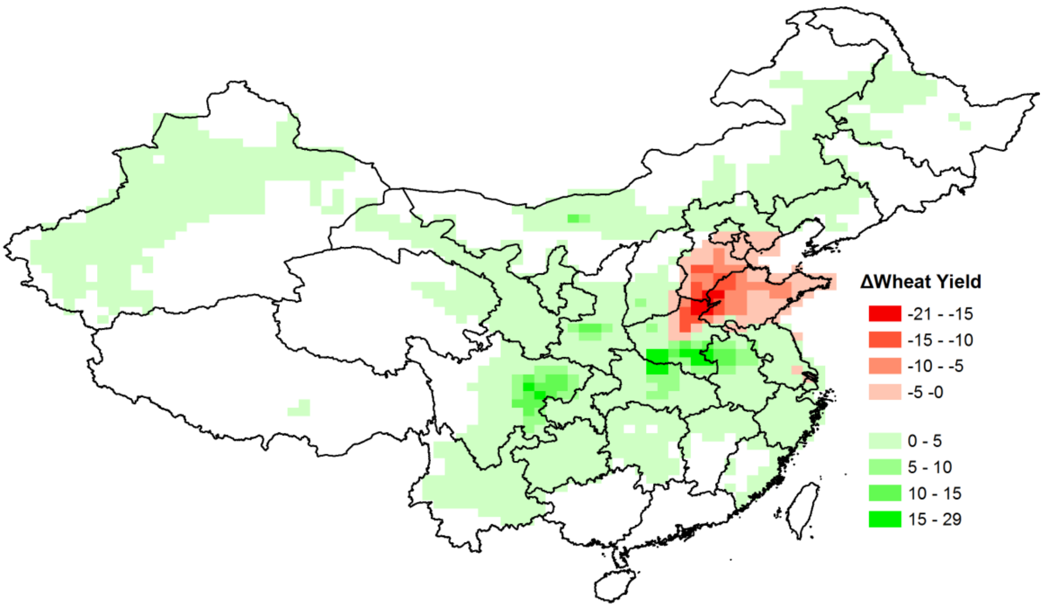


a) Scenarios F2/F4

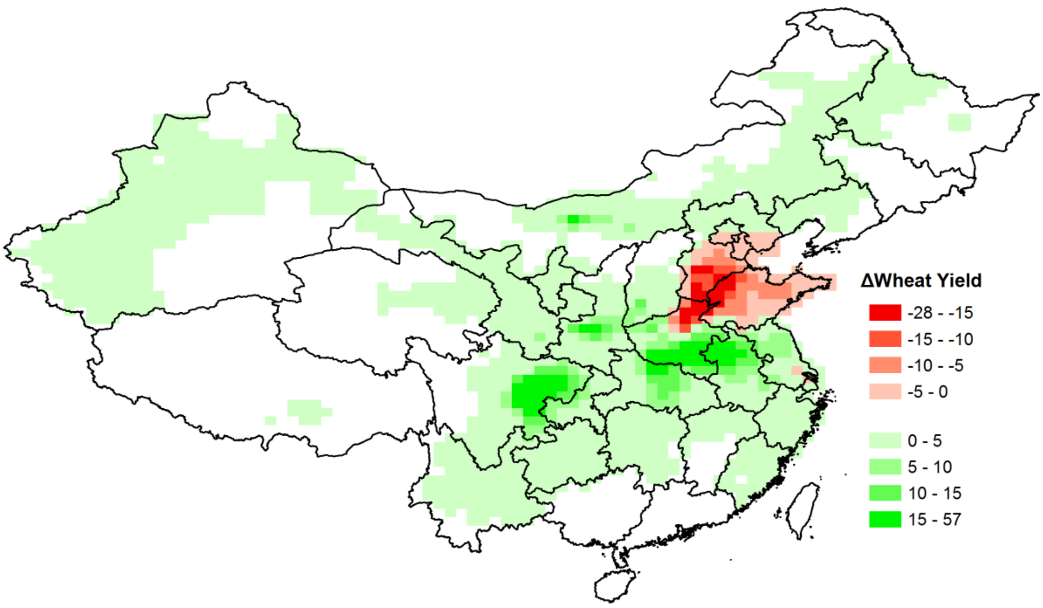


b) Scenario F3

Figure 14. Changes of wheat yields due to F2/F4 and F3 compared to the base case (in metric tons)



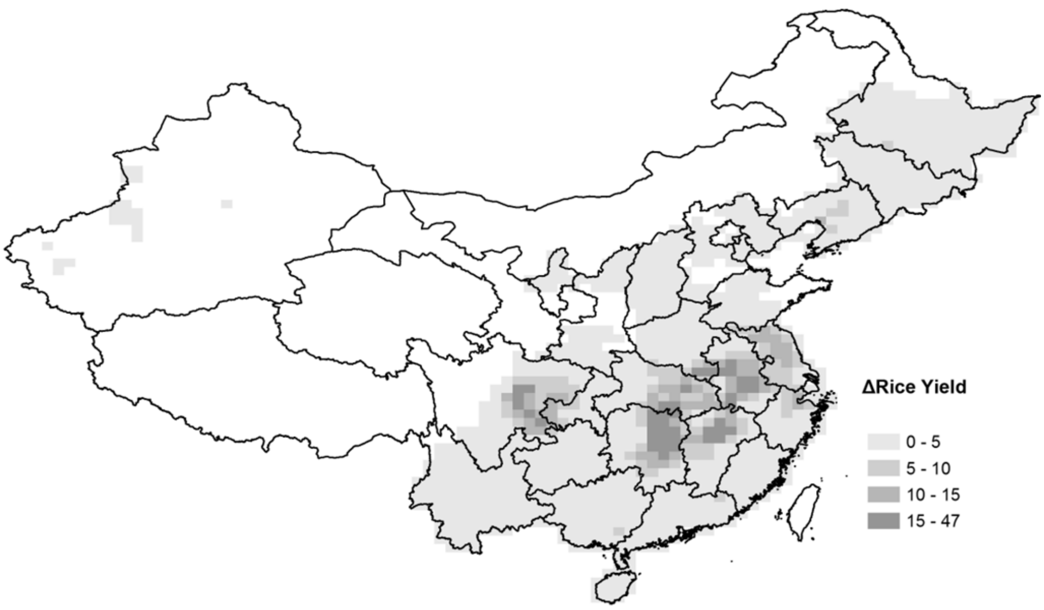
a) Scenarios F2/F4



b) Scenario F3

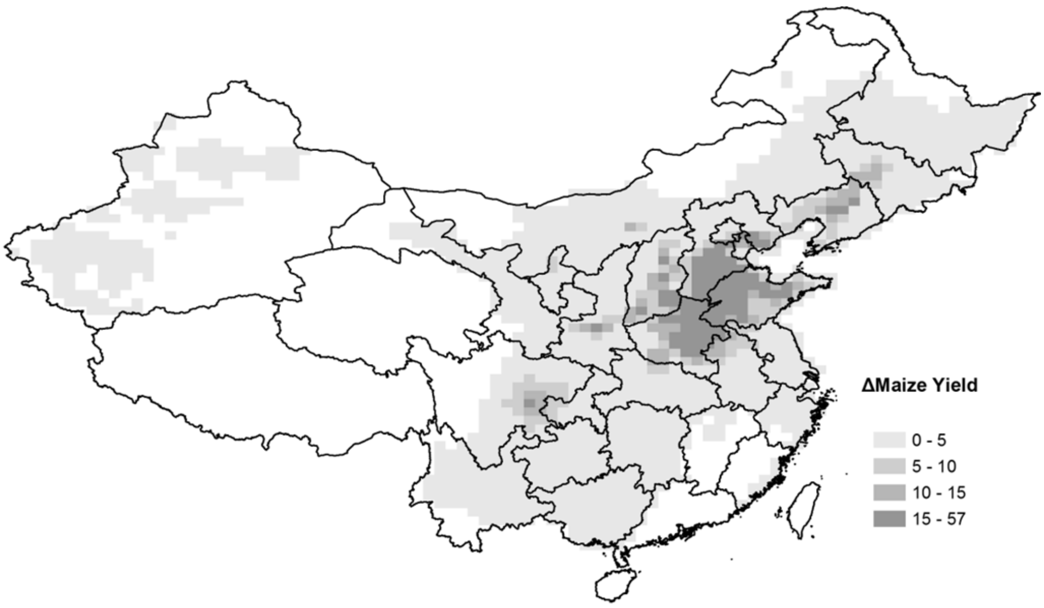
Figure 15. Changes of rice yields due to F2/F4 and F3 compared to the base case (in metric tons)

a) Scenarios F2/F4

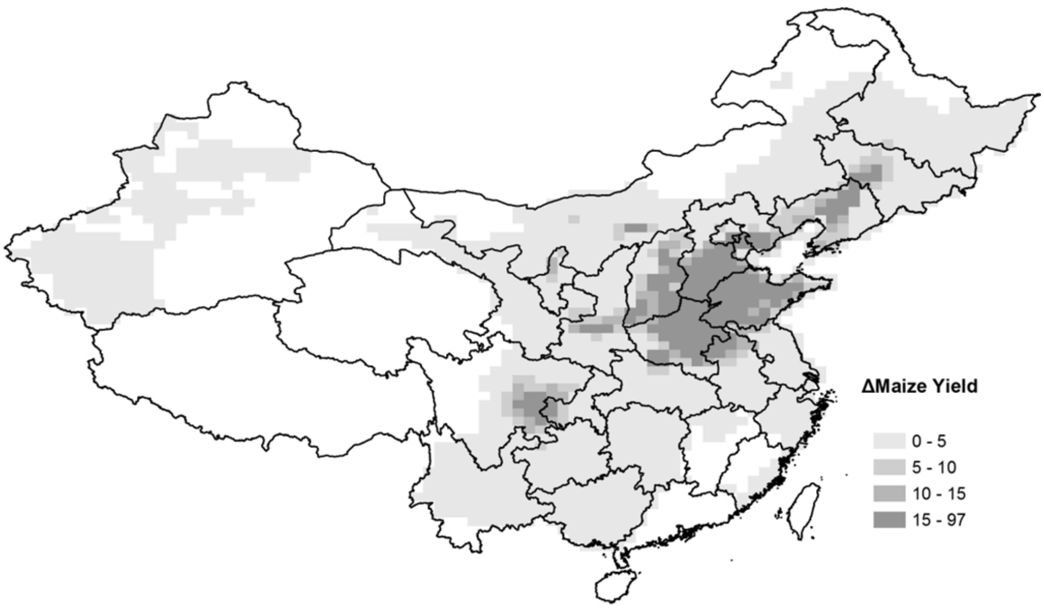


b) Scenario F3

Figure 16. Changes of maize yields due to F2/F4 and F3 compared to the base case (in metric tons)

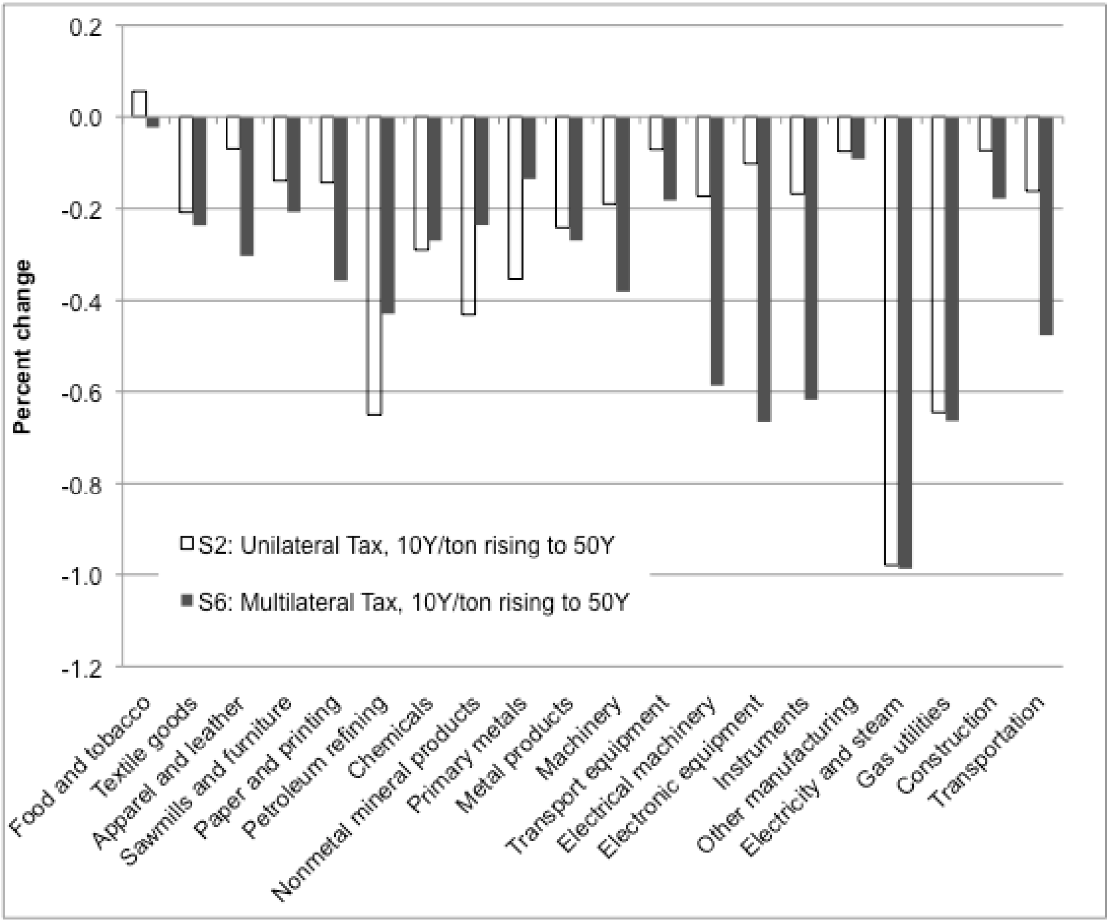


a) Scenarios F2/F4



b) Scenario F3

Figure 17. Changes in industry output, under a unilateral and multilateral carbon tax (F2 vs. F6)



References

Abboud, L. 2008. Economist strikes gold in climate-change fight: Pollution market seen as test for U.S.; one 'surreal' fall. March 13. *Wall Street Journal*, p. A1.

Adkins, L., R. Garbaccio, M. Ho, E. Moore and R. Morgenstern. 2010. The Impact on U.S. Industries of Carbon Prices with Output-Based Rebates over Multiple Time Frames. Resources for the Future, Discussion Paper 10-27, December.

Aldy, J., A. J. Krupnick, R. G. Newell, I. Parry, and W. A. Pizer. 2010. Designing climate mitigation policy. *Journal of Economic Literature* 48(4):203–234.

Bovenberg, A. L. 1999. Green tax reforms and the double dividend: An updated reader's guide. *International Tax and Public Finance* 6(3):421–443.

CDIAC (Carbon Dioxide Information Analysis Center). 2010. People's Republic of China fossil-fuel CO2 emissions. Available at http://cdiac.ornl.gov/ftp/trends/emissions/prc.dat, last accessed February 13, 2012.

EIA (Energy Information Administration). 2009. *Annual Energy Outlook 2010.* December.

Fischer, C., and A. K. Fox. 2011. The Role of Trade and Competitiveness Measures in US Climate Policy. *American Economic Review* 101(3):258–262.

Gronewold, N., and J. J. Fialka. 2011. European Commission halts transfers of carbon emissions allowances until thefts are sorted out. January 20. *ClimateWire*/*New York Times.* Available at http://www.nytimes.com/cwire/2011/01/20/20climatewire-european-commission-halts-transfers-of-carbo-22394.html, last accessed on January 23, 2012.

IEA (International Energy Agency). 2010. *World Energy Outlook 2010.* Paris.

Inman, P., and T. Webb. 2011. Seven charged in carbon trading VAT fraud case. January 26. *The Guardian*. Available at http://www.guardian.co.uk/business/2010/jan/11/eu-carbon-trading-carousel-fraud, last accessed on January 23, 2012.

Lei, Y., Q. Zhang, C. P. Nielsen, and K. B. He. 2011. An inventory of primary air pollutants and CO_2 emissions from cement production in China, 1990–2020.

Atmospheric Environment 45(1):147–154.

Liang, Q.-M., Y. Fan, and Y.-M. Wei. 2007. Carbon taxation policy in China: How to protect energy and trade-intensive sectors? *Journal of Policy Modeling* 29:311–333.

Lu, C. Y., Q. Tong, and X. M. Liu. 2010. The impacts of carbon tax and complementary policies on Chinese economy. *Energy Policy* 38:7278–7285.

NBS (National Bureau of Statistics). 2009. *Input-Output Tables of China 2007*. Beijing: China Statistics Press.

NBS and MEP (National Bureau of Statistics and Ministry of Environmental Protection). 2010. *China Statistical Yearbook on Environment*. Beijing: China Statistical Press.

Newell, R., and W. Pizer. 2003. Regulating stock externalities under uncertainty. *Journal of Environmental Economics and Management* 45(2, Suppl.): 416–432.

Nordhaus, W. 2010. Carbon Taxes to Move towards Fiscal Sustainability. *The Economists' Voice* 7(3):1–5.

Parry, I., L. Goulder, and R. Williams. 1999. When can carbon abatement policies increase welfare? The fundamental role of distorted factor markets. *Journal of Environmental Economics and Management* 37:52–84.

Su, M., Z. H. Fu, W. Xu, Z. G. Wang, X. Li, and Q. Liang. 2009. Study on levying a carbon tax in China. Research Institute for Fiscal Science, Ministry of Finance, Beijing. In Chinese.

U.S. EPA (Environmental Protection Agency). 2009. *EPA Preliminary Analysis of the Waxman-Markey Discussion Draft: The American Clean Energy and Security Act of 2009 in the 111th Congress.* 20 April. Available at http://www.epa.gov/climatechange/economics/pdfs/WM-Analysis.pdf, last accessed on February 6, 2012.

———. 2010. *EPA Analysis of the American Power Act in the 111th Congress.* June. Available at http://www.epa.gov/climatechange/economics/economicanalyses.html, last accessed on December 20, 2011.

Wang, X., J. F. Li, and Y. X. Zhang. 2011. An analysis on the short-term sectoral competitiveness impact of carbon tax in China. *Energy Policy* 39:4144–4152.

Wei, T. 2012. Officials weighing green benefits of carbon taxation. January 6. *China Daily*. Available at www.chinadaily.com.cn/bizchina/2012-01/06/content_14391943.htm, last accessed on January 22, 2012.

Xinhua News Agency. 2012. China eyes nationwide emission trading programs in 2016–2020: Official. December 6. *Xinhuanet*. Available at http://news.xinhuanet.com/english/china/2012-12/06/c_132024197.htm, last accessed on December 8, 2012.

Yi, W.-J., L.-L. Zou, J. Guo, K. Wang, and Y.-M. Wei. 2011. How can China reach its CO_2 intensity reduction targets by 2020? A regional allocation based on equity and development. *Energy Policy* 39:2407–2415.

Zhao, Y., C. P. Nielsen, and M. B. McElroy. 2012. China's CO_2 emissions estimated from the bottom up: Recent trends, spatial distributions, and quantification of uncertainties. *Atmospheric Environment* 59:214–223.