Volume Title: The Design and Implementation of U.S. Climate Policy

Volume Author/Editor: Don Fullerton and Catherine Wolfram, editors

Volume Publisher: University of Chicago Press

Volume ISBN: 0-226-36914-0; 978-0-226-26914-6

Volume URL: http://www.nber.org/books/full10-1

Conference Date: May 13-14, 2010

Publication Date: September 2012

Chapter Title: Markets for Anthropogenic Carbon within the Larger Carbon Cycle

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Chapter URL: http://www.nber.org/chapters/c12158

Chapter pages in book: (p. 93 - 102)

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Markets for Anthropogenic Carbon within the Larger Carbon Cycle

Severin Borenstein

6.1 Introduction

Among climate scientists, there is a strong consensus that carbon emissions from human activity are increasing atmospheric CO_2 concentration and causing climate change. Among economists, there is a strong consensus that the most efficient way to reduce such anthropogenic greenhouse gas emissions is to price them, through either a tax or a tradable permit system. The CO_2 emissions from burning fossil fuels and deforestation, however, are small compared to the earth's natural carbon flux. These human activities produce about nine gigatons of carbon (GtC) emissions per year against the natural carbon flux backdrop—emission and uptake—of about 210 GtC per year, to and from oceans, vegetation, soils, and the atmosphere. Human activities, however, affect the natural carbon cycle in many ways that have not been incorporated in plans for pricing greenhouse gas emissions. This in no way suggests that human activity is not the primary cause of climate change, but it does suggest that establishing markets and property rights to control these emissions may be more challenging than standard models for tradable pollution permits imply.

In this chapter, I explore the implications for pricing carbon emissions

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My thanks to Max Auffhammer, Jim Bushnell, Lucas Davis, Meredith Fowlie, Don Fullerton, Richard Muller, Wolfram Schlenker, and Catherine Wolfram for helpful comments and discussions. I am particularly grateful to Margaret Torn for taking the time to explain to me some of the science of the carbon cycle. Any remaining errors are my responsibility alone. For acknowledgments, sources of research support, and disclosure of the author's material financial relationships, if any, please see http://www.nber.org/chapters/c12158.ack.

when human impacts on the natural carbon cycle are numerous, heterogeneous, and likely to be quantitatively significant beyond the direct greenhouse gas emissions from fossil fuel combustion and deforestation. Because the natural carbon flux between oceans, vegetation, soils, and the atmosphere is so large, even small anthropogenic perturbations in it can significantly alter the impact of human activity on climate. Nearly all of the available economic analysis has treated anthropogenic emissions as a separate and measurable process distinct from the natural carbon cycle. Under certain conditions, this may be a valid approach, but climate science suggests that these condition do not hold and may not even be a good approximation. Thus, it is useful to consider more explicitly the interaction between human activity and the natural carbon cycle, as well as implications for the appropriate boundaries of a market for greenhouse gas emissions.

6.2 A Very Brief Review of the Carbon Cycle

Prior to the mid-nineteenth century when large-scale anthropogenic CO_2 emissions began, the oceans, vegetation, and soils are estimated to have released about 210 GtC of carbon into the atmosphere in the form of CO_2 every year and absorbed the same amount on average. About 90 GtC was transferred to/from the ocean and 120 GtC is transfered to/from vegetation and soils.[1] Atmospheric levels of CO_2 remained in the range of 260 to 280 parts per million (ppm), equivalent to approximately 550 to 590 GtC in the atmosphere.[2]

Nearly all of these natural processes, however, are affected by changes in atmospheric carbon and the climate. For instance, increases in atmospheric CO_2 cause plants to grow faster and absorb more carbon, and cause ocean uptake of carbon to increase; higher average temperatures and other changes in climate alter the rate at which plants decompose and release CO_2; and changes in ocean temperature affect its uptake of carbon. Prior to the fossil fuels era, this seems to have been part of the natural resilience of the biosphere that maintained fairly stable atmospheric CO_2 concentrations for millenia.

Since the mid-nineteenth century, direct anthropogenic impact on the carbon cycle has steadily increased, primarily through fossil fuel combustion—averaging about 7.6 GtC per year during 2000 to 2006—but also through human-caused deforestation and changes in land use—estimated to be about 1.5 GtC per year during 2000 to 2006.[3] The deforestation and

1. My characterization of the carbon cycle is based on Houghton (2007), Canadell, Le Quère et al. (2007), and Sarmiento and Gruber (2002).

2. If it were absorbed entirely into the atmosphere, one GtC would raise the atmospheric level of CO_2 by slightly less than 0.5 ppm.

3. See Canadell, Le Quère et al. (2007), table 1. The CO_2 release attributed to fossil fuels includes the release from heating calcium carbonate in cement production. Non-CO_2 forms of

land-use change impacts are known with considerable less certainty than fossil fuel combustion, because the full process of carbon flux between vegetation/soils and the atmosphere is not understood nearly as well as the combustion of oil, coal, and natural gas.

Anthropogenic carbon emission must go somewhere. About 45 percent shows up as an increase in atmospheric concentration of CO_2. Scientists are confident that the residual carbon ends up in vegetation, soils, and the ocean, but attempts to measure these changes directly are imperfect. Carbon is mixed much less uniformly in the ocean than in the atmosphere, so its concentration is more difficult to measure. Concentration in vegetation and soils varies even more and is an even greater measurement challenge. The best estimates are based on widespread sampling of ocean waters to estimate ocean uptake, then attributing the residual to vegetation and soils. This approach suggests that ocean uptake accounts for about 24 percent of anthropogenic carbon emissions and 30 percent goes to vegetation and soils. However, the processes of ocean and vegetation/soils carbon uptake are not well understood. Estimates of these components—often referred to as the "residual flux," or, somewhat less accurately, the "unidentified sink"—total about five GtC per year.

Figure 6.1 is a simplified representation of the carbon cycle from the US Department of Energy, with estimates of the anthropogenic carbon emissions and terrestrial and ocean uptake updated, based on figures from Canadell, Le Quère et al. (2007) (in white boxes). While there is some disagreement about the estimates of carbon uptake of vegetation, soils, and the ocean, there is widespread agreement that these have been large net carbon sinks over the last two centuries, offsetting a considerable share of the direct anthropogenic carbon emissions.

There is some evidence that the carbon uptake share of nonatmospheric sinks is declining over time, but a larger proportion is remaining in the atmosphere.[4] This suggests that the nonatmospheric sinks, both identified and unidentified, may have started to become saturated. To date, climate change models have handled ocean and terrestrial sinks fairly mechanically, assuming that they will continue to absorb about the same share of anthropogenic carbon as has been estimated from residual sink calculations for recent years, or assuming that the share will change in some gradual and linear way. This is a source of significant uncertainty because both the carbon uptake capacities of these sinks and the impact of human activities on their capacities are not well understood.

carbon in the atmosphere, such as methane, play a significant role in climate change, but are a very small fraction of the carbon cycle. Atmospheric concentration of methane is approximately 1.8 ppm.

4. See Le Quère et al. (2009).

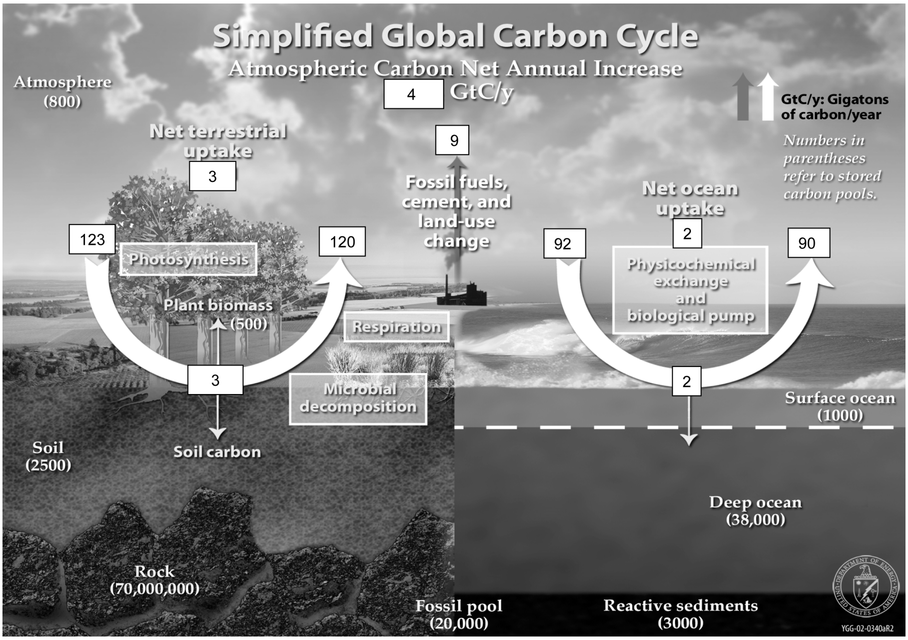

Fig. 6.1 Simplified global carbon cycle
Source: US Department of Energy and Canadell, Le Quère et al. (2007).

6.3 Markets for Carbon Emissions

If the human contribution to atmospheric CO_2 were completely distinct from the natural carbon cycle, setting and enforcing a cap on CO_2 released from fossil fuel combustion and deforestation would obviously address the carbon cycle imbalance. In that case, reduction of CO_2 emissions would translate one-for-one to reductions in atmospheric CO_2. From the description of the carbon cycle in the previous section, however, it is clear that this is not at all an accurate representation of the anthropogenic impact.

Apart from burning fossil fuels, most human activity that releases greenhouse gases is interacting with the natural carbon cycle on a short time scale. Cutting a virgin forest likely causes the trees to decompose and release carbon more quickly than would have occurred absent human interaction, in years rather than decades. Human-caused forest fires do so even faster. Agriculture raises many of the same issues, as tilling and crop management alters the soil release and uptake of CO_2. Livestock cultivation by humans also disrupts CO_2 uptake of soils and vegetation, as well as directly contributing significant quantities of methane. Nitrogen fertilizer, both at the location it is applied by humans and after it migrates through soils and water, interacts with CO_2 in complex ways to affect the growth of vegetation and its properties as a carbon sink.[5] Atmospheric anthropogenic nitrogen also seems likely to be significantly altering the carbon uptake of oceans as well as increasing emissions of nitrous oxide, potentially reducing the net carbon sink impact of oceans by more than half.[6] Man-made local air pollutants also interact with the natural carbon cycle: tropospheric ozone, a local pollutant created by the chemical interaction of man-made emissions and sunlight, disrupts the carbon sink effect of forests and other vegetation.[7]

Proposals for market mechanisms to control CO_2 emissions include restrictions on combustion of all types of fossil fuels, though usually with significant geographic and sectoral limits. Some proposals include limited applications to forestry and agriculture. Through offset programs, inclusion of some additional agriculture and livestock cultivation is often suggested, though it has played an extremely small role in the Clean Development Mechanism.[8] The impacts of nitrogen fertilization on vegetation, soils, and ocean uptake is invariably excluded, as is the impact of local air pollution. Many other ways in which human behavior impacts the natural carbon cycle to exacerbate or reduce atmospheric concentration of CO_2 are excluded from the functioning and proposed market mechanisms. The omissions are not because these are understood to be small factors. Some are estimated to be large, though none is estimated very precisely.

6.3.1 Climate Feedback Effects Are a Special Case of Interaction with the Natural Carbon Cycle

Market mechanisms do not explicitly incorporate aggregate interaction effects, known as feedback effects, in which the total planetary anthropogenic release of greenhouse gases causes changes in the nonanthropogenic carbon flux. Such effects are a function of aggregate anthropogenic emissions because CO_2 and other greenhouse gases mix nearly uniformly around the earth's atmosphere: increased atmospheric CO_2 concentration causes an increase in the carbon uptake of oceans, vegetation, and soils; it contributes directly to higher average temperatures and faster decomposing of dead vegetation, which releases more greenhouse gases; higher average temperatures cause faster melting of ice sheets, which then releases methane and also reduces the albedo of the earth. Warming also increases water evaporation and the concentration of atmospheric water vapor, which magnifies the greenhouse effect. Climate scientists attempt to account for these effects in modeling the relationship between atmospheric greenhouse gases and global temperature changes.

Conceptually these aggregate interactions are straightforward to handle within a market mechanism, though practical application faces substan-

5. See Reay et al. (2008).
6. See Duce et al. (2008).
7. See Canadell, Kirschbaumb et al. (2007).
8. See Grubb et al. (2010).

tial uncertainty about the magnitude of their climate impact. If the goal is to stabilize atmospheric carbon at a certain level, aggregate interaction effects would be incorporated into a cap-and-trade program by changing the total direct anthropogenic carbon emissions. The net effect of all aggregate interaction effects would determine a scale parameter, θ, that would change the cap on direct anthropogenic carbon emissions so as to meet the same level of atmospheric carbon as would be the target if $\theta = 1$ and there were no interaction effects. A $\theta < 1$ would indicate that the natural carbon cycle damps anthropogenic shocks, a net negative feedback effect, and a $\theta > 1$ would indicate that it exacerbates the shocks, a net positive feedback effect. The fact that about half of anthropogenic carbon is being absorbed by vegetation, soils, and the ocean suggests a θ well below one, but acceleration of vegetation decomposing and ice melting indicates the opposite. More importantly, a great deal of uncertainty remains about the longer run θ, though it seems likely to rise if the terrestrial and ocean sinks are becoming saturated and/or melting ice might accelerate the release of greenhouse gases and change the planet's albedo. Nonetheless, for any scientific model of these aggregate interaction effects, the cap on anthropogenic emissions can be adjusted in order to achieve (in expectation) any specified target for atmospheric carbon and climate change. Though the potential scientific impact of feedback effects is quite worrisome, they complicate market mechanisms much less than the idiosyncratic indirect impacts on which I have focused here.

6.4 From Incomplete Science to Incomplete Markets and Property Rights

Market mechanisms to address climate change have been aimed predominantly at reducing the greenhouse gas emissions from burning fossil fuels. Besides the enormous size of the fossil fuels industry, this focus is likely based on the fact that the scientific connection between fossil fuel combustion and greenhouse gas release is well established, and the fact that it is relatively easy to monitor fossil fuel consumption. While it is well understood that human behavior is affecting the natural carbon cycle, those effects are less direct, the relationship is less precisely established, and the emissions are more difficult to monitor. In the last decade, scientists have made important steps in understanding these relationships, but because the impacts are indirect and idiosyncratic it is likely that the links to greenhouse gas emissions will never be understood as precisely as the CO_2 release from burning a gallon of gasoline. For example, the greenhouse gas impact of nitrogen fertilizer appears to depend very much on where it is used, how it is applied, and how much escapes to neighboring soils and water.

Over time, the challenge of establishing scientific causality will transition to a challenge of establishing markets and property rights for the externalities created. Some empowered institution will have to determine a process for price setting and the initial allocation of the property rights. These appear to be particularly challenging tasks in the case of human impacts on the natural carbon cycle.

The heterogeneity and idiosyncrasy of these indirect impacts will pose a challenge for price setting. Of course, many government-regulated markets face a trade-off between precise cost-based pricing of each sale and the expense of implementing complex pricing schemes. The problem is present in congestion pricing of roads, differentiated time and locational impacts of criteria air pollutants, and time and location varying cost of supplying electricity.[9] In nearly all of these cases, prices vary much less than the underlying economic costs, usually based on appeals to equity and/or simplicity.

Such an outcome could be very inefficient in this case. While science does not yet provide complete answers, it seems likely that the variation in impact on the natural carbon cycle could be enormous for seemingly similar human activities. The impact of agricultural activities, for instance, depends not just on soil composition and alternative land use, but also on the quantities of fertilizers used and their ultimate disposition. Likewise, criteria air pollution has very different impacts on the natural carbon cycle depending on where the pollution is released. Due to the interaction with the natural carbon cycle, it seems quite possible that an activity could raise greenhouse gases if undertaken in some locations and lower it if the same activity is undertaken in other locations.

The idiosyncrasy of human impacts on the natural carbon cycle is also likely to greatly increase the complexity of allocating property rights and monitoring outcomes. Indirect impacts on the natural carbon cycle are likely to be difficult to monitor by their very nature, and large variation in impact from seemingly similar activities will make simplifying approaches less reliable—for example, a standard assumption about the carbon impact of releasing one pound of atmospheric nitrogen. Likewise, because property rights allocation will be concerned with distributional issues, difficulty in determining a participant's probable liability under a proposed price schedule could slow the political process and raise costs.

Scientific uncertainty is also likely to compound the difficulties of reaching agreements on property rights. Previous debates over the costs of environmental degradation—health impacts of criteria air pollutants, ozone depletion caused by chlorofluorocarbons (CFCs), and fossil fuels causing climate change—suggest that potential losers in the allocation of property rights will appeal to residual scientific uncertainty as a reason to postpone creation of the market. Indirect impacts on the natural carbon cycle seem likely to be particularly vulnerable to these delay strategies.[10]

9. See Tietenberg (1995).

10. Recent arguments over life cycle analyses of petroleum products and corn-based ethanol in California, including the impact of indirect land-use changes, are certainly consistent with this view. The parties that would have been harmed by recognizing indirect land-use effects argued that because considerable uncertainty about their magnitude existed, they should be counted as zero.

Ultimately, the value of incorporating human impact on the natural carbon cycle as part of carbon markets also depends on the potential for price incentives to change that interaction. In this dimension, it seems that the value is likely to be high. The human activities that science has already identified—including land management, use of nitrogen fertilizers, and control of criteria air pollutants—are generally thought to be responsive to economic incentives, certainly likely to be as responsive as energy demand. These are empirical questions, however, that remain to be addressed.

6.4.1 Can Carbon Offsets Better Address Interactions with the Natural Carbon Cycle?

The effects that I am discussing here are similar in practice to excluding a sector of the economy, or region of the world, under cap and trade. Carbon offsets are often presented as a way to reduce emissions from an excluded sector or region, as described by Bushnell (chapter 12, this volume). But the political, jurisdictional, and distributional concerns that give rise to sectoral or regional exclusion are not the primary impediments to incorporating interactions with the natural carbon cycle. Rather, uncertain science and costly monitoring of the human behavior that causes the interaction have led to the exclusion of these emissions from market mechanisms. Carbon offsets do not address either of these problems. If these barriers were remediated, policymakers still might run into the concerns that are addressed by carbon offsets depending on the location of the activity and people involved in it. There is, however, no obvious reason to think that the range of human activities that constitute interaction with the natural carbon cycle are more amenable to control through carbon offsets than through direct inclusion in a market mechanism such as cap and trade or a carbon tax.

6.5 Conclusion

Climate scientists have determined that many different human activities impact the levels of atmospheric greenhouse gases, not just burning fossil fuels. Many of these interactions are not well understood, but they are almost surely both heterogeneous and important in addressing climate change. Recent research suggests that human-caused air pollution, fertilizer dispersion, soil disruption, and other activities are having a significant effect on the net carbon uptake of vegetation, soils, and oceans. To date, market mechanisms for reducing greenhouse gases have largely ignored these interactions between human activity and the natural carbon flux.

My goal in this chapter is to argue that the scientific research on these interactions has matured to the point that it is time for economists and policymakers to take note, and to consider whether market mechanisms for greenhouse gases need to be extended to incorporate these complexities. Such extensions would be very challenging. The heterogeneity and idiosyncrasy of human impact on the natural carbon cycle would make appropriate pricing quite difficult, and the remaining scientific uncertainty about these interactions would likely impede efforts to assign property rights. Addressing some interactions would require determining property rights for a much broader range of activities than has ever before existed.

The costs of extending carbon markets in this direction must be weighed against the potential benefits. The benefits will depend on the magnitude of the interaction effects, which is the domain of natural scientists, and the price elasticities of the human activities that cause them, the determination of which should be economists' comparative advantage.

Finally, while I have focused here on market mechanisms—taxes or tradeable permits—the same concerns of heterogeneous and idiosyncratic interactions with the natural carbon cycle would apply to any attempt to address greenhouse gases with command and control regulation. Just as many more prices and property rights determinations are needed in a market setting due to indirect impacts on the natural carbon cycle, many more regulations would be needed under a command and control approach.

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Comment Wolfram Schlenker

The chapter by Severin Borenstein discusses how market-based approaches might have to be adjusted for human activities that impact the carbon flux differently across locations. The question is whether geographic variations in the carbon flux are large enough and measureable enough to usefully employ a spatially varied carbon-pricing scheme. Experience with markets for sulfur-dioxide emissions indicates that pollution-pricing mechanisms can greatly enhance efficiency, even if they do not perfectly account for geographic differences in the marginal costs and benefits of emissions.

Market-Based Regulation

The main appeal of market-based regulations (taxes or permits) is that they minimize abatement cost for a given reduction of pollution. Sulfur-dioxide (SO_2) emissions were subject to a permit trading system in the United States in the 1990s. Stavins (1998) argues that it resulted in annual cost savings of more than $1 billion as firms with the lowest abatement cost reduced SO_2 emissions. It is celebrated as a big success story and has become a benchmark for modern environmental policy.

A tax or permit system can lead to suboptimal outcomes if it interacts with other distortions, or a unit of pollution causes damages depending on where it is emitted. For example, under the NO_x budget program, regulated or publicly owned utilities were more likely to install costly capital equipment (Fowlie 2010). These capital investments generated excess permits that could be sold to firms in deregulated and restructured electricity markets. Since NO_x is a local pollutant, it matters where a unit is emitted. As it turns out, deregulated markets are dirtier to begin with. Permit trading therefore shifted pollution toward areas where a unit of pollution is more damaging.

Market-based regulations have the potential to increase pollution damages if the location of the emission matters (a nonuniformly mixing pollutant). In such a case the tax rate would have to differ between locations, or permits would no longer be traded one-for-one. Instead, differentiated tax and trading ratios incorporate that marginal damages vary between regions.

While CO_2 perfectly mixes in the atmosphere, Borenstein emphasizes that

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For acknowledgments, sources of research support, and disclosure of the author's material financial relationships, if any, please see http://www.nber.org/chapters/c12159.ack.