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Markets for Anthropogenic Carbon Within the Larger Carbon Cycle

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I. 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. Man-made CO_2 emissions, however, are small compared to the earth's natural carbon flux. Human activity results is about 9 gigatons of carbon (GtC) emissions per year against the backdrop of the natural carbon flux – emission and uptake – of about 210 GtC per year, to and from oceans, vegetation, soils and the atmosphere. This in no way suggests that man-made CO_2 emissions are 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 paper, I explore the implications for pricing CO_2 emissions when the anthropogenic emissions that have thrown the system out of balance are small compared to the total carbon flux between oceans, vegetation, soils, and the atmosphere. Nearly all of the 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 it seems quite likely that those conditions do not hold, and climate science suggests that they may not even be a good approximation. In that case, it is useful to consider more explicitly the interaction between the natural carbon cycle and human activity, and the appropriate boundaries of a market for greenhouse gas emissions.

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II. A Very Brief Review of the Carbon Cycle

Prior to the mid-19th 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 transferred to/from the ocean and 120 GtC to/from vegetation and soils.[2] Atmospheric levels of CO_2 remained in the range of 260-280 parts per million (ppm), equivalent to approximately 550-590 GtC in the atmosphere.

None of these natural processes, however, is static. All are affected by climate change: increases in atmospheric CO_2 cause plants to grow faster, absorbing 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 CO_2. 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-19th century, anthropogenic impact on the carbon cycle has steadily increased, primarily through fossil fuel combustion – averaging about 7.6 GtC per year during 2000-2006 – but also through human-caused deforestation and changes in land use – estimated to be about 1.5 GtC per year during 2000-2006.[3] The deforestation and 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% 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 quite 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

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[2] My characterization of the carbon cycle is based on Houghton (2007), Canadell et al (2007b), and Sarmiento & Gruber (2002).

[3] See Canadell et al (2007b), 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 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.

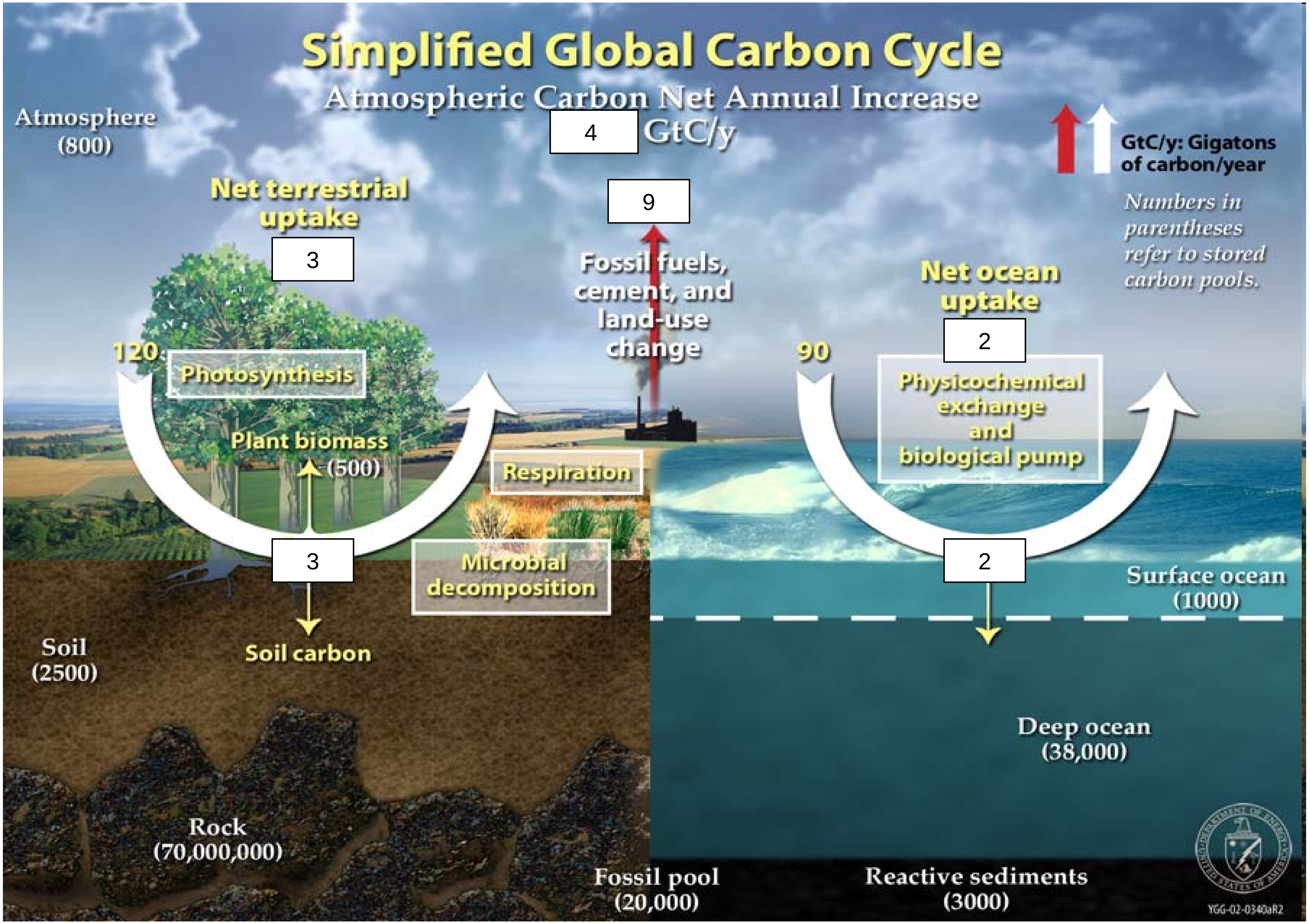

Figure 1: Carbon Cycle Representation Updated with Data from Canadell et al (2007b)

the residual to vegetation and soils. This approach suggests that ocean uptake accounts for about 24% of anthropogenic carbon emissions and 30% goes to vegetation and soils. The processes of ocean and vegetation/soils carbon uptake, however, are not well understood. Estimates of these components – often referred to as the "residual flux," or, somewhat less accurately, the "unidentified sink" – total about 5 GtC per year.

Figure 1 is a simplified representation of the carbon cycle with estimates of the anthropogenic carbon emissions and terrestrial and ocean uptake updated with the figures (in white boxes) from Canadell et al (2007b).

There is some evidence that the non-atmospheric uptake share of carbon is declining over time, a larger proportion is remaining in the atmosphere.[4] This suggests that the non-atmospheric sinks, both identified and unidentified, may be becoming 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.

III. Markets for Carbon Emissions

Climate change is occurring because large quantities of carbon that were being stored in stable form – for extremely long periods in fossil fuels or shorter periods in trees and soil composition – are being released, mostly as CO_2, by human activity. Anthropogenic carbon releases are a small share of the total carbon flux between the atmosphere and oceans, vegetation, and soils, but their rapid addition has disrupted the previously-balanced carbon cycle. Market mechanisms for carbon control propose to slow this process drastically by making it economically costly to humans to burn fossil fuels or deforest land.

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 human activities would obviously cut 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, it is clear that this is not at all an accurate representation of the anthropogenic contribution.

4 See Le Quéré et al (2009)

Beyond burning fossil fuels, human activity that releases greenhouse gases is interacting with the natural carbon cycle on a short time scale.[5] 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 where it migrates to through soils and water, interacts with CO_2 in complex ways to affect the growth of vegetation and its properties as a carbon sink.[6] Anthropogenic atmospheric nitrogen also seems likely to be significantly altering the carbon uptake of oceans, potentially reducing the net carbon sink impact of oceans by more than half.[7] 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.[8]

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.[9] 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. This is not because these are understood to be small factors. Some are estimated to be large, though none is estimated very precisely.

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[5] Technically, even burning fossil fuels is an interaction of human activity with the natural carbon cycle, though on such a long time scale that it is appropriately treated as solely anthropogenic for the purpose of climate change.

[6] See Reay (2008).

[7] See Duce et al (2008).

[8] See Canadell (2007a).

[9] See Grubb et al (2010).

Can carbon offsets address interactions with the natural carbon cycle?

The effects that I am discussing here are very 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 impact emissions from an excluded sector or region, as described by Bushnell in another chapter of 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 addressed either of these problems. If these barriers were remediated, one 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.

Climate feedback effects are a special case of interaction with the natural carbon cycle

Market mechanisms also 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 non-anthropogenic carbon flux. Such aggregate effects occur 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 themselves then release methane and also reduce 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 in practice there is substantial 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, there is a great deal of uncertainty 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 hit any specified target for atmospheric carbon and climate change.

IV. From Incomplete Science to Incomplete Markets and Property Rights

Market mechanisms to address climate change have thus far focused predominantly on reducing the greenhouse gas 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 just the last decade, scientists have made important steps in understanding these relationships. Still, because these impacts are indirect and idiosyncratic it is likely that the links to emission of greenhouse gases 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, of course, the science of climate change will progress and the mechanisms of these indirect impacts will be better understood. As science proceeds, the challenge of establishing scientific causality will transition to a challenge of establishing markets and property rights for generation of an externality. 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 cost 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. In most of these cases, based on appeals to equity and/or simplicity, prices vary much less than the underlying economic costs.

Such an outcome could be particularly inefficient in this case. While science does not yet provide complete answers, it seems likely that the variation in costs associated with seemingly similar human activities could be much greater for the indirect human impacts on the natural carbon cycle than in most other cases of government-regulated pricing. The impact of agricultural activities also depends on soil composition and alternative land use, as well as the quantities used and ultimate disposition of fertilizers. 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 very similar human activity could raise greenhouse gases in some locations and lower it in others.

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 – for example, a standard assumption about the carbon impact of releasing one pound of atmospheric nitrogen – less reliable. Likewise, because property rights allocation will be concerned with distributional issues, difficulty in determining a participant's probable liability *ex ante* could slow the political process and raise costs.

Scientific uncertainty is also likely to compound the difficulties related to property rights. Previous debates over the costs of environmental degradation – health impacts of criteria air pollutants, ozone depletion caused by 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]

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.

V. Conclusion

The rate of increase in atmospheric CO_2 from human activity is being buffered by the natural carbon cycle through increased uptake of oceans and terrestrial carbon sinks. Much of the impact of human activity on the natural carbon cycle is not well understood, but it seems likely that the interactions are 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 natural carbon flux.

My goal in this paper is to argue that the scientific research on these interactions has developed to the point that it is time for economists and policy makers to take note, to consider whether market mechanisms for greenhouse gases need to be extended to incorporate these complexities. Such an extension would be very challenging. The heterogeneity and idiosyncrasy of human impact on the natural carbon cycle would make appropriate pricing quite difficult and the scientific uncertainty that remains about these interactions would likely impede efforts to assign property rights.

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.

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[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 there was considerable uncertainty about their magnitude, so they should be counted as zero.

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