Counting Carbon: Is the CO₂ Uptake by the Land Changing?

The ocean and the land absorb roughly half of the human-caused carbon dioxide emissions that would have otherwise accumulated in the atmosphere, acting as “carbon sinks.” These processes have partially slowed the rate of global warming since pre-industrial times. Two independent studies in 2016 focused on an enhanced terrestrial carbon sink observed in recent decades (Zhu 2016; Keenan 2016). Because the land is both a source and a sink of carbon, better understanding of the driving mechanisms in this two-way process and the resulting net effect for carbon emissions is a critical factor in predicting the trajectory of greenhouse gas forcing and the resulting change in climate.

The concentration of carbon dioxide in the atmosphere continues to increase – now over 400 ppm, some 120 ppm above pre-industrial measures. The Global Carbon Project (GCP), a massive international effort of researchers from numerous institutions, produces periodic updates on the carbon dioxide budget tracking sources and sinks and how they change over time.
The above diagram from the GCP 2016 assessment shows the global average emissions in gigatonnes of carbon (GtC) per year between 2006 and 2015 (Le Quéré 2016). Table 1 below shows averages from the last decade (as in the GCP diagram), compared to the single year results for 2015. It’s important to note that the land sink in 2015 was 1.2 GtC less than the previous decade average, which partially explains the 1.8 GtC gain in the growth rate of the atmospheric CO₂ concentration.

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<th>Table 1: Mean GtC yr⁻¹</th>
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Excerpt from Table 8 C. Le Quéré et al.: Global Carbon Budget 2016

The Earth’s carbon cycle operates on many time scales, from the few seconds it takes a mammal to exhale to the slow process of tectonic plate subduction carrying carbon into the mantle over tens of thousands of years. On century timescales—most relevant to human interactions with the climate—is the partitioning of annual carbon dioxide emissions into three reservoirs: the atmosphere, the land, and the ocean. Humans add to these reservoirs by combustion of fossil fuels and other industrial processes such as cement manufacture, and by changes in vegetation and land use. In round numbers the annual disturbance is 10 gigatonnes of carbon emitted in the form of carbon dioxide annually with about 1 GtC from land use change.

The ocean takes up about a third of these emissions and the land about a fifth. The fraction of total carbon dioxide emissions remaining in the atmosphere from human sources (not absorbed by the ocean and land sinks) is the airborne fraction (AF). In a sense, the airborne fraction is a marker of the industrial age. A noteworthy aspect of the airborne fraction (see Figure 1) is that while it has fluctuated year to year, on average it remains about 45 percent of anthropogenic emissions over recent decades even though emissions have been increasing for decades. Two key questions arise from this: 1) How is the remaining half of emissions partitioned between the land and ocean sinks? And 2) are the land and ocean sinks able to keep pace, or will they become saturated, eventually becoming sources of carbon rather than sinks?

Zaichun Zhu and colleagues examined how terrestrial vegetation is responding to changing environmental factors such as climate change. They utilized three satellite datasets to derive a global leaf area index (a measure of leaf area to ground area) for the years 1982-2009 combined with a set of vegetation models to determine key attributes of the greening effect. The study concluded that CO₂ fertilization, nitrogen deposition, climate change, and land cover change are driving the increase in global vegetation, which would indicate a greater terrestrial sink for carbon (Zhu 2016).

In the paper by Keenan and colleagues, their focus was on understanding a decrease in the airborne fraction of CO₂ in the atmosphere between 2002 and 2014 compared to an increase in
previous decades. This decrease in the AF is surprising, given that emissions steadily increased during this period, as shown in Figure 1b from Keenan (2016).

Figure 1. Fig 1a shows the growth rate of atmospheric CO$_2$ ppm per year. Fig 1b shows both the airborne fraction and carbon emissions per year. The black line in Fig 1a shows the observed growth rate in atmospheric CO$_2$ in ppm per year from 1959 to 2012. The solid red line shows the trend from 1959 to 1990. The dashed red line, the trend until 2002. The blue line shows that from 2002 to 2014 there was no trend. In Fig 1b the dashed black line shows the annual fossil fuel emissions from 1959 to 2014. The solid red line represents the trend in the airborne fraction from 1959 to 1988. Black dots, the annual AF. The dashed red line shows the trend in AF from 1959 to 2002. The blue solid line illustrates the decreasing trend in the AF from 2002-2014. Volcanic eruption dates coincide with a reduction in the AF. Caption abbreviated from Keenan et. al. 2016.

Keenan’s analysis used a set of methods including ground and satellite observations, carbon budget estimates and global vegetation models. Their results show an increase in the airborne fraction of 1.8 percent per year from the 1960s to the 1990s, but for the period 2002 to 2014 the airborne fraction decreased by 2.2 percent per year. They attribute this decrease in the AF primarily to a positive change in the land sink—a greening of the Earth’s vegetative cover resulting from a variety of factors similar to Zhu’s finding. They concluded the fertilization effect as the key factor. Keenan cautions that the recent enhanced terrestrial uptake, while welcome for its dampening effect on the increase of atmospheric CO$_2$ and slowdown in the pace of global warming, may have already ended with the El Niño of 2015 and 2016.

The result of these recent studies is that there has been an observable greening of the Earth, which has increased the terrestrial sink for carbon. Fire and deforestation drive carbon emissions into the atmosphere from the land, but haven’t changed as much over the same period as the enhanced greening of the Earth. The net effect has been a greater land sink. The increase in the terrestrial sink has slowed the accumulation of carbon dioxide in the atmosphere and thereby reduced the warming that would have otherwise been realized in recent years. While the increase in the terrestrial sink is a welcome turn, most research indicates it is temporary. As global warming proceeds, many studies indicate the land sink is expected to diminish (Canadell 2007; Raupach 2014; Arneth 2017) and potentially become a net source of carbon (Weider 2015). The implication of a contraction of carbon sinks is that as we move forward in time, for each quantity of carbon dioxide emitted, a greater percentage will remain in
the atmosphere directly affecting climate change. Curbing deforestation activities and stepping up reforestation projects are key forest management practices to bolster the carbon land sink (Arneth 2017).


**Putting a Price on Health Impacting Pollutants**

It's no secret that our economy has environmental externalities not accounted for in the cost of energy. For years, researchers and economists have honed techniques for calculating the Social Cost of Carbon, which aims to internalize those environmental and health damages caused by greenhouse gases. By plugging the Social Cost of Carbon into various models, researchers have demonstrated its utility in improving energy efficiency, reducing energy consumption, changing energy generation technologies, and reducing airborne pollutants. In a recent study by Brown et al. (2017), researchers have taken this type of experiment one step further.

![Figure 1. Health-impacting pollutant emissions in 2045 for selected fee cases.](image-url)
further by applying damage-based fees to greenhouse gases as well as well as to health-impacting pollutants (HIPs) to see how possible fee structures potentially impact one another. Brown et al. examined fee structures for health-impacting pollutants NOx, PM2.5, PM10, SO2 and VOCs. Fees for these pollutants were drawn from recent literature, and population concentration of emissions was also factored into the analysis. Greenhouse gases examined included CO2 and methane, with the fee based on the US Government 2013 calculation of the Social Cost of Carbon. The MARKAL model period spanned from 2005 to 2055, and incorporated existing regulations and carbon capture and storage (CCS) options, and then compared against a business-as-usual model. The MARKAL model uses linear trends to determine the lowest cost set of generation or conservation technologies to meet end use energy demand. Model runs were completed for fee scenarios on only health-impacting pollutants, only greenhouse gases, and both pollutants and greenhouse gases combined.

The model runs revealed that not only did emissions of pollutants and greenhouse gases go down when they had their respective fees applied, but emissions also declined when the other fee was in place (i.e., lower pollutant emissions with greenhouse gas fees in place, and lower greenhouse gas emissions when pollutant fees were applied). When both fees were applied in combination, the reductions were even more pronounced.

The largest responses to the fee scenarios were seen in the electricity sector, including the mix of electricity generation technologies. In both the pollutant fee and greenhouse gas fee scenarios, coal production dropped dramatically, often replaced with natural gas combined cycle generation. Depending on how high greenhouse gas fees were, renewables played more of a role in displacing coal generation. In all cases, demand for electricity went up substantially. Other sectors were less affected by the fees: The transportation, residential, and commercial sectors were relatively unresponsive to fee scenarios, although they collectively generated hundreds of billions of dollars in revenue. Based on this finding, the authors acknowledge that while a fee structure may be an appropriate policy recommendation for the electricity sector, it may not be the most effective regulatory structure in the other sectors.

Figure 2. CO2 emissions by sector in 2045 for various fee cases.
Figure 3. Fuels and technologies used to generate electricity in 2045 based on all fee cases.

The authors note that the Clean Power Plan’s goal of reducing CO₂ emissions 32 percent by 2030 could be achieved through several of their test scenarios—either through a greenhouse gas fee of between three and five percent, or through their mid and high pollutant fee scenarios. They also note that in many sector-specific cases, the reductions in emissions were driven more by availability and generation technology price, rather than fees. This underscores the importance of continuing to drive down renewable energy technology prices.

In summary, Brown et al. illustrate that damage-based fees are effective at decreasing emissions, but their study underscores how that reduction is not a linear trend, and that reductions sometimes rely on certain threshold fees. CCS methods often diminished co-benefits of a greenhouse gas fee because of the additional inefficiency CCS introduced to the electricity generation process, ultimately resulting in more non-CO₂ pollutants. On the whole, targeting all pollutants with fees was more effective than relying on co-benefits of greenhouse gas fees alone. Finally, the authors encourage future model studies as we come to know more about the true cost of our energy system and its externalities.