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Terrestrial Carbon Sequestration

INTRODUCTION

Terrestrial carbon sequestration is the practice of storing carbon within biomass and soils. With rising concentrations of CO_2 in the atmosphere causing increased concern about global warming, techniques to sequester carbon or otherwise lower the earth's temperature are beginning to be considered. The ideas of geoengineering, "the intentional large-scale manipulation of the environment, particularly manipulation that is intended to reduce undesired anthropogenic climate change" (Keith, 2000) are being proposed, and the public is beginning to consider that such action might be necessary.

The types of ideas for geoengineering vary greatly, and include such things as fertilizing the ocean with iron to increase carbon uptake, placing mirrors or lenses in space to reduce the amount of sunlight incident on the earth, injecting sulfur aerosols or dust into the upper atmosphere to increase the albedo of the planet, and changing land management strategies to increase terrestrial uptake of carbon (Keith, 2000). Some options seem more drastic than others, and each comes with its own set of benefits as well as social, political, and environmental consequences.

Terrestrial sequestration is appealing as an option for several reasons. First, it seems like a "greener" or more natural option: by planting trees and making some land management changes some of the carbon emissions can be offset. This idea is easier to swallow for many people in comparison with some of the other proposed solutions that resemble science fiction. Terrestrial sequestration also deals with the problem more directly, by taking CO_2 out of the atmosphere, rather than dealing with the effects of the CO_2 by changing the albedo or incident solar radiation and not directly assessing the cause. The structure to manage land also already exists; in many ways humans have been geoengineering for millennia in the form of agriculture. Thus, if land use practices need to be changed or enhanced for terrestrial sequestration a network or farmers and forestry workers already exists to help put such changes in place.

Upon examination of terrestrial carbon sequestration it has several downsides too. The dynamics and controls and the terrestrial carbon sinks, especially soil, are not fully understood, which makes using these sinks challenging because the magnitude and specific sequestration mechanisms are unknown. Also carbon in these systems is much less fixed than in other systems, so even once carbon is sequestered, there is no guarantee another change in land management will not release it in to the atmosphere once more. It also is expensive, and gets significantly more expensive the more carbon sequestered.

This paper will first give a brief overview of the carbon dynamics of the earth, and how terrestrial sequestration fits in, then follow with some of the science behind sequestering carbon terrestrially. Then it will give a brief overview of cost estimates, and the current methods for calculating the amount of carbon sequestered in different types of soil environments. In conclusion, terrestrial carbon sequestration by itself is not the complete solution to the climate problem, and the science is not well enough understood to make accurate estimates for the amount of carbon stored in terrestrial sinks.

GLOBAL CARBON

There are five major carbon pools on the planet (Fig. 1). The ocean is the largest, containing 38,000 Pg, followed by the geologic with 5,000 Pg, soils with 2,500, the atmosphere with 760 Pg, and biota with 560 Pg (Lal, 2004). The soil and biotic pools together comprise the terrestrial reservoir.

Figure removed due to copyright restrictions.

Figure 1. Carbon in each of the major pools. Geologic is broken up into coal (green), oil (red), and gas (blue). Soil is broken into soil inorganic carbon (red) and soil organic carbon (blue).

From 1850 to 1998, 270 +/- 30 Pg CO_2 has been emitted from fossil fuel combustion and cement production, while 136 +/- 55 Pg has been emitted as a result of land use change 78 +/- 12 Pg of which was from anthropogenic decrease of soil organic content (Lal, 2004). This means that a significant portion of the carbon emitted since the industrial revolution has been from land use changes, and thus come from the terrestrial reservoir. However, since 1980 most emission has been from fossil fuels with 10-30% of emissions from land use change and tropical deforestation (Lal, 2004).

The carbon budget in the 1990s for emissions: 6.3 +/- .6 Pg C/yr emitted by fossil fuels, and 1.6 +/- .8 Pg C/yr emitted by land use change. For absorption: 3.3 +/- .2 Pg C/yr absorbed by the atmosphere, 2.3 +/- .8 Pg C/yr absorbed by the ocean, and 2.3 +/- 1.3 Pg C/yr absorbed by unknown terrestrial sinks (IPCC 2001). The first thing to note is that emissions from land use change is still about 20% of emissions. The second thing to note is that the uncertainties on both the emissions by land use change and the absorption by terrestrial sinks is quite large, greater than 50% uncertainties. Most of the emissions from land use change come from tropical deforestation, as in most temperate countries the amount of deforestation is at least compensated by new growth (NAS 1992). In the US about 40% of the planting is done by the forestry industry (NAS 1992).

Estimates for how much impact on the global carbon cycle terrestrial sequestration could have vary, but Moulton and Richards (1990), estimate that more than 50% of carbon emissions could be compensated by reforestation.

SOIL C SEQUESTRATION

Carbon in soils is stored in two forms, soil inorganic carbon (SIC) and soil organic carbon (SOC). SOC is more plentiful, easier to manipulate, and shorter lived. SIC is mostly carbonate minerals, and composed of two sections, pedogenic and lithogenic. The Lithogenic portion is derived from direct weathering of rocks. The pedogenic portion forms from the reaction of Ca^{2+} and Mg^{2+} with atmospheric CO_2, and it is the most common form of carbon sequestration in arid and semiarid environments (Lal, 2004).

The SOC mostly takes the form of humus, which is a dark, amorphous material with a high surface area and charge density, which clings to clay sized particles and is a mix of plant, animal, and microbial byproducts. The residence time of SOC varies from 0.1 yr to 2200 yr (Lal, 2004). The SOC content of the soil is the easier of the two forms of soil carbon to manipulate with land use practices, so land practices which increase SOC are desirable, as well as land use practices which increase the residence time for SOC. Carbon-content of soil is linked to nitrogen, phosphate, and water so perturbations of any of these systems can lead to carbon-loss. Depletion of SOC can come from physical, chemical, and biological processes. Physical processes include a decrease in stable aggregates, crusting, compaction, and erosion. Chemical processes include acidification, salinization, and changes in the elemental balance. Biological processes include reduction of biologic activity and change in species diversity (Lal, 2004).

Agricultural and land use practices can significantly affect the SOC content of soil. Table 1 shows a list of the different types of practices which are beneficial and harmful for carbon storage in the soil. Particularly, deforestation and biomass burning, removal of biomass for fuel and foder, tillage, and the drainage of wetlands release carbon into the atmosphere. Biomass burning produces charcoal, which is a long-lived form of carbon, so even though it releases carbon into the atmosphere, it helps sequester some carbon for longer (Lal, 2004). The climate type, soil type, and natural vegetation also have a very large impact on the amount of carbon which can be stored in the soil, and how much effect different land use practices have on the carbon content.

Table 1. From Lal (2004)

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There is significant erosion of the organic portion of soil when land is transitioned from the natural environment to cropland. The first stage of erosion is breakup of soil aggregates by kinetic movement by wind or water. Soil aggregates are composed of clay, organic matter, and polyvalent cations (Lal, 2001). The next step is transport of detached and entrained particles by fluids, and finally deposition of the material in the new locations. There are three main places where the eroded material can end up. It can end up being redistributed over the land surface, which leads to decomposition of organic matter, and probably a net emission of carbon, estimated at 1.14 PgC/yr. The carbon that is transported by rivers is not well understood, but it is thought that this ends up decomposing as well, one estimate is that European rivers emit 30-60 TgC/yr, 5-10% of Europe's total carbon emissions (Lal, 2001). Another view is that rivers bring organic matter to the ocean for long-term storage (Lal 2004). Soils can also end up being buried in depressions, which is thought to enhance aggregation and storage, it is estimated that 0.57-1 PgC/yr is stored this way. However if conditions are anaerobic, burial can lead to the production of methane and the release of N_2O (Lal, 2001).

The types of plants on the land also affect the amount of carbon sequestered in the soil. Thus it is important to choose the correct plant type to maximize sequestration. Different traits are more valuable for increasing soil sequestration depending on the biome in which the plant resides (De Deyn et al., 2007). Rapidly changing climate could change the biome in a specific location, and have effects on the carbon stored in these ecosystems. There are two methods of enhancing carbon storage, first by fast input of carbon through high primary productivity, and second by slow output by slow decomposition. De Deyn et al. find that in ecosystems where soil nutrients are the limiting factor, slow growth and long litter residence time tend to dominate, while in rich-soil ecosystem where light is the limiting factor the opposite is true. De Deyn et al. also indicate many areas for further research, which indicates that this part, as the other parts, of soil sequestration is not fully understood.

BIOTIC STORAGE

There is also carbon that is stored in biomass itself, thus increasing the amount of biomass takes carbon out of the atmosphere. This leads to the idea of reforestation, or planting large plantations of trees. One of the problems with this method though is that it is a relatively short-term sink, as it is necessary to keep the carbon from oxidizing to CO_2 after the biomass dies. Lumber, soil and roots are longer-term storage, and one suggestion is to use the biomass to substitute for some of the fossil fuel usage (NAS 1992). It generally takes 20 to 40 years for the biomass to mature, and then the plantation no longer acts as a large sink, it reaches steady state. Thus this method should be viewed more as a short-term solution, a fix while carbon emissions are reduced in other manners.

There are also other side effects of having plantations of trees, and these effects differ based on the biome and the soil type, so some areas are much more suited for plantations than others. Other aspects include effects on groundwater, stream runoff, and soil. A study by Jackson et al. (2005) found that there were dramatic changes in stream flow within the first few years of planting, an average of 38% decrease, with 13% of streams drying out for at least a year. Climate feedbacks of reforestation can sometimes offset these effects by increased transpiration and convective rainfalls, but convective rainfalls were only found to occur in Florida and southern Georgia. The increased transpiration made for slightly lower summer surface temperatures in some places. Increasing the biomass also changes the soil chemistry significantly (Jackson et al., 2005). First most trees have acidic litter (i.e. fallen leaves), and this causes a lowering of the pH of the soil, unless the trees are growing on a well-buffered medium like limestone. There is also an increase in Na in the soil, which can cause saline ground water. Depending on the soil type and the groundwater patterns, planting trees in an area which was not originally forested can cause groundwater to become to salty for human use (Jackson et al., 2005). In some areas though, for instance southern Australia and places which were once forested and now cropland, reforestation can help the water quality by reducing dryland salinization and reducing pesticide and fertilizer runoff. Tree plantations are better in some areas than others, and that environmental planning is needed before starting large-scale projects.

Keith (2000) also briefly mentions the idea of genetically modifying organisms to make capture more efficient, which could be an area of further research.

COSTS

There were several estimates of the cost of implementing techniques of biological sequestration. The National Academy of Sciences report (1992) found reforestation to be one of the more expensive methods that they explored at $5.80 to $47.75 per ton carbon, and they state that it gets progressively more expensive the more carbon it attempts to store.

Spearow et al. (2007) estimated the cost of carbon storage by setting aside highly erodable cropland (HEL). To estimate the marginal costs, they took the profit that value of the crop that would be grown on the land and compared it to land rental prices. Some of the prices came from the USDA Farm Resource Regions Data. The marginal cost could be looked at as a proxy for what farmers would have to be paid to adopt the sequestration practices.

Carbon storage of the land was estimated using the method outlined by the IPCC, which uses native soils as a reference for carbon storage potential. Depending on the soil and how long it has been put to agricultural use, it is estimated that the agricultural soil has lost 70-75% of the potential carbon storage. Soil is thought to reach equilibrium in about 20 years, when it becomes neither a net source nor a net sink. The soil type and tillage practices also change the amount of carbon sequestered, with mud based soils sequestering better than sandy soils (Spearow et al., 2007).

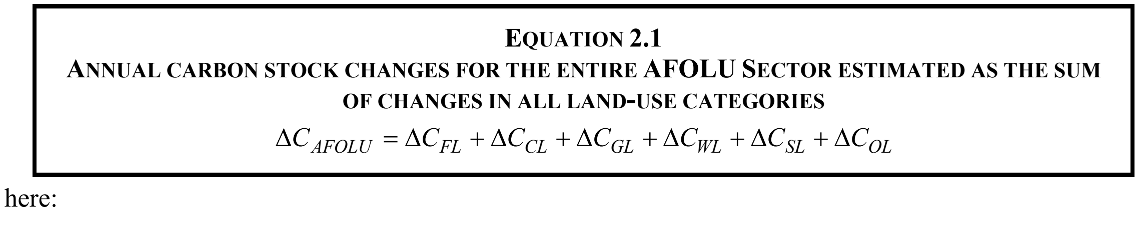
Cost estimates ranged significantly, from $11 per Mg C for some cotton land to $4492 per Mg C for soybeans on sandy soil. Average was $288 per Mg C. Costs were elastic until about $200 per Mg C, after which they became inelastic, meaning large costs for small increases. They also estimated the effect on total cost production, saying for sorghum it had the most effect, 81% decrease of ending stocks, while cotton had the least, with 17% of ending stocks. This would affect the price of crops though, which would probably affect the marginal cost of carbon sequestration, to make it more expensive (Spearow et al., 2007).

Because terrestrial sequestration gets incrementally more expensive, and is relatively expensive anyway, it seems likely that terrestrial sequestration is not suitable for a full-scale geoengineering solution for the climate problem, it is likely that is would only be used as an interim solution, or a partial solution.

QUANTIFYING SEQUESTRATION

The standard method of quantifying the amount of carbon sequestered in soils and agricultural land is the method outlined by the IPCC in 2006. This is a report on the methodology of calculating the sequestered carbon for individual counties. The first step is to choose Tier 1, 2, or 3. Tier 1 is the most general, using only the tables of coefficients from the report, where as Tier 2 and 3 are more empirical.

The Tier 1 technique is outlined specifically in the report, and worksheets are included for the calculations. Generally the calculation is split up into very small specific pieces starting with:



EQUATION 2.1

ANNUAL CARBON STOCK CHANGES FOR THE ENTIRE AFOLU SECTOR ESTIMATED AS THE SUM OF CHANGES IN ALL LAND-USE CATEGORIES

$$\Delta C_{AFOLU} = \Delta C_{FL} + \Delta C_{CL} + \Delta C_{GL} + \Delta C_{WL} + \Delta C_{SL} + \Delta C_{OL}$$

here:

Where AFOLU is agriculture, forestry, and other land use; FL is forestry land; CL is cropland; WL is wetlands; SL is settlement lands; and OL is other lands.

Each of these is farther broken down:

EQUATION 2.3
ANNUAL CARBON STOCK CHANGES FOR A STRATUM OF A LAND-USE CATEGORY AS A SUM OF CHANGES IN ALL POOLS

$$\Delta C_{LU_i} = \Delta C_{AB} + \Delta C_{BB} + \Delta C_{DW} + \Delta C_{LI} + \Delta C_{SO} + \Delta C_{HWP}$$

here:

Where LU is the specific land use, AB is above ground biomass, BB is below ground biomass, DW is dead wood, LI is litter, SO is soils, and HWP is hard wood products.

Each of these categories is further spit up and calculated separately using the worksheets in the annex of the report, and example of which is shown in Figure 2. There are about 50 worksheets has a column for each value, and tells how to calculate the value if it is a calculation, and what table to find a constant if it is a constant. The tables of constants are found in the relevant chapters of the report. This is useful, but the accuracy is somewhat questionable, estimating each piece separately from generic coefficients may have large errors. The fact that the calculation is parsed up so many times may be a relic of the fact that this not completely understood.

The tables of coefficients used for calculating the carbon are based on relevant portions of the scientific literature. For instance The table of default carbon stocks for mineral soils with native vegetation is based largely on a paper by Jabbagy and Jackson (2002) entitled “The Vertical Distribution of Soil Organic Carbon and its Relation to Climate and Vegetation”. In that article they try to characterize soil carbon in the top 3 m of soil based on more than 2700 profiles in

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Figure 2. Example of a worksheet from the IPPC (2006) Report, Annex 1.

three global databases, paying attention to variables such as vegetation type, climate, and land use. They found that the plant type affected soil carbon significantly, and had more of an affect than the direct effects of precipitation.

Eve et al., (2001) use the method set out by the IPCC (the 1996 precursor to the 2006 version) to calculate the changes in carbon storage in U.S. croplands since the 1990 baseline. They find that soil use practice changes have resulted in a net sink to mineralized soils of 11.31 million metric tons carbon per year, however the organic portion of soils is still a net source of 6.03 million metric tons per year. The warm temperate moist mineral soils are the largest sink, whereas the sub-tropical moist organic soils have the largest emissions.

Another method besides the IPCC method was outlined Gross et al., (2001). This approach has not been put into practice yet, but involves modeling and monitoring carbon storage in U.S. farmland east of the Rockies. This was achieved using a model called EPIC-Erosion/Productivity Impact Calculator, which clusters soils and climate areas by their characteristics. The goal of this project is to establish a baseline of the 1992 levels of soil carbon sequestration, and monitor changes over time.

These are all method solely of estimating carbon sequestration. This is hard to measure on the large scale, so it is challenging to tell the accuracy of these techniques.

CONCLUSION

Terrestrial carbon sequestration is a set processes that involve the interaction of soils, biota, and the climate system, and is not fully understood. It could be a part of a multi-faceted solution for the climate problem, but on it's own it does not represent a full-scale geoengineering solution. This is partially because the dynamics of carbon sequestration are not understood well enough to be controlled and the amount of carbon sequestered accurately calculated. Also biotic and some types of soil sequestration are not very long lived, so they are only effective as short-term solutions. In general terrestrial carbon sequestrations merits more research, but is not a complete solution.

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