Long-Term Sequestration of Woody Biomass

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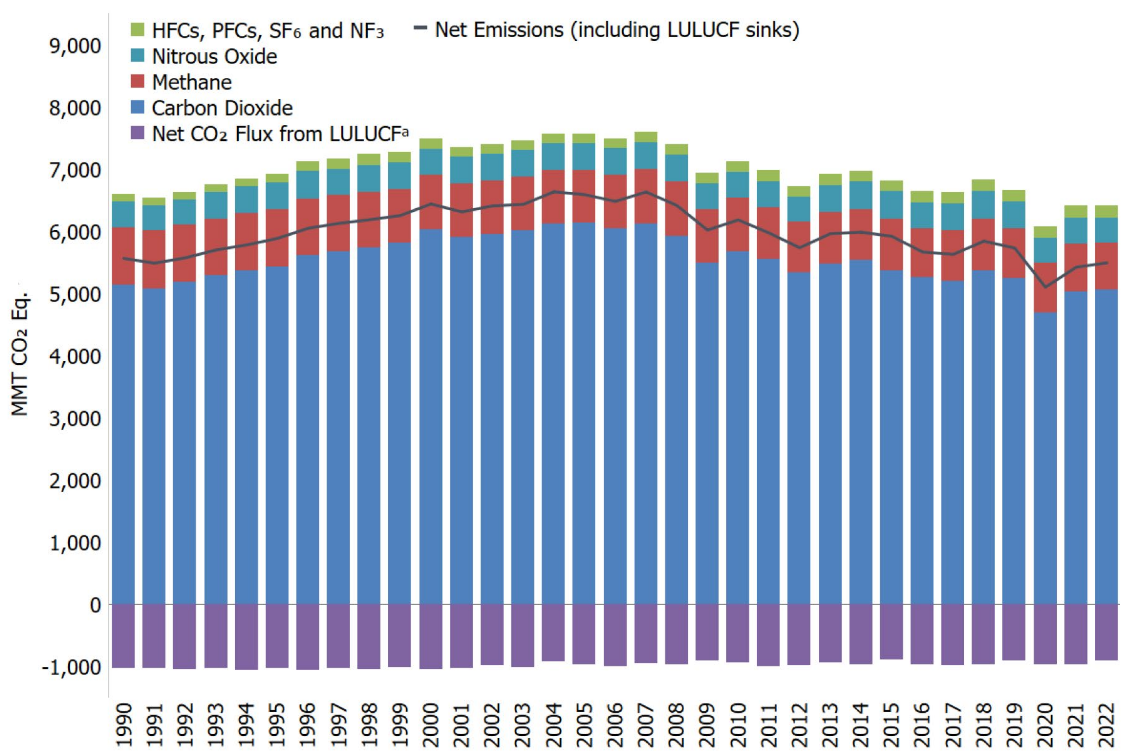
November 2024

1. Introduction

Climate change is primarily caused by human-generated greenhouse gasses. For the U.S. the recent releases can be seen in the chart below.[1]

U.S. Greenhouse Gas Emissions and Sinks by Gas



[a] Land Use, Land-Use Change, and Forestry

Note that the volume is measured by CO_2 Eq (carbon dioxide equivalent), that is by the greenhouse (global warming) potential when compared to CO_2. Given that, it is obvious that CO_2 is, by far, the most significant greenhouse gas (GHG).

The next question is, how long does each GHG remain in the atmosphere? From reference 1, that, and other information can be seen in the table below.

[1] U.S. Greenhouse Gas Emissions and Sinks, 1990-2022, U.S. Environmental Protection Agency, April 2024, https://www.epa.gov/system/files/documents/2024-04/us-ghg-inventory-2024-main-text_04-18-2024.pdf

Table 1-1: Global Atmospheric Concentration, Rate of Concentration Change, and Atmospheric Lifetime of Selected Greenhouse Gases

Atmospheric Variable	CO_2	CH_4	N_2O	SF_6	CF_4
Pre-industrial atmospheric concentration	280 ppm	0.730 ppm	0.270 ppm	0.01 ppt	34.1 ppt
Atmospheric concentration	419 ppm[a]	1.912 ppm[b]	0.336 ppm[c]	11.02 ppt[d]	85.5 ppt[e]
Rate of concentration change	2.28 ppm/yr[f]	8.83 ppb/yr[f,g]	1.01 ppb/yr[f]	0.32 ppt/yr[f]	0.81 ppt/yr[f]
Atmospheric lifetime (years)	See footnote[h]	11.8	109[i]	About 1,000[j]	50,000

The rate of concentration change for CO_2 is an average of the rates from 2007 through 2022 and has fluctuated between 1.5 to 3.0 ppm per year over this period (NOAA/ESRL 2024a). The rate of concentration-change for CH_4 (Methane), N_2O (Nitrous Oxide), and SF_6 (Sulfur hexafluoride), is the average rate of change between 2007 and 2022 (NOAA/ESRL 2024b; NOAA/ESRL 2024c; NOAA/ESRL 2024d). The rate of concentration change for CF_4 is the average rate of change between 2011 and 2019 (IPCC 2021).

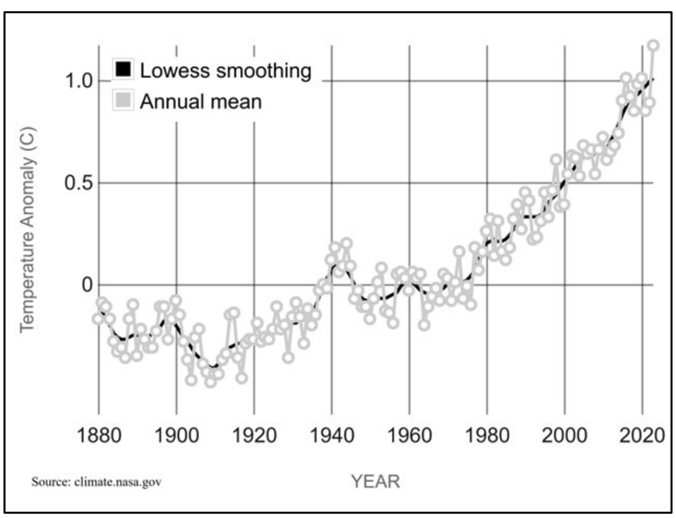
The growth rate for atmospheric CH_4 decreased from over 10 ppb/year in the 1980s to nearly zero in the early 2000s; recently, the growth rate has been about 13.22 ppb/year (NOAA/ESRL 2024b).

For a given amount of CO_2 emitted, some fraction of the atmospheric increase in concentration is quickly absorbed by the oceans and terrestrial vegetation, some fraction of the atmospheric increase will only slowly decrease over a number of years, and a small portion of the increase will remain for many centuries or more.

This table reports the "perturbation lifetime" for both CH_4 and N_2O, which takes into account the interactions between emissions of the gas and its own atmospheric residence time.

The lifetime for SF_6 was revised from 3,200 years to about 1,000 years based on recent studies (IPCC 2021).

The following is a chart of global temperature rise caused by greenhouse gases.[2]



Given the major contribution of CO_2 to climate change, its long residence time in the atmosphere and its rapid rate of increase, it is not surprising that climate change mitigation is focused on this major GHG. Other factors in this CO_2-focus are that we nowhere close to reducing its emissions to zero (most optimistic estimates are that most nations might reach this goal by 2050), who knows what worsening effects of climate change we will be experiencing by then, and most of these effects take decades to centuries to play-out.

[2] https://climate.nasa.gov/vital-signs/global-temperature/?intent=121

Thus, it is important that, in addition to reducing the emission we need to start directly removing CO_2 and its precursors from the biosphere.

And, finally we get the title subject of this paper. A recent discovery may give us a short-cut to isolate biomass from the biosphere for a very long time without extensive processing (read: combusting and geologically sequestering the resulting CO_2).

2. Woody Biomass Burial

Limiting climate change requires achieving net-zero carbon dioxide emissions. Although substantial reduction in fossil fuel emissions is essential, it is insufficient for achieving the international goal of restricting global warming to 1.5° or 2°C above preindustrial levels. This target, established by the Paris Agreement, aims to avoid severe impacts of climate change by keeping the global average temperature increase within this limit. Achieving net-zero necessitates approaches that remove carbon dioxide from the atmosphere, known as carbon dioxide removal (CDR).[3]

Engineering CDR methods, such as direct air capture, are expensive and energy-intensive. Nature-based CDR, such as reforestation and afforestation, are cheaper but face land-use competition, scalability, and carbon leakage risks.

Forests are central to climate change discussions because of their critical role as a dominant land carbon sink in natural carbon cycles. They sequester carbon from the atmosphere through photosynthesis. This carbon is stored in wood with ~50% carbon content that varies by species. The carbon is released back to the atmosphere through burning (forest fires or prescribed burning for fire risk management) or decomposition of woody biomass. Globally, 10.9 ± 3.2 Gt (gigatonnes, or billion tonnes) of carbon could be emitted from deadwood per year, higher than anthropogenic carbon emissions from fossil fuels. If an approach can extend the duration of carbon storage in wood to hundreds of years or longer and prevent the release of carbon back into the atmosphere, it would naturally be an effective CDR approach.

Zeng et al. describe a pathway to making deadwood carbon storage a reality (below). The authors present a CDR approach involving the burial of sustainably sourced wood in an underground engineered structure called a "wood vault" to prevent wood decomposition.

3. Wood Vaulting as a Carbon Removal Method

Six-times more carbon dioxide (CO_2) is removed each year by terrestrial photosynthesis than fossil fuel emissions. However, the carbon is mostly returned to the atmosphere by decomposition. We found a 3775-year-old ancient wood log buried 2 meters below-ground that was preserved far beyond its expected lifetime. The wood had near-perfect preservation, with carbon loss less than 5% compared to a modern sample.

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[3] Yuan Yao, Center for Industrial Ecology, Yale School of the Environment, Yale University, New Haven, CT, USA, "A woody biomass burial," Sep 27, 2024, https://www.science.org/doi/full/10.1126/science.ads2592 , Note that access is limited.

The lack of decay is likely due to the low permeability of the compact clay soil at the burial site. Our observation suggests a hybrid nature-engineering approach for carbon removal by burying woody biomass in similar anoxic environments. We estimate a global sequestration potential of up to 10 gigatonnes CO_2 per year with existing technology at a low cost of $30 to $100 per tonne after optimization.[4]

Greenhouse gas emissions from burning fossil fuel must be drastically reduced by transitioning to renewable energy sources to prevent climate change from exceeding 1.5° to 2°C global warming above preindustrial levels. In addition, up to 10 gigatonnes of atmospheric carbon dioxide ($GtCO_2$) per year must be removed and sequestered by 2060 to counter legacy and hard-to-decarbonize emissions.

In the emerging field of carbon dioxide removal (CDR), also known as negative emissions technology (NET), a variety of promising engineering-based methods have been proposed. These include direct air capture and direct ocean capture. However, these approaches are energy intensive and expensive owing to the high cost of capturing highly diluted CO_2. Primarily using these to address the ongoing climate emergency may prove to be challenging.

Alternatively, proposals for various nature-based solutions take advantage of "free" photosynthesis, such as by promoting forest growth to enhance carbon storage in the active biosphere. These solutions are attractive because of their low cost and potential: The terrestrial biosphere removes 220 $GtCO_2$ from the atmosphere each year. This quantity, called the net primary productivity (NPP), is six times the rate of current annual fossil fuel emissions of 37 GtCO2. However, in the natural carbon cycle, captured carbon is ultimately returned to the atmosphere on relatively short timescales owing to the decomposition or burning of biomass, leaving little impact on the atmospheres CO_2.

Cutting off the return pathway of even a small fraction of the photosynthetic carbon, say 4.5% of NPP, would allow longer-term sequestration of 10 $GtCO_2$ per year, amounting to 27% of the current fossil fuel emissions rate. One way of diminishing the return path in the carbon cycle is to preserve biomass and prevent its decomposition. But given the long lifetime of anthropogenic CO_2 in the atmosphere, the removed carbon must be stored for hundreds of years or longer. Even wood, the most decay-resistant component of a tree, lasts just a few decades before it is degraded by fungi, insects, and micro-organisms. At the core of the biomass preservation concept is a question of permanence and durability. What is not clear is whether we can preserve woody biomass beyond its usual timescales to hundreds of years or longer in a way that is practical and inexpensive. One somewhat obvious method is to bury wood underground. This possibility is suggested from archaeological and geological evidence of buried ancient wood materials. However, the circumstances for preservation and longevity are not well-known. A better understanding of the environmental burial conditions and preservation state is necessary to guide potential engineering interventions for durable carbon removal.

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[4] Ning Zeng (University of Maryland), Xinpeng Zhao (University of Maryland (MAPAQ, Montreal), Ghislain Poisson3, Bryson Clifford (University of Maryland), et al, "3775-year-old wood burial supports "wood vaulting" as a durable carbon removal method," Sep 27, 2024, https://www.science.org/doi/10.1126/science.adm8133 , Access is limited.

We demonstrate a carbon sequestration method that combines the advantage of natural photosynthesis with minimal but effective engineering, in which sustainably sourced woody biomass is buried underground in an engineering structure called "wood vault" to prevent decay and decomposition (Fig. 1B). Our approach is grounded in the results of a natural wood burial "experiment." In March 2013, while excavating a trench for a wood vault prototype, we discovered an ancient yet well-preserved wood log of Eastern red cedar buried just 2 m below the ground surface (Fig. 1, C and D). The wood was subsequently carbon-14 dated to be 3775 ± 35 years old, providing direct evidence for the viability of wood burial as an approach for carbon removal and durable storage. We carefully examined the burial environment and analyzed the wood sample for its physical characteristics and chemical composition to understand how to best preserve wood for long-duration carbon sequestration.

3.1. Ancient wood burial

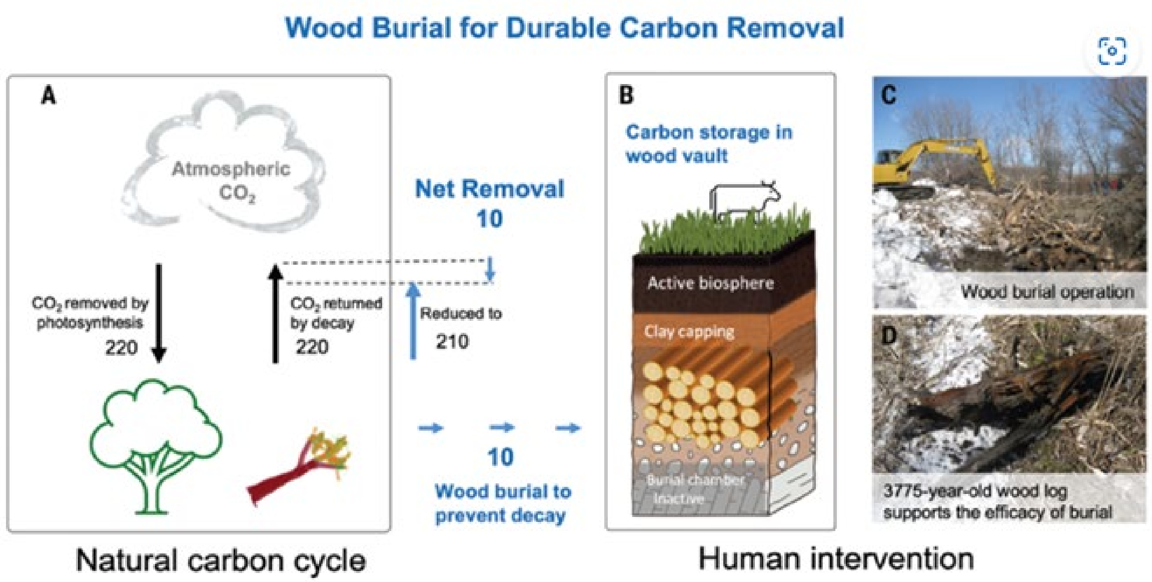

Fig. 1: Carbon sequestration through wood burial. *(A) In the natural terrestrial carbon cycle, the annual NPP from terrestrial photosynthesis is 220 $GtCO_2$ / year but is largely balanced by decay and decomposition, resulting in near zero net CO_2 removal. (B) We can bury up to 10 $GtCO_2$ / year (4.5% of NPP) in wood vaults, which are structures engineered to prevent decay, resulting in a net CO_2 removal of the same quantity. (C) A demonstration wood burial experiment conducted in 2013 near Montreal. (D) A 3775-year-old ancient wood log was discovered during the trench excavation, which supports the efficacy of burying wood in low-permeability soil to prevent decay. Black arrows represent natural carbon fluxes and blue arrows represent fluxes resulting from human intervention. Carbon fluxes are in $GtCO_2$ / year.*

The discovery site was located at Saint-Pie, Quebec, Canada, 50 km east of Montreal, at the corner of a crop field that gently slopes toward a creek. The surface was covered by sparse vegetation of grass and shrubs with scattered small trees. Most of the roots were within 1 m of the surface, with no visible roots below 1.5 m.

A 1959 Bagot soil survey identified this zone as belonging to Levrard Clay soil series. The soil profile showed an O-horizon from 0 to 0.1 m (litter, leaves, humus), a clay loam A-horizon from 0.1 to 0.7 m, a B-horizon from 0.7 to 2 m, and a C-horizon starting at 2 m, which was a water-logged blue clay deposited by the Champlain Sea that followed the end of the last ice age 13,000 years ago. The site is now located 44 m above sea level owing to the gradual rebound of the continent after the withdrawal of the Laurentide Ice Sheet.

The ancient log of Eastern red cedar was found at a 2-m depth. The log was surrounded by clay soil. The log featured loosely attached bark, which came off easily. Additionally, the log was saturated with water, but felt otherwise solid. We cleaned the log of loose soil and stored it in an air-conditioned room to naturally dry. In early 2022, we analyzed the sample for its microscopic structure, mechanical strength, density, and chemical composition.

For comparison, we also analyzed a freshly cut modern sample of same species Eastern red cedar.

3.2. Physical and chemical analysis

Both the modern and ancient samples were cut at one end to show the interior. Compared to the modern sample, the outermost layer of the ancient log was slightly flayed, but the wood was otherwise solid. We took subsamples from the sapwood region for subsequent analysis. We first used scanning electron microscopy to observe the cell structure, with the modern sample being intact and the ancient sample being generally well preserved. A small portion of the ancient sample shows slight cell wall thinning and cell distortion. This minor thinning occurs in the early wood section (larger lumen, due to rapid growth in spring and early summer), but not late wood (thick cell walls with small lumen). We can explain this location dependence of the decay as being due to the larger openings in the early wood more easily allowing penetration by decomposers. By contrast, the late wood portion appears perfectly preserved.

We subsequently characterized the physical properties and chemical components of both ancient and modern wood to determine the extent of carbon loss. The ancient wood has a density of 0.40 ± 0.02 g/cm^3, marking a 13.6% reduction compared to the modern sample, which has a density of 0.46 ± 0.023 g/cm^3. Although this may in part reflect carbon loss, the quantitative interpretation is complicated by a number of factors, such as variability within wood samples and different climatic growth conditions. Wood consists of holocellulose, lignin, extractives, and ash. Holocellulose (cellulose and hemicellulose) and lignin form the basic wood cell structure, which typically accounts for 80 to 95% of the wood carbon. Extractives are macromolecules that reside inside the cell walls, and ash is primarily mineral particles. In a typical wood decay, cellulose and hemicellulose are more easily decomposed, whereas lignin is highly resistant because its amorphous polymer structure is hard to digest by most decomposers…

3.3. Mechanisms for preservation

In terms of the preservation condition, we attribute the slow wood decomposition process to the characteristics of clay soil at the site. Biological degradation of wood requires three factors: oxygen, moisture, and suitable temperature (22). At the Montreal site, moisture is not a limitation, and the temperature is relatively cool at an annual average of 7°C, which can slow down but not stop biological activity. Therefore, we identify the lack of oxygen as the main reason for the observed preservation. Clay soil with low permeability prevents or drastically slows down oxygen from penetrating into the burial space. Any initial oxygen at the time of enclosure would have long since been consumed by a small amount of organic decomposition. Also, soil and root respiration in the active biosphere above constantly consumes oxygen such that an oxygen extinction depth is reached typically at 1 to 2 m below the surface.

Final author's comment: One other method for intermediate carbon storage in wood – build long-lived structures out of the wood, and at the end of their life sequester the demolished structure's wood as described above.