Why Not Soil Carbon?
Atmospheric CO_2 Reduction in Soils of Agroecosystems- A Logical, Practical and Economical Solution!

In 2009, the U.S. Environmental Protection Agency formally declared carbon dioxide (CO_2) a dangerous pollutant, and started looking for: "the most efficient, most economy-wide, least costly, and least disruptive way to deal with CO_2 pollution"[1]. There are three approaches for reducing the amount of CO_2 in our atmosphere: employ energy efficiency and conservation practices, use low-carbon or carbon-free energy technologies for energy production(renewables), and/or capture and store CO_2 from the combustion of fossil fuels or capture it directly from the atmosphere. There have been sustained efforts for significant adoption of conservation and efficiency practices and renewable-energy technologies over the previous two decades; however, global energy use is predicted to increase 25% between now and 2040. Oil consumption will continue to increase in coming decades, due to rising petrochemicals, trucking and aviation demands. Coal, and gas will remain as the largest and second-largest energy resource for electricity generation.[2] Since renewables and conservation practices are not reducing emission of CO_2 from fossil fuel use at pace significant enough to reduce atmospheric CO_2, the only option remaining is to capture and store the carbon resulting from fossil fuel combustion. The "ideal" attributes for any technology employed to capture and store these carbon emissions are: it must be robust, efficient, safe, economically feasible, and ready to implement. A majority of the currently proposed solutions for capturing and storing atmospheric CO_2 do not fulfill any of these attributes.

Carbon Capture Utilization and Storage (CCUS) is promoted as a process for reducing CO_2 emissions from power plants, but the economics of CCUS systems are proving to be cost prohibitive. Of the three surviving "pilot" CCUS projects in North America, all have gone over budget[3] and their estimated CAPEX costs are now ranging between \$48 to \$109 ton^{-1} of CO_2 captured[4]. The add-on costs for: overhead and maintenance ; transportation and storage; parasitic loads; and financing are not included in these estimates, and the cumulative costs for CCUS could more than double the electricity-rate costs for residential and commercial consumers[5]. Besides for the contingencies related to capture, the proof of concept for how to utilize or store the captured CO_2 coming from CCUS plants, still remains an issue. Transportation and geo-storage of captured CO_2 from a CCUS system carries the potential for migration and leaks, increased seismic activity, and aquifer acidification. The long-term liability issues related to geo-storage will be shouldered by the taxpayer with mechanisms similar to the liability structures in the nuclear energy industry. CCUS projects that employ Enhanced Oil Recovery (EOR) will store no net CO_2. Industry estimates for EOR efficiency ranges from 11%-42% of CO_2 remaining underground after

[1] Broder, J.M. (2011) EPA clears way for greenhouse gas rules, The New York Times 4/17/2009

http://www.nytimes.com/2009/04/18/science/earth/18endanger.html

[2] https://www.iea.org/weo2017/
[3] https://theenergymix.com/2018/12/05/ieefa-sees-failure-in-four-north-american-ccs-projects/
[4] https://fas.org/sgp/crs/misc/R44902.pdf
[5] https://theconversation.com/the-latest-bad-news-on-carbon-capture-from-coal-power-plants-higher-costs- 51440

injecting a ton of CO_2 into an oil-bearing formation.[6, 7] Other real-world studies estimate between 3.7 and 4.7 metric tons of CO_2 are emitted for every metric ton of CO_2 injected when considering the amount of oil produced[8]. Studies concerning readiness and scale have determined that the expected build rates, for future CCUS infrastructures, are now expected to be 100 times too slow and will capture less than 12% of the CO_2 reductions needed to meet a 2°C target.[9] Direct-air capture (DAC) using mechanical and/or chemical capture is expected to cost from \$92-\$234 and potentially up to \$600 ton^{-1} CO_2 and storage or utilization is still a problem[10].

Another alternative CO_2 capture and storage technology promotes forest growth on land previously cleared for agriculture. This approach captures small amounts of CO_2 as plant biomass. Research on reforestation[11] concluded, in the first 13 years, an average of 200-400 grams dry biomass m^{-2} year^{-1} were captured, or a little less than 0.23 tons of carbon captured ha^{-1} year^{-1}. These carbon sinks are not robust enough and are susceptible to rapid release of captured CO_2 if subjected to fire, as witnessed across the Western U.S. the last few years. This approach also has the long-term effect of reducing agricultural land and its potential productivity in a world that is gaining population as it loses productive land. These issues place the expected benefits of cropland re-forestation into uncertainty because cropland has decreased to 0.23 hectares per capita for a world of over 7 billion people[12]. Per capita cropland in 1960 was 0.5 hectares when world population was only 3 billion.[13] Another emerging critical agricultural problem, coupled with these land-area reductions, is the degradation in fertility of a significant portion of remaining soils as a result of conventional agricultural practices (plowing, synthetic fertilizer addition, herbicide, insecticide, fungicide applications). Each year 10 million hectares are abandoned due to soil erosion and/or diminished productivity, and another 10 million hectares due to salinization[14]. It is projected that globally, almost one-third of agricultural land has been lost since 1960 and those that remain are losing topsoil[15] at rates considered 6-10 times greater than the rate of soil formation. To compensate, this lost cropland is being replaced by clearing substantial portions of the world's rain forests promoting land area losses representing more than 60% of the deforestation now occurring worldwide[16].

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[6] United States Carbon Sequestration Council, Enhanced Oil Recovery & CCS, January 14, 2011.

[7] Peck, W.D. et al. (2018) Quantifying CO_2 storage efficiency factors in hydrocarbon reservoirs: A detailed look at CO_2 enhanced oil recovery. International Journal of Greenhouse Gas Control, 69: 41-51.

[8] Jarmillo, P., Griffin M.W., McCoy, S.T. (2009) Life Cycle Inventory of CO_2 in an Enhanced Oil Recovery System

Environ. Sci. Technol. 2009, 43, 8027–8032.

[9] Haszeldine, R.S., Flude, S. Johnson, G. Scott, V. (2018) Negative emissions technologies and carbon capture and storage to achieve the Paris Agreement commitments. Phil. Trans. R. Soc. A 376: 20160447. http://dx.doi.org/10.1098/rsta.2016.0447

[10] http://www.sciencemag.org/news/2018/06/cost-plunges-capturing-carbon-dioxide-air

[11] Turner, D.P., Guzy M., Lefsky M.A., Ritts, W.D., Tuyl, S.V., Law, B.E. (2004) Monitoring Forest Carbon Sequestration with Remote Sensing and Carbon Cycle Modeling Environmental Management, 33:457-466.

[12] Pimentel, D., (2000), Soil as an Endangered Ecosystem Bioscience, 50: 947

[13] Pimentel, D., Pimentel, M. (1996), Food, Energy and Society, Boulder, CO, Colorado University Press.

[14] Doeoes, B.R. (1994) Environmental degradation, global food production, and risk for larger scale migrations, Ambio 23:124-130

[15] Nearing M.A., Xieb Y., Liu, B., Ye, Y. (2017) Natural and anthropogenic rates of soil erosion. International Soil and Water Conservation Research 5: 77–84.

[16] Myers, N.A. (1990) The non-timber values of tropical forests forestry for sustainable development program, University of Minnesota, Nov. Report 10.

As this search for an effective solution continues, concerned governments around the globe are increasing their efforts to reduce CO_2 emissions. Countries are making an effort to conform to global treaties designed to reduce global atmospheric CO_2 concentrations but almost all are falling short of desired goals[17].

There is now a viable path forward that will allow robust, practical and economical carbon capture!

The COP 21 officially recognized soil carbon increases as legitimate CO_2 offsets on the world stage, opening the door for carbon capture in agro-ecosystems. The EU has created a similar regulatory framework for Climate-Smart Agriculture;[18] however, our conventional approach to agriculture will not be able to participate in this approach as it has been a big part of the problem. Conventional agricultural practices are net emitters of ~6% of annual world CO_2 emissions[19], causing unsustainable losses of soil and biodiversity; and the synthetic fertilizer and pesticide applications used to maintain productivity are polluting the water, air, soils, foods and environment of this planet[20].

Research at the Institute for Sustainable Agricultural Research (ISAR) at New Mexico State University (NMSU) and California State University Chico's Regenerative Agricultural Initiative (RAI) is demonstrating a viable, agricultural-based approach to carbon sequestration that avoids the problems related to conventional agriculture while fulfilling the "ideal attributes" for a bio-technological solution to reduce atmospheric CO_2 concentrations. This "**regenerative**" approach to agriculture, if applied at scale, could safely capture and sequester all annual anthropogenic GHG emissions for many decades. It is easy to implement, low cost, scalable, provides multi-decade storage capacity, utilizes a time-tested stable storage medium (soil organic matter), promotes added benefits for improving agro-ecosystem soil fertility and long-term sustainability of our agriculture systems. Adoption in agroecosystems prevents: both near and long-term depletion of natural resources (soil, water, mined nutrients, energy, etc.), soil degradation, biodiversity loss and legacy downstream environmental pollution by avoiding the application of synthetic fertilizers, herbicides, insecticide, and fungicides. This "agricultural approach for carbon capture" is implementable now, with no need to develop new infrastructure or train personnel; it is safe, clean, competitively priced; can be adopted worldwide (third world to first), and will eventually be self-promoting, requiring no further need for financial incentives.

The efficacy of this approach is based on mimicking biological mechanisms that evolved in grassland ecosystems over the last 50+ million years. Grasslands, along with the grazers that frequented them helped develop deep soil carbon profiles by pumping plant exudates through deep-rooted plants along with gradual buildup of high carbon soil surface profiles. This soil carbon build-up was encouraged by the actions of grazing animals (buffalo) herded into tight groups by predators, allowed to only graze about 30%-40% of the available forage, trample down the rest into the topsoil with hoof action and deposit close-proximity dung piles. These dung piles were then visited by dung beetles to roll this dung into balls to be place into the soil for food storage and breeding chambers. The existing soil temperature and humidity allowed this dung to compost in place and produce a soil that had high populations and beneficial structures of microbes. These systems had increased biodiversity and fully functioning soil

[17] https://www.unenvironment.org/interactive/emissions-gap-report/
[18] Towards an EU Regulatory Framework for Climate-Smart Agriculture: The Example of Soil Carbon Sequestration https://doi.org/10.1017/S2047102517000395
[19] https://www.c2es.org/content/international-emissions/
[20] Carvalho, F. (2017) Pesticides, environment, and food safety. Food and Energy Security 6-2:48-60

microbiota that worked mutualistically with the plants. The soils in these systems were re-inoculated with every pass the grazers made through an area. All of these actions stimulated improved forage productivity and significant soil carbon buildup.

ISAR' and RAI have built research on these biological phenomena, and is observing that promoting beneficial interactions between plants and soil microbes increases farm and rangeland's efficiency for the capture and storage of carbon in soil. These same interactions produce healthier soils that increase soil microbe carbon-use efficiencies reducing the relative rate at which soil carbon, as CO_2, is respired from the soil. When this Biologically Enhanced Agricultural Management (BEAM) technology is promoted in agro-ecosystems, it is feasible to capture and sequester an average of >11 metric tons of CO_2 hectare^{-1} year^{-1} in rangeland soils[21] and >36.7 metric tons CO_2 hectare^{-1} year^{-1} in transitioning farmland soils[22] for approximately $17-$22 ton^{-1} CO_2, or less than one-tenth the cost of EPA's recommended Carbon Capture Utilization and Storage (CCUS) technologies.

The health of a soil's microbiota is crucial for all plant growth occurring on this planet and low carbon stocks within these soil environments are detrimental to soil fertility, microbial community development, and plant survival. Human appropriation of land for agroecosystems has reduced earth's photosynthetic productive capacity approximately 14.8 Gt C y^{-1}[23] and decreased soil carbon resources 50% to 66% providing a historical carbon loss in soil systems of from 42 to 78 gigatons of soil carbon[24]. This loss of photosynthetic capacity can be restored through adoption of BEAM management protocols in soils of agroecosystems. The BEAM protocols improve the population, structure, bio-diversity and biological functionality of the microbiota in the soil. This biological functionality includes microbial processes that promote: free-living and symbiotic nitrogen fixation, carbon and nitrogen cycling, elemental (nutrient) metal oxidation, phosphorus solubulization, metabolism of methane and nitrous oxide, antibiotic/antimicrobial production, pesticide/xenobiotics bio-degradation, phytohormone production, and upregulation of biofilm formation andquorum sensing. Re-establishing a diverse and biologically functional microbial community into soil structures enables agricultural systems to mimic the biological dynamics present in natural ecosystems. Natural ecosystems require no nutrient amendments, no tillage, and no weeding, but they remain some of the most productive with regards to biomass production. Old growth forests, riparian zones and estuaries produce the largest terrestrial quantities of annual biomass (1570-1783 grams dry biomass/m^2/year)[25] and have historically promoted transfer of large quantities of carbon into soils.

ISAR's research, on BEAM fields in agro-ecosystems, has demonstrated biomass production greater than 3,100 grams dry biomass m^{-2} year^{-1}, by mimicking nature's biological barter between plants and microbes using regenerative agriculture practices. This is over double the biomass production of natural ecosystems, and ~3 times greater than the 937 grams dry biomass m^{-2} year^{-1}, estimated in cultivated land[24], all from focusing on enhancing microbial communities in agricultural soils.

[21] http://www.jswconline.org/content/71/2/156.full.pdf+html

[22] https://peerj.com/preprints/789/

[23] Krausmann F., Erb. K.H., Gingrich S., Haberl, H., Bondeau, A., Gaube, V., Lauk, C., Plutzar, C., Searchinger, T.C. (2013) Global human appropriation of net primary production doubled in the 20th century. Proceedings of the National Academy of Sciences. 110 (25) 10324-10329; DOI: 10.1073/pnas.1211349110

[24] Lal, R. (2004) Soil Carbon Sequestration Impacts on Global Climate Change and Food Security. www.sciencemag.org Science 304:1623-1627 doi: 10.1126/science.1097396

[25] https://daac.ornl.gov/NPP/other_files/worldnpp1.txt

Slowing the turnover of these carbon components in the soil is a critical issue for the success of this approach. The average mean residence times for organic carbon in boreal, temperate and tropical ecosystems ranges from 200-1200 years[26]. Biomass structure, microbial actions, and environmental conditions are key mechanisms for promoting efficient long-term capture of soil carbon derived from atmospheric CO_2. Regenerative agriculture management systems accomplish this by both working with nature to capture larger quantities of atmospheric CO_2 through improved growth of biomass, and as well demonstrate increases in soil microbiome carbon-use efficiency with a 4 to 6 times decrease in the relative respiration rate of the carbon. Essentially this approach **increases the amount of carbon flowing in**" from improved system efficiency for energy (carbon) capture while simultaneously "**reducing the amount of carbon flowing out**" resulting from microbial community structure related increases in carbon-use-efficiency.

Both the carbon excess in our atmosphere and the carbon deficit in our agricultural soils can be managed with one simple solution: the capture and incorporation of atmospheric CO_2 into plant and soil microbial biomass to promote buildup of soil carbon pools, effectively and economically reducing excess atmospheric CO_2 to the benefit and promotion of a sustainable regenerative agricultural model.

An electrical utility company could fulfill any commitments it makes for CO_2 emissions reduction through purchase of soil carbon offsets from an agricultural trading exchange and offer them to their customers for approximately $0.01/kWh. Fuel costs for gasoline and diesel would realize a ~$0.15 - $0.18 increase per gallon. Airlines could become "Carbon Neutral" where each passenger could contribute less than the cost of a beverage on that flight (~$2.43/passenger for medium distance flights). Each of these examples represents an average 6% increase in energy costs for consumers.

This regenerative approach does not require high-tech equipment or have high costs for implementation. It can be practiced in any country, by farmers and ranchers of any ability, creating economic opportunities and benefits worldwide, even including third world countries. This process treats CO_2 as a critical nutrient, not a pollutant, completing a normal, natural cycle for global carbon flow, one that nature has perfected over the last ~437 million years. Atmospheric carbon reduction, resulting from implementation of regenerative agriculture practices, leaves no toxic byproducts, regenerates oxygen back into our atmosphere, builds soil fertility, improves the efficiency of water infiltration, storage and use in agro-ecosystems, while promoting sustainable production of food and fiber.

Due to its low cost, regenerative agriculture will enable and encourage society to proactively address the impacts of increased atmospheric CO_2 concentrations while simultaneously easing extraction pressures on natural resources and our environment. Implementation of this agro-ecosystem-based approach, for reducing atmospheric CO_2, will buy us time and conserve economic resources that can be better applied towards developing clean energy systems. This approach will offer a CO_2 sequestration technology that is traceable, verifiable, reliable, safe, and economically and environmentally friendly. Regenerative agriculture demonstrates a logical solution with multiple benefits for our society, our economy and the environment.

[26] Trumbore, S. (2000) Age of soil organic matter and soil respiration: radiocarbon constraints on Belowground C Dynamics, Ecological Applications 10:399-411