SEQUESTERING OF ATMOSPHERIC CARBON THROUGH PERMANENT DISPOSAL OF CROP RESIDUE

ROBERT A. METZGER[1] and GREGORY BENFORD[2]

[1]*Georgia Institute of Technology, Atlanta, GA, U.S.A.*
[2]*University of California, Irvine, CA, U.S.A.*

Abstract. We propose the sequestering of crop residues to capture a significant fraction (12%) of the present U.S. atmospheric carbon emission through disposal in deep oceans below the thermocline or in river deltas. In the United States, the annual carbon content in residues from corn, soybeans and wheat crops is approximately 250 million tonnes. Globally, an additional 1 billion tonnes of carbon in the form of crop residues may be available. Implementation of this sequestering proposal would allow the US to approach the CO_2 reductions stipulated under the Kyoto Protocol.

Seen in the largest perspective, our current atmospheric buildup of CO_2 stems from our first great invention, the discovery of fire. Given that, our eventual discovery of fossil fuel and our short political time horizons made a greenhouse problem inevitable. Perhaps we can offset our species' greenhouse effects by using our second great invention, agriculture, with some help from the wheel. Farming is the largest scale human activity, covering about 10% of the globe's land area. Perturbing this large effect offers a potential mechanism to help reduce anthropogenic carbon released into the atmosphere, based on a simple fact: a field of corn captures about 400 times as much carbon as there is in the annual increment of man made atmospheric carbon in the entire column of air above the field, from ground to space.[⋆] Harnessing this prodigious method of arresting carbon could give us great leverage over the global CO_2 imbalance.

It is estimated that worldwide human activities of fossil fuel and forest burning in the mid-1990's have resulted in annual carbon emissions of 7.4 Gigatonne of carbon (GtC). These emissions result in an atmospheric carbon increase of 3.5 GtC/year, with the remaining emitted carbon removed from the atmosphere by way of photosynthesis and plant growth (1.7 GtC) and transfer to the oceans (2.1 GtC) (Houghton, 1995; Schmidt and Kaiser, 1998; IPCC, 1996).

[⋆] This calculation assumes that an average acre of corn has a dry mass of 10 tonnes (grain, stalks, leaves and roots – with an average carbon content of 40%), containing 4.0 tonnes of carbon. In the air above the corn field, the additional CO_2 placed in the atmosphere due to human activities is 1.6 ppm per year, representing a total of 10 kg of carbon in the column of air above the cornfield to the reaches of space. Therefore, one acre of corn incorporates an equivalent amount of excess atmospheric carbon in the air column above 400 acres.

Climatic Change **49:** 11–19, 2001.

As pointed out by Dyson and Marland (1979), the solution to this dilemma must focus on ways to either accelerate carbon transfer from the atmosphere to other reservoirs of carbon or to bypass the atmosphere and place the CO_2 directly into other reserves. We view this acceleration of carbon transfer or complete bypass of certain segments of the carbon cycle to be divided into two distinct approaches: the first approach we refer to as pre-emission carbon sequestering, in which carbon is removed *before* emission, typically captured during the combustion process and subsequently sequestered. The second approach we refer to as post-emission carbon sequestering, in which the carbon is removed from the atmosphere *after* emission has taken place. Post-emission processes offer an intrinsic advantage over pre-emission processes, in that for a post-emission process, one can view the carbon cycle pathways in which anthropogenic carbon is transferred to plants through photosynthesis, or to the oceans, as partner mechanisms in removing carbon from the atmosphere. This partnership mechanism is evidenced by the fact that of the 7.4 GtC annually emitted into the atmosphere due to man's activities, atmospheric CO_2 increases by only 3.5 GtC.

Pre-emission approaches to anthropogenic carbon reductions are being actively considered. It has been proposed that CO_2 in either gaseous or liquid form, produced as a byproduct of combustion or hydrogen production, can be sequestered in the deep oceans (Marchetti, 1997; Herzog et al., 1997; Parson and Keith, 1998). Brewer et al. (1999) have recently examined the behavior of liquid CO_2 in ocean depths in excess of 3000 m, observing the behavior of hydrate formation. Other plans on using the deep oceans as a sequestering site include the use of solid CO_2 in the shape of torpedoes which can be dropped into the ocean and subsequently penetrate the ocean floor where temperatures and pressures will keep the CO_2 in solid form (Murray et al., 1996). Other sequestering sites for gaseous CO_2 include the injection into deep saline reservoirs, such as the effort which has been implemented by STATOIL, a Norwegian energy company, beginning in 1996, which has been separating CO_2 from natural gas and injecting it, at a rate of 1 million tonnes per year, into a deep saline reservoir 800–1000 meters below the ocean floor in the North Sea (Korbol and Kaddour, 1995). Other potential sequestering sites include active and depleted oil and gas reservoirs, and mined cavities in salt domes (Holloway, 1997; Hertzog et al., 1997).

In terms of post-emission proposals, one of the earliest was that by Dyson (1977) and Dyson and Marland (1979) in which they propose that increased growth of plants, in particular, in the form of trees, would act as a reservoir of carbon. While the potential carbon storage for such an approach can be large, it is a temporary sequestering approach in which the carbon will be returned to the atmosphere when the plants die – but has the potential to sequester large amounts of carbon while other long-term sequestering approaches are being developed. Other post-emission approaches include the seeding of the Southern Ocean around Antarctica with powdered iron which increases plankton growth, and in turn removes atmospheric CO_2, in which the carbon content of the plankton may sink and be

TABLE I

Carbon reservoirs (Houghton, 1995; Schmidt and Kaiser, 1998; IPCC, 1996)

Atmospheric:	720 GtC
Biosphere:	550–830 GtC
Soils	1500 GtC
Fossil fuel reserves	6000 GtC
Deep oceans	38,000 GtC
Marine sediments	20,000,000 GtC

sequestered in the deep ocean when the plankton die (Martin et al., 1990; Peng and Broecker, 1991).

We propose a new post-emission sequestering approach, crop residue sequestering (CRS), which takes advantage of the biosphere's ability to cycle large amounts of carbon as pointed out by Dyson (1977), but bypasses the atmospheric portion of the carbon cycle, so that the byproducts of decay do not enter into the atmosphere. We propose to sequester carbon in the form of unwanted crop residues in river deltas or the deep ocean, where the unwanted crop residues are those portions of crops which remain above ground after harvesting and which are not needed to control soil erosion.

The great advantages of sequestering carbon from crop residues are that this approach:

(a) uses biomass that is now mostly left to rot in the fields,
(b) demands no new land,
(c) uses residues that can be gathered and shipped with the same equipment used to bring in the crop,
(d) requires no new technologies or transport systems to gather and ship the residues,
(e) available crop residues scale with population growth since food production scaleswith population growth, and
(f) is a post emission process.

In the global carbon budget, as illustrated in Table I (Houghton, 1995; Schmidt and Kaiser, 1998; IPCC, 1996), the deep oceans sequester the vast bulk of the world's carbon. The oceans are not CO_2 saturated, and the deep ocean circulates carbon back to the surface in times measured in millennia (Watts, 1997; Marchetti, 1997; Kitani and Hall, 1989). The time scale, t_d , for vertical transport of materials within the oceans at a depth, d, back to the surface can be estimated by (Hoffert et al., 1980):

$$t_d = d^2/k \text{ where } k \text{ approx } = 0.6 \times 10^{-4}\ \mathrm{m^2/s} \text{ or approx } 2000\ \mathrm{m^2/yr}\,.$$

For the case of transporting crop residues to regions of deep oceans and letting them sink to the ocean floor, a depth of 4000 meters would exhibit a vertical transport of 8000 years for their decay products (CO_2 and various hydrocarbons). This is a worst case situation in which the crop residues lay exposed on the ocean floor and their decay byproducts easily enter into the ocean's waters. If the crop residues become embedded beneath the ocean floor during sinking, or by subsequent covering due to silting or other covering mechanisms, then this time would be much greater. The critical point is that sequestering of crop residues on or within deep ocean floors inhibits their decay byproducts from entering the atmosphere for many millennia.

For this analysis we focus upon using farm residues in the U.S., for which data is extensive (Bull and Sandretto, 1996; Agricultural Statistics, 1997; Kitani and Hall, 1989; Heid, 1984). Generally, most crop residues have 40% by weight of carbon (Donahue et al., 1977). We analyze primarily corn production because it is the single largest U.S. crop in both acreage planted and crops produced. It is extremely efficient at fixing carbon, using a highly efficient C4 photosynthesis process (Purvis and Orians, 1983), yielding about three times more grain per acre harvested than wheat, which grows under more common C3 photosynthesis processes (Agricultural Statistics, 1997). In 1996, according to U.S. Department of Agriculture statistics, 79 million planted acres produced 236 million tonnes of corn, or 3.00 tonnes/acre. Crops typically generate 1.5 pounds of residue for each pound of harvested material, so in the case of corn, residues of 4.5 tonne/acre can be expected (Heid, 1984).

Most crop residues can be removed without nutrient penalty. Historically, farmers tilled residue back into the soil, believing that it would increase the soil organic matter (SOM) content. However, research shows that in fact this practice leads to long term reduction of organic matter in the soil, due to disruption of soil microfauna (Vyn and Raimbault, 1993; Janovicek et al., 1997; Capbell et al., 1995; Franzluebbers et al., 1995; Peterson et al., 1998). As a specific example, it was found that under no-till methods (in which crop residue was left on the soil surface), when compared to conventional tillage, that the carbon content in the soil was 35%, 39%, and 53% greater for wheat, sorghum, and soybean crops, respectively (Franzluebbers et al., 1995).

Varying degrees of conservation tillage methods (of which zero tillage represents the extreme) – those in which at a minimum, at least 30% of the soil surface is covered by residue after planting – are available. Conservation tillage is used primarily on corn, soybeans and small grains (Bull and Sandretto, 1996) – those crops which we are proposing to use as our primary sources of crop residue. By 1994, more than 45% of corn and soybean acreage was conservation-tilled. Zero till methods for corn production more than tripled from 1989 to 1994, increasing from 5% to 17%. Such statistics clearly show trends toward less and less tilling (Bull and Sandretto, 1996). This suggests that as conservation and zero tillage methods are more widely used, greater amounts of crop residue will be available for harvesting.

TABLE II

Major united states crop

Crop	Acres planted (million)	Residue/acre (tonne)	Total residue (million tonne)	Total carbon (million tonne)
Corn	79	4.5	356	142
Soybeans	63	2.0	126	50
Wheat	76	1.5	114	46
Total			596	238

After corn, the three next largest U.S. crops by acreage are wheat (76 million acres), soybeans (63 million acres), and hay (61 million acres). For this analysis we assume that hay generates no collectable residues, since the crop is usually taken down to the roots. We also neglect rice, though in the U.S., much of its residue rots in moist fields, releasing methane, a much more powerful greenhouse gas than CO_2. Crop residues of those we are interested in for this study typically yield 1.5 times the harvested crop mass (Heid, 1984), and we shall consider this also the case for soybeans for this analysis. (Often, though, soybean residues are plowed under to replace nitrogen in the soil. Whether this practice would survive a carbon credit pricing is unclear.) Table II illustrates the amounts of residues available from these major crops as well as the equivalent carbon, based on an average carbon content in these crops of 40% (Donahue et al., 1977).

If we assume a typical erosion abatement policy that leaves 25% of the residue on the field, this yields a total potential carbon reserve in these crop residues of 180 mtC (million tonne of carbon). In terms of United States carbon emissions, in 1990, the U.S. emitted 1340 MtC (Sutherland, 1998). For a compounded annual emission increase of 1.5% (Sutherland, 1998), current emission levels (2000) can be estimated to be approximately 1550 MtC. The 180 MtC of available crop residues represents nearly 12% of total U.S. carbon emissions. Under the Kyoto Protocol, U.S. emissions are to be reduced to a level of 7% below the 1990 level by 2012, which represents an annual emission of approximately 1250 MtC – a level of 300 MtC below current emission levels. If permanently sequestered, the 180 MtC available in crop residues, would offset 60% of the *excess* U.S. CO_2 emissions above the level stipulated by the Kyoto Accord. In addition, it should be noted that because this is a post-emission approach, that much more than 180 MtC would need to be removed in a pre-emission process in order to show the same net decrease of 180 MtC in atmospheric CO_2.

Because other nations, particularly those just developing, make more extensive use of their crop residue for animal fodder, fuel and manufacture, estimating waste in these locations is difficult. China appears to use about 40%, whereas

Bangladesh is nearer 90%. Availability will depend on any carbon credit which enters as another 'market' to compete for these uses.

However, the potential can be estimated. Considering only grains (wheat, milled rice, and corn), the total combined world production in 1996 was 536 million tonnes of wheat, 372 million tonnes of milled rice, 810 million tonnes of corn and other coarse grains, for a total of 1718 million tonnes (Agricultural Statistics, 1997). Assuming an average crop residue of 1.5 times the crop yield implies 2.58 Gt total available world crop residue, representing 1.0 GtC. This amount of carbon represents nearly 17% of the ROW (rest of world) carbon emission [World emission – U.S. emission].

Having established the availability of vast carbon sources in crop residues, how can one permanently sequester the carbon? Three possible methods appear practical: sequestering in exhausted oil/gas fields or beneath salt domes (Watts, 1997); sinking in oceans (both shallow and deep beneath the thermocline); or burning in power plants to replace oil and coal (Watts, 1997).

In each case the crop waste must first be harvested, bailed, and readied for transport. Estimated costs for this range from \$8 to \$26 per ton for various studies and different crops, with a mean cost of about \$20 per ton for biomass uses. (Currently, only 3% of U.S. biomass power production comes from farm waste (Watts, 1997). Crop residue for energy production is generally undesirable, burning at low temperatures and depositing unwanted minerals on heat exchange surfaces (Kitani and Hall, 1989).)

Sequestering in depleted gas/oil fields and beneath salt domes would require grinding up the waste, and transforming it into a slurry to be pumped down. This is a distinct cost disadvantage, although there may be some advantages to this approach if one could use existing pipelines to transport it, and transportation distances might not be far. Both salt domes and depleted gas/oil fields are plentiful in the U.S.A. midwest, the region producing much corn waste. These methods should be explored, but face questions about how long carbon can be so trapped.

Here we propose two sequestering sites – near the coast in shallow waters above the thermocline, and further out, beneath the thermocline. Simply offloading corn waste into an actively depositing river delta like the Mississippi's can bury it within days as later river silt falls upon it. We know of no study measuring how long deposited organic matter takes to decay into gas which reaches the surface (CO_2 or methane), though short times $\sim$ years seem probable. Gulf deposits near the coast save on transport at sea, but deposition times of only years may preclude their use (Murray et al., 1996; Zepp and Sonntag, 1995; Hedges and Keil, 1995).

In the Gulf of Mexico, excursions $\sim$100 km from the delta reach deep ocean waters. Below ocean depths of about 1 km lies the thermocline, where there is little oxygen and temperatures are only a few degrees above 0 °C. This anaerobic environment mixes with surface waters very slowly, requiring centuries to millennia (Watts, 1997; Hoffert et al., 1980). Simply dropping baled waste, with weights attached to ensure that trapped air does not make the bales float, should then sequester the waste. (The weights could be made of carbon-rich solid wastes which, left on land, would normally decay into CO_2; this sequesters more carbon.)

To make doubly sure, and extend the sequestering time, one might shape the waste into cylinders with conical weight heads. These ‘carbon torpedoes’ would penetrate the bottom sediments to several meters, sealing in decay products. This may prove particularly useful, since then trapped methane or CO_2 can attain the concentration where stable hydrates of methane or CO_2 form, securing the carbon for very long times (Murray et al., 1996; Zepp and Sonntag, 1995; Hedges and Keil, 1995).

Depositing the entire disposable U.S. waste tonnage, 450 Mt, would cost about $22.5 billion if total collection and transport costs were $50/ton.* Still, $22.5 billion seems a small cost to hide 12% of all U.S. emitted carbon; and nearly satisfying Kyoto levels. Scaling this result to other nations makes sense only for those nations already producing substantial crops that may be easily moved to ocean dumping sites. This probably includes some European states, the Ukraine and a few developing nations such as South Africa.

This proposal is qualitative, outlining areas that should be explored: the fate of wastes in deltas, shipping costs for farm residue, and other economic factors. Intended as stimulating, not definitive, we conclude with a few thoughts on tradeoffs and political realities.

Hiding waste carbon is a general strategy suggesting other approaches. There can be many local adaptations, large and small. For example, many cities separate organic waste during their trash collections and dump it in landfills or nearby ocean beds, where it quickly generates both CO_2 and methane (a far worse greenhouse offender than CO_2). New York City dumps most of its general wastes off the aptly named Fresh Kill point, creating a large, lifeless, anoxic zone. Far better to send barges of organic waste 200 miles offshore, where it would fall to the deep ocean bed beneath the thermocline.

The U.S. confronts an embarrassing mismatch between its high emissions and a general unwillingness to incur high costs to offset these. Estimates of $100 billion to comply with the Kyoto Protocols are common and the need for 15 TWatt of power by the year 2050, with no net carbon emission has been argued (Hoffert et al., 1998). Much political opposition also arises from the perception that Kyoto means sending tax dollars to distant lands, through a system of carbon credits, for which there is little domestic support.

Farm waste disposal promises to lower such costs, with political bonuses. The $10–$20 billion per year spent to sequester farm residue will go to the American heartland, into the hands of ordinary laboring people such as farmers and truck drivers. It demands no new infrastructure and is easily stopped if unwanted effects occur.

---

* The $50/tonne estimate uses the average value of $20/tonne to collect and ready the crop residue for transport, with the remaining $30/tonne allocated for transportation costs.

A program of domestic carbon credits exchanged in a market could drive efficiencies in disposal. After all, waste need not be cleanly handled, as are edible crops; coal barges will serve nicely. Such bulk disposal is the simplest, lowest tech way to hide carbon from our atmospheric cycle. As a bonus, it will give ordinary working people a feeling that they, too, can do something active about climate change. And because farm waste plausibly rises with population, as does energy use, this sequestering method will then keep pace with the predicted rise of our numbers to ten billions within a half century.

References

Agricultural Statistics: 1997, United States Department of Agriculture, National Agricultural Statistics Service ISBN 0-16-049031-6. For wheat I-1, for corn, I-25 for soybeans, III-13.

Brewer, P. G., Friederich, G., Peltzer E. T., and Orr, F. M.: 1999, 'Direct Experiment on the Ocean Disposal of Fossil Fuel CO_2', *Science* **5416**, 943–945.

Bull, L. and Sandretto, C.: 1996, *Crop Residue Management and Tillage System Trends*, ERS Statistical Bulletin #930, August.

Capbell, C. A., McConkey, B. G., Zenter, R. P., Dyck, F. B., Selles, F., and Curtin, D.: 1995, 'Carbon Sequestration in a Brown Chernozem as Affected by Tillage and Rotation', *Can. J. Soil Sci.* **75**, 449–458.

Donahue, R. L., Miller R. W., and Shickluna, J.: 1977, *Soils – An Introduction To Soils and Plant Growth*, Prentice Hall, Englewood Cliffs, NJ, p. 145.

Dyson, F. J.: 1977, 'Can We Control the Carbon Dioxide in the Atmosphere?', *Energy J.* **2**, 287–291.

Dyson, F. J. and Marland, G.: 1979, *Technical Fixes for Climatic Effects of CO_2 in Workshop on the Global Effects of Carbon Dioxide from Fossil Fuels, 1977*, Rep. CONF-770385, U.S. Dept. of Energy, Washington D.C., pp. 111–118.

Franzluebbers, A. J., Hons F. M., and Zuberer: D. A., 1999: 'Tilage and Crop Effects on Seasonal Soil Carbon and Nitrogen Dynamics', *Soil Sci. Soc. America* **59**, 1618–1624.

Hedges, J. I. and Keil, R. G.: 1995, 'Sedimentary Organic-Matter Preservation – An Assessement and Speculative Synthesis – Closing Comment', *Marine Chem.* **49**, 137–139.

Heid, G. W.: 1984, *Turning Great Plains Crop Residues and Other Products into Energy*, USDA Economic Research Service, Agricultural Economic Report 523, November.

Hertzog, H. J. and Drake, E. M.: 1998, 'CO_2 Capture, Reuse, and Sequestration Technologies for Mitigating Global Climate Change', in *Proceedings of the 23rd International Technical Conference on Coal Utilization & Fuel Systems*, Clearwater, FL, March 9–13, pp. 615–626.

Hertzog, H. J., Drake, E., and Adams, E.: 1997, *CO_2 Capture, Reuse and Storage Technologies for Mitigating Global Climate Change*, Final Report DOE Order No. DE-AF22-96PC01257, Energy Laboratory, Massachusetts Institute of Technology, Cambridge, MA.

Hoffert, M. I., Caldeira, K., and Jain, A. K., 1998: 'Energy Implications of Future Stabilization of Atmospheric CO_2 Content', *Nature* **195**, 881–884.

Hoffert, M. I., Callegari A. J., and Hsieh, C. T., 1980: 'The Role of Deep Heat Storage in the Secular Response to Climatic Forcing', *J. Geophys. Res.* **85** (C11), 6667–6679.

Holloway, S.: 1997, 'An Overview of the Underground Disposal of Carbon Dioxide', *Energy Convers. Mgmt.* **38**, s193–s198.

Houghton, R. A.: 1995, 'Land-Use Change and the Carbon Cycle', *Global Change Biol.* **1**, 275–287.

IPCC: 1996, 'Climate Change 1995: The Science of Climate Change: Contribution of Working Group I to the Second Assessment of the Intergovernmental Panel on Climate Change', in Houghton J. T., Meira Filho, L. G., Collander, B. A., Harris, N., Kattenberg, A., and Maskell,

K. (eds.), *Intergovernmental Panel on Climate Change 1996*, Cambridge University Press, Cambridge, U.K.

Janovicek, K. J., Vyn T. J., and Voroney, R. P.: 1997, ‘No-Till Corn Response to Crop-Rotation and In-Row Residue Placement’, *Agron. J.* **89**, 588–596.

Kitani, O. and Hall, C. W. (eds.): 1989, *Biomass Handbook*, Gordon and Breach Science Publishers, Chap. 1.1.5, p. 56.

Korbol, R. and Kaddour, A.: 1995, ‘Sleipner Vest CO_2 Disposal – Injection and Removed CO_2 into the Utsira Formation’, *Energy Convers. Mgmt.* **36**, 509–512.

Marchetti, C.: 1997, ‘On Geoengineering the CO_2 Problem’, *Clim. Change* **1**, 59–68.

Martin, J. H., Fitzwater S. E., and Gordon, R. M.: 1990, ‘Iron Deficiency Limits Phytoplankton Growth off Antarctic Waters’, *Global Biogeochem. Cycles* **4**, 5–12.

Murray, C. N., Visintini, L., Bidoglio, G., and Henry, B.: 1996, ‘Permanent Storage of Carbon Dioxide in the Marine Environment: The Solid CO_2 Penetrator’, *Energy Convers. Mgmt.* **37**, 1067–1072.

Parson, E. A. and Keith, D. W.: 1998, ‘Climate Change: Fossil Fuels without CO_2 Emissions’, *Science* **282**, 1053–1054.

Peng, T. H. and Broecker, W. S.: 1991, ‘Dynamical Limitations of the Antarctic Iron Fertilization Strategy’, *Nature* **349**, 227–229.

Peterson, G. A., Halvorson, A. D., Havlin, J. L., Jones, O. R., Lyon D. J., and Tanaka, D. L.: 1998, ‘Reduced Tillage and Increasing Cropping Intensity in the Great Plains Conserves Soil C’, *Soil Tillage Res.* **47**, 207–218.

Purvis, W. K. and Orians, G. H.: 1983, *Life – The Science of Biology*, Sinauer Associates, Sunderland, MA, p. 200.

Schmidt, K. and Kaiser, J.: 1998, ‘Coming to Grips with the World’s Greenhouse Gases’, *Science* **281**, 504–506.

Sutherland, R. J.: 1998, ‘Strategies for Carbon Reduction’, *Science* **281**, 647–648.

Vyn, T. J. and Raimbault, B. A.: 1993, ‘Long-Tern Effect of 5 Tillage Systems on Corn Response and Soil-Structure’, *Agron. J.* **85**, 1074–1079.

Watts, R. G. (ed.): 1997, *Engineering Response to Global Climate Change*, Lewis, New York.

Zepp, R. G. and Sonntag, Ch.: 1995, *Process that Control Storage of Nonliving Organic Matter in Aquatic Environments*, John Wiley and Sons.

(Received 26 March 1999; in revised form 21 August 2000)