# The Charcoal Vision:
# A Win–Win–Win Scenario
## for Simultaneously Producing Bioenergy, Permanently Sequestering Carbon, while Improving Soil and Water Quality

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in Agron J 100:178-181 (2008) DOI: 10.2134/agrojnl2007.0161

Processing biomass through a distributed network of fast pyrolyzers may be a sustainable platform for producing energy from biomass. Fast pyrolyzers thermally transform biomass into bio-oil, syngas, and charcoal. The syngas could provide the energy needs of the pyrolyzer. Bio-oil is an energy raw material (~17 MJ $kg^{-1}$) that can be burned to generate heat or shipped to a refinery for processing into transportation fuels. Charcoal could also be used to generate energy; however, application of the charcoal co-product to soils may be key to sustainability. Application of charcoal to soils is hypothesized to increase bioavailable water, build soil organic matter, enhance nutrient cycling, lower bulk density, act as a liming agent, and reduce leaching of pesticides and nutrients to surface and ground water. The half-life of C in soil charcoal is in excess of 1000 yr. Hence, soil-applied charcoal will make both a lasting contribution to soil quality and C in the charcoal will be removed from the atmosphere and sequestered for millennia. Assuming the United States can annually produce $1.1 \times 10^9$ Mg of biomass from harvestable forest and crop lands, national implementation of The Charcoal Vision would generate enough bio-oil to displace 1.91 billion barrels of fossil fuel oil per year or about 25% of the current U.S. annual oil consumption. The combined C credit for fossil fuel displacement and permanent sequestration, 363 Tg per year, is 10% of the average annual U.S. emissions of $CO_2$–C.

THE TWIN CRISES of global climate change and the rapidly approaching inability of oil supplies to meet global energy demand are major social, political, and economic challenges of our time. There is growing scientific consensus that climate change is driven by anthropogenic emissions of greenhouse gasses to the atmosphere and that the use of fossil fuels for energy is the dominant source of the emissions (Intergovernmental Panel on Climate Change, 2007). Whether peak global oil production has already occurred or will occur in 30 yr is a subject of intense debate (Witze, 2007). However, finite reserves and rapidly increasing demand for oil will inevitably force world economies to abandon oil as the primary source of energy. No single solution to these challenges will likely ever be found; however, described herein is a vision for an integrated agricultural biomass–bioenergy system that could make a significant contribution to the solution to both problems and have the added benefits of enhancing soil and water quality.

The potential for ethanol production from cellulose is generating excitement and is currently the focus of much research and development activity. The capacity to produce ethanol from cellulose, using co-crops such as corn and wheat stover and dedicated biomass crops such as hybrid-poplars and switchgrass, greatly exceeds our capacity to produce ethanol from grain. The USDOE recently announced $385 million in Federal funding to support construction of six second-generation cellulosic biofuel plants that will each process 700 to 1200 tons of dry biomass per day to produce a total of >130 million gallons of cellulosic ethanol per year (USDOE, 2007). Within 10 yr numerous mega-biorefineries (~1800 metric tons of dry biomass per day) may be operating in the United States. The large size of these plants is envisioned to take advantage of inherent economies of scale.

Many agricultural scientists, farmers, and conservationists are concerned about the potential impact of biomass harvesting on soil and water quality. Crop residues, although often referred to as agricultural waste, are in fact a vital component of soil agroecosystems. Crop residues contain substantial amounts of plant nutrients (primarily C, N, K, P, Ca, and Mg), and if crop residues were harvested every year these nutrients would have to be replaced by increased fertilizer use. Many soil organisms utilize crop residues as their primary substrate, and these organisms are responsible for nutrient cycling, building of biogenic soil organic matter, and maintaining levels of soil organic C. Crop residues are critically important for building and maintaining soil structure, which facilitates root penetration and the movement of both air and water in soils. And, crop residues on soil surfaces enhance water infiltration, which increases available water to growing plants, and decreases the destructive effects of raindrop impact and surface runoff, which are the dominant causes of soil erosion. If all aboveground crop residues were removed year after year, the quality of our soils would rapidly deteriorate (Wilhelm et al., 2004). Production agriculture would require more fertilizer, more tillage, and more irrigation water to produce the same crops, and the quality of our surface and ground water would deteriorate due to increased leaching of plant nutrients and agrochemicals and higher sediment loads due to increased soil erosion. Furthermore, any C credit claimed for bioenergy production would have to be significantly discounted because of the loss of soil organic C and the substantial energy required for increased fertilizer manufacture and tillage. Much of the current scientific debate on the harvesting of biomass for bioenergy is focused on *how much can be harvested without doing too much damage*. I propose a fundamental paradigm shift, the scientific debate should be focused on *how to design integrated agricultural biomass-bioenergy systems that build soil quality and increase productivity so that both food and bioenergy crops can be sustainably harvested.*

Processing biomass through a distributed network of fast pyrolyzers has many potential advantages relative to the cellulosic ethanol platform. Fast pyrolyzers rapidly (~1 s) heat dry biomass (10% $H_2O$) to ~500°C and thereby thermally transform biomass into bio-oil (~60% of mass), syngas (~20% of mass), and charcoal (~20% of mass). The energy required to operate a fast pyrolyzer is ~15% of the total energy that can be derived from the dry biomass. Modern systems are designed to use the syngas generated by the pyrolyzer to provide all the energy needs of the pyrolyzer. Bio-oil is an energy raw material (~17 MJ $kg^{-1}$) that can be burned directly to generate heat energy or easily shipped to a refinery for processing into transportation fuels and various co-products (Bridgwater et al., 1999). Charcoal is also a potential energy product, however, I advocate returning the charcoal to the soils from which the biomass was harvested thereby closing the nutrient cycle in a way the mimics the soil building effects of natural prairie fires.

Applying charcoal to agricultural soils is a unique and vital part of The Charcoal Vision (Lehmann, 2007; Fowels, 2007; Laird, 2005). Recent research has shown that soils already contain substantial amounts of charcoal (Brodowski et al., 2005; Skjemstad et al., 2002). Reports vary, but our best guess is that 5 to 15% of the C in Midwestern prairie soils is charcoal, a legacy of 10,000 yr of prairie fires. More importantly, charcoal is hypothesized to have several positive impacts on soils (Glaser et al., 2002). First, charcoal is a fantastic adsorbent and when present in soils it increases the soil's capacity to adsorb plant nutrients and agricultural chemicals and thereby reduces leaching of those chemicals to surface and ground water. Second, charcoal contains most of the plant nutrients that were removed when the biomass was harvested and has the capacity to slowly release those nutrients to growing plants. Third, charcoal is a relatively low-density material that helps to lower the bulk density of high clay soils, increasing drainage, aeration, and root penetration, and charcoal increases the ability of sandy soils to retain water and nutrients. Fourth, charcoal is a liming agent that will help offset the acidifying effects of N fertilizers, thereby reducing the need for liming. Because of the positive aspects, substantial crop yield increases have been reported for the few trials where charcoal has been added to agricultural soils (Glaser et al., 2002). The half-life of C in soil charcoal is in excess of 1000 yr (Glaser et al., 2002). Thus soil-applied charcoal will make both a lasting contribution to soil quality and the C in the charcoal will be removed from the atmosphere and sequestered in the soil for millennia.

Assuming the United States can sustainably produce $1.1 \times 10^9$ Mg of biomass at 10% moisture annually from harvestable forest and crop lands (Perlack et al., 2005), then, national implementation of The Charcoal Vision would generate enough bio-oil to displace 1.91 billion barrels of fossil fuel oil per year (Fig. 1 ). This is about 25% of the current U.S. annual oil consumption and this would offset 224 Tg of fossil fuel C emissions to the atmosphere per year. Furthermore, assuming that fixed C in the charcoal (Bryan, 2006) is not biologically degraded; application of the charcoal to soils would sequester 139 Tg of C per year. The combined C credit for fossil fuel displacement and permanent sequestration, 363 Tg per year, is 10% of the average annual U.S. emissions of $CO_2$–C.

The potential to generate large quantities of carbon negative energy in a form that can replace petroleum-based liquid transportation fuels is a major advantage of The Charcoal Vision. Extrapolating this strategy to a global scale coupled with substantial increases in energy use efficiency and greater use of nuclear and other non-$CO_2$ generating energy sources, humanity could actually start decreasing levels of greenhouse gases in the atmosphere (Lehmann et al., 2006).

The Charcoal Vision also has numerous economic and infrastructure advantages over mega-biorefineries for the production of bioenergy. Pyrolyzers can be scaled from small to large to match locally distributed sources of biomass, thus minimizing transportation costs for bulky biomass (Badger and Fransham, 2006). Pyrolyzers are robust as they can process diverse sources of biomass. Cleanliness during harvesting, storage, and processing of biomass is not a major concern for the pyrolysis platform, but is problematic and raises the cost of the cellulosic ethanol platform. Biomass such as corn stover can be harvested with existing farm equipment (e.g., large round bales) when time, weather, and biomass condition permit, and can be stored on farm for timely delivery to a local pyrolyzer. By contrast, the harvesting of corn stover for a cellulosic ethanol plant will require a farmer to purchase a new combine that harvests both the grain and stover (Hoskinson et al., 2007), will require additional labor to handle both crops simultaneously, and will require new equipment and facilities to ensile the stover. Pyrolyzers are relatively inexpensive and can be financed locally. A distributed network of pyrolyzers will bring jobs and entrepreneurial opportunities to rural communities and allow a greater portion of revenue to be retained by those communities.

There are a few potential problems with The Charcoal Vision. The biggest problem is economics. If an energy company is paid only by the volume of fuel delivered, there will be no incentive to convert any of the biomass to charcoal. The charcoal will represent diverted raw material that could otherwise be turned into fuel, and hence, profits. Farmers will have a small incentive to apply charcoal to their fields, that is, long-term increases in crop yields and lower fertilizer bills. But, transportation and application of charcoal will take time and cost money with returns in future years. Hence, farmers renting land on short-term leases will have no incentive to apply charcoal. The obvious solution is some form of compensation to the owner of the pyrolyzer to make charcoal and to the farmer to apply the charcoal. The compensation could be through the sale of high value C sequestration credit contracts in the commodities markets or through direct government payments. Currently, contracts for C sequestration in agricultural soils are highly discounted because of uncertainty about the amount and the duration of C sequestered in agricultural soils, and because the United States opted out of the Kyoto treaty (Weersink et al., 2005). Contracts for C sequestration through charcoal applications to agricultural soils have the potential to be high value contracts, because the buyer would know exactly how many tons were applied and the buyer would have confidence that the C would be stable for 1000 yr. But without access to international markets, any such contracts would still be greatly discounted. Alternatively, direct government payments to farmers for charcoal applications could easily be justified, as the farmers would be providing critical environmental and ecosystem services to the rest of the nation.

Other potential problems with The Charcoal Vision include the development of technology needed to handle, spread, and incorporate charcoal into soils. Mishandling could result in substantial amounts of dust, which could pose air quality issues and be a threat to human health. Poor engineering and/or poor management of pyrolyzers could result in emissions of $NO_x$, CO, various volatile organic compounds, and dust, which would degrade air quality and release potent greenhouse gasses to the atmosphere. Properly engineered and managed, modern fast pyrolyzers will emit only $CO_2$ and water vapor.

None of the potential problems appear insurmountable. But to achieve this vision we need more research to verify the hypothesized positive aspects of charcoal applications to soils and to develop new agricultural management systems that incorporate charcoal applications as an integral component with the goal of enhancing soil quality and thereby increasing production of both food and fuel for society. Engineering research is needed to design robust and efficient pyrolyzers with effective emissions control systems, bio-oil refineries, and agricultural equipment for handling and incorporating charcoal. Economic research is needed to identify the optimum scale for a distributed network of pyrolyzers and to define aspects of government policy needed to incentivize the vision. Assigning a monetary value to intangible benefits such as reducing the threat of global climate change and enhancing energy security, food security, water quality, and rural economies is vital to development of visionary policies.

## ACKNOWLEDGMENTS

The author acknowledges Pierce Fleming for technical assistance and numerous discussions over coffee that help crystallize and focus The Charcoal Vision.

## NOTES

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