Can Portable Pyrolysis Units Make Biomass Utilization Affordable While Using Bio-Char to Enhance Soil Productivity and Sequester Carbon?

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Abstract—We describe a portable pyrolysis system for bioenergy production from forest biomass that minimizes long-distance transport costs and provides for nutrient return and long-term soil carbon storage. The cost for transporting biomass to conversion facilities is a major impediment to utilizing forest biomass. If forest biomass could be converted into bio-oil in the field, it may be more profitable to utilize forest biomass for bioenergy. Bio-oil can substitute for fuel oil, or be used as a crude oil and further refined into additional products. Transporting energy-dense bio-oil is more cost effective than transporting bulky, low-value biomass. In-woods pyrolysis can also address concerns over removing nutrients and carbon from forest sites through reapplication of bio-char, a pyrolysis byproduct, which is equivalent to the charcoal found in all fire ecosystems. Bio-char is 70-80 percent carbon and retains most nutrients contained in biomass. It can be used as a soil amendment to enhance soil productivity through a liming effect, which improves cation exchange capacity and base saturation, increasing anion availability, improving water holding capacity and decreasing bulk density. Charcoal is known to remain stable in soils for hundreds to thousands of years. Long charcoal residence times provide a way to quickly sequester atmospheric carbon by assimilating it into a recalcitrant form that can be applied to soils. In total the portable pyrolysis approach has the potential to improve the economic efficiency of biomass removal from overstocked forests through the in-woods conversion of biomass to bio-oil that avoids the costs and emissions of transportation to central facilities. Bio-char can be returned to the forest economically if pyrolysis occurs at or near the site of biomass removal. Reapplication of bio-char will sequester carbon in soil and may enhance site productivity.

Keywords: bioenergy, bio-oil, carbon sequestration, fuels reduction, soil productivity

Introduction

Forest biomass accumulation is both a problem and an opportunity. Increasing forest biomass is a consequence of continuous forest growth, effective fire suppression tactics, lack of harvest activities, and other management practices. Young growing forest stands quickly become overstocked with numerous small diameter tree stems, slowing individual tree growth and causing stem exclusion processes to initiate (Oliver and Larson 1990). Prior to implementing effective fire suppression tactics, some fire-adapted ecosystems (i.e. low-elevation, frequent fire regime forests), burned regularly, often as cooler understory fires or moderate severity fires that served to limit biomass accumulation, release nutrients

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and improve stand vigor (Agee 1996; Stanturf and others 2002). Pre-commercial thinning is also used to restore ecological function (Thibodeau and others 2000). Without frequent burning or thinning such overstocked forests contain abundant ground level biomass and experience considerable mortality of subordinate trees as dominant stems emerge. This fuel buildup has resulted in high-severity stand replacing fires, which captures the attention of those living in developments at the wild land interface. As a consequence of increasing wildfire occurrence and intensity, public land managers in fire-prone areas have once again begun to thin overstocked stands with a focus on fuels reduction, even though the area actually being treated is small relative to that in need of treatment.

Removed biomass adds to the equally large volume of biomass that is commonly found at landings of logging operations where whole-tree yarding is practiced (Perlack and others 2005). This accumulated biomass from thinning and harvesting practices is typically flared to avoid continued risk of fire as the slash piles dry. Onsite flaring releases greenhouse gases, energy and carbon captured by natural forest processes, and concentrates nutrients at burn pile locations.

Opportunity for Bioenergy

Utilization of biomass offers a potential solution to the problem of hazard fuel accumulation. Developing markets for biomass may provide managers and land owners a way to achieve management objectives if forest operators have a viable opportunity to sell biomass and land managers have the ability to contract for product removal. Potential markets for biomass utilization include products such as small-wood furniture and structures, garden mulch, bioenergy, chemicals, and other products (Hakkila 1989; LeVan-Green and Livingston 2003). Of particular interest at this time is abundant energy contained in biomass that can be tapped as an alternative to fossil fuels and avoid greenhouse gas emissions. Bioenergy production is most attractive when fossil fuel energy prices increase, but as greenhouse gas emissions become an increasing concern it also causes us to look for alternative, renewable and low emissions energy sources. Bioenergy production from forests may meet that need. It is particularly interesting with the coincident occurrence of enhanced energy security needs, requirements to reduce emissions of carbon, and the requirement to remove biomass from forest stands.

Biomass utilization for bioenergy has a long history. Much of the nation's energy needs were met by wood fuel prior to widespread use of coal and petroleum. Even now it is common to find combined heat and power production operations where there are abundant biomass supplies such as in pulp mills and lumber yards. Recent interest has also been spurred by government programs promoting alternatives such as heat for schools, prisons, hospitals, etc. (Richter and others 2009). Even with this level of utilization, there is still over 300 million tons of unused biomass coming available annually nationwide (Perlack and others 2005). However, adoption of bioenergy production practices typically occurs only where there is a ready biomass supply on site, such as forest product facilities, or where modest feedstock requirements are met within close proximity to the energy conversion facility, such as a low-demand educational heating facility in a forested region.

The importance of the biomass supply being localized to minimize transport costs cannot be overstated. While there are significant costs for biomass removal, those costs may be exceeded by revenue gained through the sale of that material to a local conversion facility (Evans 2008). However, delivery to distant conversion facilities frequently causes the delivered cost to exceed revenues making the biomass utilization process economically unviable (Stokes and others 1993).

Consequently, despite abundant supply, biomass is commonly not removed for utilization due to expenditures exceeding potential revenues and instead is cut, piled and burned at significant expense and with important consequences to consider.

Biomass Disposal Concerns

Both off- and on-site consequences occur from pile-burning biomass. Dried biomass is about 50 percent carbon and when biomass slash piles are flared that carbon is oxidized and released back to the atmosphere as carbon dioxide or other organic compounds. Such disposal is questionable in light of efforts to reduce greenhouse gas emissions and sequester carbon. In addition to volatilizing carbon, other essential plant nutrients are also lost from the site by burning. These losses include several processes such as oxidation, vaporization, convective ash losses, leaching and erosion (Fisher and Binkley 2000). The two main inorganic nutrients lost to oxidation are nitrogen and sulfur, which are typically released as air pollutants in the smoke produced by open-air burning. Phosphorous can also be lost, but in lower quantities than nitrogen and sulfur. In hot fires, such as in well seasoned slash piles, oxidative losses of nitrogen can be 25-65 percent and for sulfur they can be 25-90 percent. These nutrients are frequently growth limiting in forest environments (Fox and others 2007; Kishchuk and Brockley 2002), so it is equally unwise to cause such losses rather than conserving onsite stores. Nutrients are also lost from site in smoke emissions. Convective losses of particulates occur during burning that contain the full range of mineral nutrients found in biomass, many of which are concentrated in ash (Fisher and Binkley 2000). Finally, other pollutants including particulates, carbon monoxide, and a variety of volatile aromatic carbon compounds are also released in smoke (U.S. National Research Council 2004). These pollutants are typically regulated in urban and agricultural areas requiring permits to release. Smoke management procedures are also in place to limit forest biomass pile burning to favorable atmospheric conditions (e.g. http://www.smokemu.org/).

Piling and burning slash concentrates nutrients in the fire ring, which may lead to lower average site productivity. The site preparation practice of shearing, piling and burning was discontinued in southern pine plantations after it was recognized that the redistribution of nutrients resulted in productivity declines (Carter and Foster 2006). Similar results were observed in other regions (Binkley 1986), some of which may be explained by topsoil displacement as well as biomass redistribution. Regardless, the concentration of biomass into piles and release of nutrients localizes nutrients and can potentially saturate nutrient exchange capacity in the burned area, leading to greater leaching loss.

While utilization of abundant forest biomass for bioenergy is appealing, it too may result in removal of nutrients from sites. Environmental critics of forest bioenergy production systems frequently cite the concern of nutrient removal and over-exploitation of the resource as an expected negative consequence of biomass harvesting for energy production (Kimmins 1997). We know from timber harvesting that bole-only removal has an undetectable impact on the regrowth of subsequent forest stands; however, if we remove whole trees from nutrient poor sites, impacts on growth of the next forest rotation have been detected (Kimmins 2004). More certainly we know that removing litter and displacing soil will have significant impact on the next rotation (Fleming and others 2006; Van Miegroet and Johnson 2009). But we have little or no information on the impacts of removing small diameter biomass material, such as tops, branches and needles that contain high concentrations of nutrients (Evans 2008; Palviainen and others 2004). We do not know if those removals will impact subsequent forest productivity, but it will likely depend on the inherent site quality, the frequency and intensity of harvest and the ability of the site to replenish nutrients removed (Kimmins 2004). The forest system is resilient and maintains large stocks of nutrients that, given adequate time, can meet the requirements of forest growth, but an accelerated frequency of removal may exceed the replenishment capacity. Consequently, there is an urgent need to understand the implications of biomass removal. A sustained bioenergy production system might include removing the energy and not the nutrients, or returning the nutrients after energy is extracted from the biomass.

Pyrolytic Biomass Conversion Solution

Both profit and sustainability are essential where financial analysis controls the viability of alternative energy projects and the feedstock derives from venerated forested ecosystems. The mobile fast pyrolysis bioenergy production system (Badger and Fransham 2006) may be one approach to profitable and sustainable biomass utilization. The mobile pyrolysis unit has potential to cover the cost of biomass removal through the production of a crude oil product known as "bio-oil" that has higher density and energy content than biomass. In addition to the bio-oil, there is also a "bio-char" byproduct that has market value of its own, but might best be used by returning it to the site of energy extraction as a soil amendment and as a means of soil carbon sequestration. Such an approach has recently been advocated for agricultural systems (Laird 2008; Lehmann and others 2006), but it makes even greater sense for forest ecosystems when the bio-char is produced at and immediately returned to the site of energy extraction.

Table 1 shows value comparisons for fast-pyrolysis products. The pyrolysis actually has three product phases: gas, liquid and solid (Bridgwater 2004). The flammable gas is used to fuel the pyrolysis process in a self sustaining combustion. So although in some situations the heating value of the gas can be quantified as a product, in this case it provides the energy for producing the other products. The gas amounts to ~48 percent of the energy in dry wood (Raveendran and Ganesh 1996). The bio-oil is the liquid phase product and fast pyrolysis will produce more than 120 gallons per dry ton of biomass (Mohan and others 2006). We determined the value of bio-oil by comparing it to substitute market products. Bio-oil is discounted by 60 percent in this analysis to account for the lower heating value relative to the petroleum products. Minor furnace or boiler modifications are also

Table 1—Value of pyrolysis products from one air dry ton of biomass.

1. Syngas (fuel for Pyrolysis)
2. Bio-oil = 120 gal of bio-oil
    - $64 ($0.89 / gal[1] Bunker Fuel Houston, TX, Bunkerworld.com)
    - $94 ($1.30 / gal[1] Wholesale fuel oil, tonto.eia.doe.gov)
3. Bio-char = 500 lbs of bio-char
    - $65 ($260/ton, author market survey)
    - $9-$18 ($35-$70 / ton[1] EU carbon trading EU ETS, www.pointcarbon.com)

One ton Forest Biomass = $73-$159 (sum of bio-oil and bio-char products

[1] Prices as of 20 April 2009

required in handling and burner/boiler design to allow for unique chemical and physical bio-oil properties (Mohan and others 2006). This comparison gives a value of $64 - $78 of bio-oil produced per dry ton of biomass. The third product of pyrolysis is the solid bio-char and it is similarly valued by substitute market products. Bio-char can be sold for horticulture or barbeque charcoal at a value of ~$65 of bio-char per dry ton of biomass. Although bio-char does have this wholesale market, the real benefit of the bio-char produced from forest biomass using a portable pyrolyis unit might be in leaving it on the site from where the biomass was extracted and using it for soil conditioning and carbon sequestration. As with biomass, the bio-char is a low-density, bulky material (0.35 specific gravity, (Antal and Gronli 2003)) and transport cost may overcome the value and favor leaving it on site. Carbon sequestration might provide a value of $9 and $18 per air dry ton. If ten air dry tons of biomass can be removed from an acre, the potential market value of bio-oil plus bio-char might result in revenue of $730 to $1430 per acre. In comparison to the median cost of biomass removal of $625 per acre (Evans 2008), there appears to be a reasonable potential for profit considering production, relocation, and transport costs must still be accounted.

One of the key features of the mobile pyrolysis approach is the ability to take the conversion unit to the biomass source and avoid biomass transport. In-woods pyrolysis operations allows us to convert biomass into an energy rich high-density bio oil. Transporting a value-added high-density product not only decreases transportation costs, but also decreases fossil fuel emissions required for transport. Therefore, life-cycle analysis is another aspect of the portable vs. centralized pyrolysis plant for which accounting should occur.

The capital and operating costs of small scale conversion units are high relative to larger units (Bridgwater 2004). Greater efficiencies are created by using higher capacity pre-processing and handling equipment: relatively fewer personnel requirements, lower maintenance and greater operating hours per year. For instance, moving the mobile pyrolysis unit into the woods, conducting startup procedures, consuming available biomass, shutting down and relocating may have a significant impact on operating efficiency. It is likely that the portable pyrolysis unit will be located at a single central location within one or more project area(s) and operated at that one location for considerable time, requiring minimal transport of biomass, but still incurring some short-distance biomass transport costs. Consequently, mobile pyrolysis units have both the advantage of limiting transport distance over that of the centralized fixed-location conversion facility and the disadvantage of having greater capital, operating, and relocation costs. Our research is evaluating these operational and economic tradeoffs.

Figure 1 demonstrates the hypothetical operating range of mobile pyrolysis units within the Umpqua and Willamette National Forest woodshed. Biomass from the Umpqua would otherwise be transported to a centralized plant located in Roseberg, OR. The central plant draws from a broader region beyond the indicated National Forests, including surrounding Bureau of Land Management ground as well as other public and private lands in and beyond the area illustrated. Travel routes affect the efficiency with which biomass can be moved to Roseburg and road networks are being used to calculate transportation requirements. Operational efficiency of fixed and mobile pyrolysis units is being evaluated. Capital costs and operational requirements of fixed location units are known through commercial applications (Bridgwater 2004) and are being compared to information from development-stage mobile units.

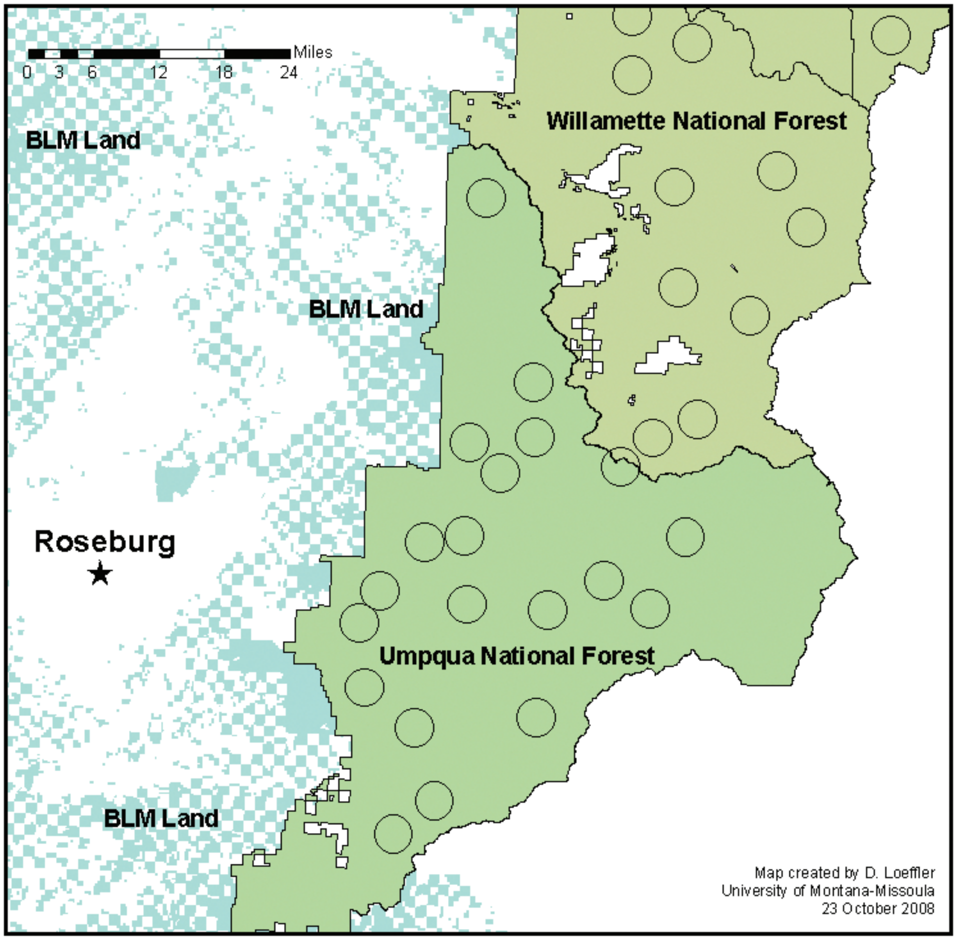

Figure 1—Map of biomass supply area with circles representing portable pyrolyzer supply areas within the Willamette and Umpqua National Forests and a centralized processing facility located in Roseburg, OR with a supply area extending beyond the map area.

Bio-Char Advantage

The bio-char produced through these mobile units is equivalent to charcoal that is manufactured for numerous other purposes through traditional and modern pyrolysis techniques. Charcoal manufacture has been used throughout human history including fuel for iron and bronze metallurgy starting 4,000 years ago and lasting until the use of fossil fuel became widespread during the 19th century (Rackham 1980). Modern charcoal uses include air and water filtration, cooking charcoal, horticultural media, bioremediation, medicinal purposes, among others. As an equivalent to charcoal, bio-char is also an artificially produced analog to charcoal found in many fire ecosystems. This black carbon has been defined as a natural component of fire ecosystems that lends favorable properties to soils and enhances soil productivity (DeLuca and others 2008; Pietikainen and others 2000; Zackrisson and others 1996). Therefore, it can be applied to native ecosystems without concerns of contamination. Bio-char presents an opportunity to return nutrients removed in the biomass from project locations, and as mentioned above, reapplication of bio-char to project sites also has potential value in carbon sequestration. Both the nutrient return and carbon sequestration values of bio-char reapplication to project sites may outweigh other potential uses. Segments of the public are increasing demands for limits on forest product utilization from public land, which may prompt requirements for nutrient conservation. Geopolitical decisions are expected to expand limits on carbon emissions and reward carbon sequestration. On-site retention may be the best option in light of these social pressures.

Charcoal also has important horticultural values and soil enhancement characteristics. It can be used in greenhouses as a plant growth media. Figure 2 compares poplar trees growing in potting soil blends with increasing bio-char proportions. Poplar was used as a bioassay because of its responsiveness to variable growing conditions and sensitivity to soil growth media. In this case, each is growing equally well regardless of the amount of char included. Bio-char can be used as an effective soil media in the greenhouse and at forest sites because of the favorable properties provided to the soil.

Bio-char contains the majority of nutrients found in biomass feedstock (Gaskin and others 2008). Nutrients such as nitrogen and sulfur can be volatilized during the pyrolysis process, but the bio-char produced may also contain significant amounts of these nutrients. This means that the bio-char resulting from extracting energy in bio-oil production can be returned to the site to replenish soil nutrient stocks.

Returning the bio-char to the site can also enhance soil organic matter. Bio-char is mainly carbon held in aromatic form, which results in it being inert when added as an amendment. As a consequence, it quickly builds the recalcitrant soil carbon fraction of soil. We know from research on wildfire occurrence and the development of anthrosols that charcoal-derived carbon can remain in the soil for hundreds to thousands of years (Agee 1996; Lehmann and Rondon 2006). Enhancement of the soil organic matter pool with charcoal provides the numerous benefits of other organic matter including large surface area for exchange of water and nutrients; however bio-char also has other characteristics that create additional soil improvements.

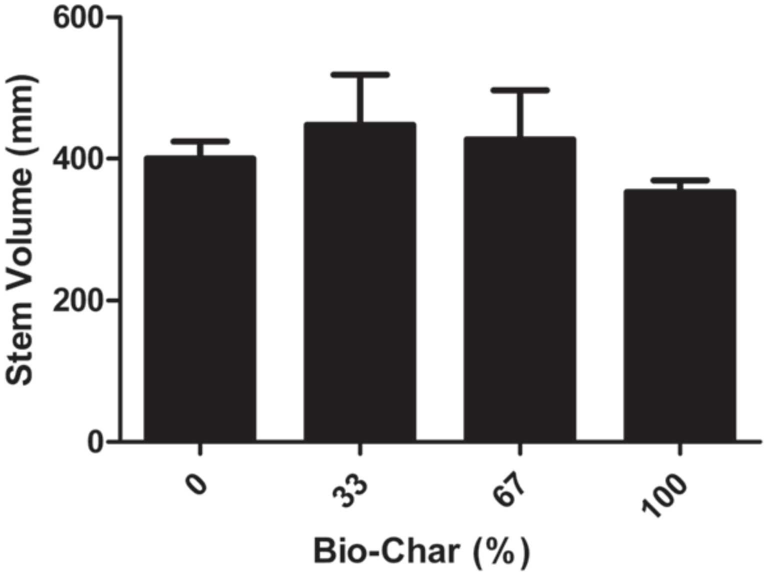

Figure 2—Poplar trees growing for 12 weeks in potting soil with different proportions of bio-char. Each pot received 1.5 g slow release fertilizer (18-6-12). Differences between treatment were not significant ($P = 0.63$). Error bars are standard errors.

Bio-char acts as a liming agent resulting in increased soil pH and nutrient availability for a number of different soil types (Glaser and others 2002; Lehmann and Rondon 2006). Soil liming results in pH increases of one-half to one pH units. The liming of acidic soils decreases Al saturation, while increasing cation exchange capacity and base saturation. These responses following bio-char additions are common soils responses to lime additions (Tisdale and Nelson 1975) indicating that the effects of bio-char are similar to those of other liming agents. Nutrient availability may actually increase beyond the amount expected by cation exchange sites due to soluble salts available in the char. Anion availability may also increase suggesting that anion exchange may be enhanced by bio-char additions to soils (Glaser and others 2002). Microbial biomass and diversity is also known to increase with greater bio-char including more abundant mycorrhizal associations and enhanced biological nitrogen fixation (Lehmann and Rondon 2006). Therefore, when bio-char is added to soil it “sweetens” the soil by raising the pH, improving the fertility level through additions of nutrient ions commonly associated with ash additions, and enhances symbiotic soil microbe populations.

Bio-char may also increase the water holding capacity of forest soils. This is especially important on western soils where the growing season is determined by the length of time into seasonal summer droughts where soil moisture remains favorable to growth. It may become more important in other forest ecosystems where extended summer drought can significantly decrease growth and the frequency and amount of summer rain events are expected to decrease with predicted climate change. Improved water holding capacity through char additions is most commonly observed in coarse textured or sandy soils (Gaskin and others 2007; Glaser and others 2002). Just as increased surface area improves water holding capacity of ash deposits (Dahlgren and others 2004; McDaniel and Wilson 2007), the impact of bio-char additions on moisture content may be due to increased surface area relative to that found in coarse textured soils (Glaser and others 2002).

The residence time of bio-char in soils may be in excess of 1000 years making it a potential tool for carbon sequestration. Bio-char consists of highly aromatic organic material having carbon concentrations of 70 to 80 percent (Lehmann and others 2006), and it is highly resistant to decay by common soil saprophytes. Evidence for the residence time of bio-char comes from several lines of research. Fire ecology typically makes use of the long residence times of bio-char in dating fire events through the latest interglacial period (Agee 1996). Archeologists similarly have demonstrated the use of coppiced woodlands for prehistoric metallurgy by dating the charcoal remains of historic operations back some four millennium (Rackham 1980). Furthermore, the rich Terra Preta soils produced through charcoal additions by a poorly understood Amazonian society occur in a matrix of highly weathered tropical Oxisols (Mann 2008). These soils were developed over 2000 years ago as the agricultural basis of this sophisticated society and are still regarded today as high quality top-soils with charcoal as the vital component (Glaser and others 2001).

The potential to sequester carbon by char additions to soils creates an important possibility to mitigate greenhouse gas emissions. This idea is not new (Seifritz 1993), but has recently gained interest with greater public awareness of the effect of greenhouse gas emissions on climate. The portable pyrolysis units at scattered locations throughout the forest may create greater opportunity to sequester carbon than pyrolysis conversion at a centralized plant. For large fixed-location pyrolysis plants, the economic incentive to return bio-char back to the woods is low because of high transport costs and alternative uses for filtration, clean energy, cooking, horticulture, etc. Furthermore, biomass moved from the woods is just as likely to be used by any number of other processes in addition to pyrolysis including fueling industrial boilers where char would not be a significant byproduct. From a forest management perspective, the preferred use for bio-char may not be for transport to alternative use markets, but as an on-site soil amendment. Bio-char reapplication represents the middle ground that might make biomass utilization a reality.

Conclusion

The portable pyrolysis system offers a solution to biomass accumulation in forest ecosystems. By utilizing the abundant forest biomass that is annually produced through forest harvest residues and hazard fuel reduction projects it may be possible to produce a liquid fuel that will reduce dependence on foreign energy sources. If biomass conversion can occur in the woods it will improve the economic and environmental impact of biomass utilization for energy production. In addition, the bio-char byproduct can be redistributed to the site of energy extraction and thereby return nutrients to the site to maintain site quality. The additional properties of char additions, including liming, microbial enhancement and improved water holding capacity, create the opportunity to maintain or improve soil quality. Furthermore, bio-char's recalcitrance can sequester carbon for centuries. Such an approach is advocated for agricultural systems (Laird 2008; Lehmann and others 2006), but the arguments are even stronger for portable pyrolysis units used in forestry systems where long distances make onsite reapplication a better option than long-distance transport of biomass to and return of char from a centralized processing facility.

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