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A Supply Chain Approach to Biochar Systems

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Abstract

Biochar systems are designed to meet four related primary objectives: improve soils, manage waste, generate renewable energy, and mitigate climate change. Supply chain models provide a holistic framework for examining biochar systems with an emphasis on product life cycle and end use. Drawing on concepts in supply chain management and engineering, this chapter presents biochar as a manufactured product with a wide range of feedstocks, production technologies, and end use options. Supply chain segments are discussed in detail using diverse examples from agriculture, forestry and other sectors that cut across different scales of production and socioeconomic environments. Particular attention is focused on the environmental impacts of different production and logistics functions, and the relationship between supply chain management and life cycle assessment. The connections between biochar supply chains and those of various co-products, substitute products, and final products are examined from economic and environmental perspectives. For individuals, organizations, and broad associations connected by biochar supply and demand, achieving biochar's potential benefits efficiently will hinge on understanding, organizing, and managing information, resources and materials across the supply chain, moving biochar from a nascent to an established industry.

2.1 Biochar in a Supply Chain Context

Biochar production and application as a commercial enterprise connects a diverse constellation of organizations with varying capabilities, expertise, and objectives. From an industrial perspective, these organizations are bound together by a single goal: efficiently manufacture and deliver a product that effectively meets the needs of end users. This network of organizations is collectively known as a supply chain. Using the customer and organization focused framework of supply chain management (SCM), this chapter examines

Figure 2.1. Charcoal produced from loblolly pine (*Pinus taeda*) sawmill planer shavings using a high temperature (800–1100°C) pyrolysis system. Based on its feedstock and conversion process, this product will be classified as biochar if it is used as a soil amendment. Photograph by Nate Anderson.

biochar as a manufactured product used to meet soil improvement and climate change mitigation objectives, as well as waste management and energy needs.

In some ways, biochar supply chains are millennia in the making, dating back to the anthropogenic Terra Preta soils of the Amazon Basin, but as a component of modern economies biochar supply chains are new and rapidly evolving. Unlike many major agricultural and forest commodities, supply chains for biochar products are currently characterized by growing spot markets for diverse uses that are often in the early stages of development, with little or no historical information or market data to guide pioneering entrepreneurs. Varied raw material options, emerging conversion technologies, and intermittent distribution channels complicate this landscape. Furthermore, the needs of end users can be narrow, such as replacing mineral vermiculite in nursery potting media with a suitable organic alternative (Dumroese et al., 2011), or multifaceted, such as simultaneously managing crop residues, improving crop yields, and sequestering carbon in the soil to generate carbon credits (Roberts et al., 2010).

Biochar is well suited to examination in a supply chain context because its classification is closely bound to its end use. Charcoal is the carbon-rich solid product of thermal decomposition of biomass in the absence of oxygen (i.e. pyrolysis), and is used in a wide range of products, including solid fuels, industrial chemicals, sorbents, and consumer products like rubber, plastic, paints, inks and pigments. Charcoal that is used to improve the properties

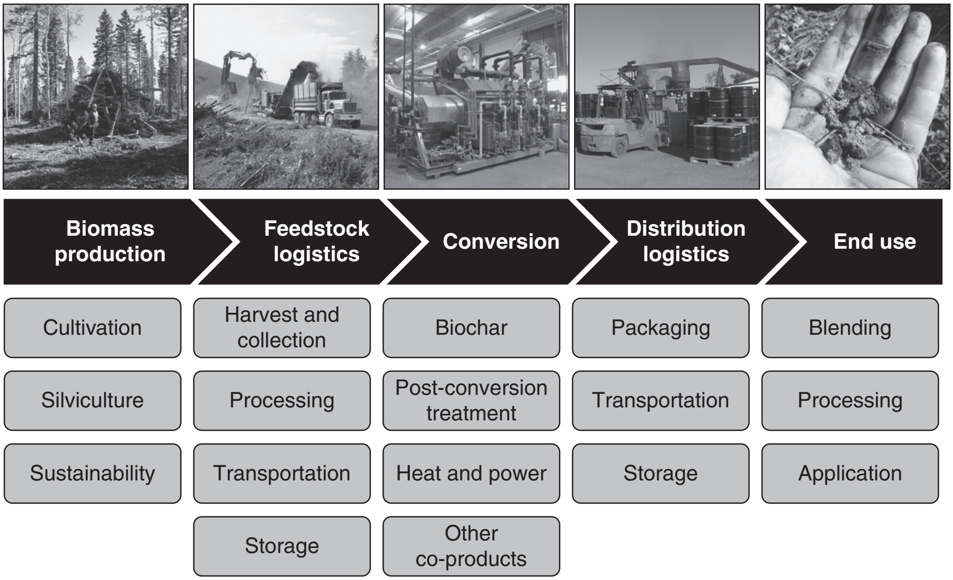

Figure 2.2. The primary segments of the biochar supply chain and associated activities related to material production, logistics, conversion, and end use. Photographs by Nate Anderson.

of soil, especially productivity, carbon storage and water holding capacity, is known as biochar (Lehmann and Joseph, 2009). This means that the charcoal shown in Figure 2.1, which was produced from loblolly pine (*Pinus taeda*) sawmill planer shavings using an advanced high temperature pyrolysis system, may or may not become biochar depending on how it is eventually used. If it is pelletized and used as solid fuel for co-firing with coal in a power plant, it remains charcoal, but if it is used as a soil amendment it becomes biochar. Similarly, though activated carbon (AC) shares many physical and chemical properties with biochar, AC used as a soil amendment for remediation of organic pollutants (as in Vasilyeva et al., 2006, for example) would not be classified as biochar if it is manufactured from fossil coal rather than biomass. In practice, classification of biochar based on end use as well as its parent material and production process links biochar to multiple co-products, substitute products, and end uses in complex and dynamic supply chains, but all biochar supply chains follow the same general supply chain model.

2.2 A Model Biochar Supply Chain

The biochar supply chain can be divided into five segments: biomass production, feedstock logistics, conversion, distribution logistics and end use (Figure 2.2). In manufacturing supply chains, each segment includes a variety of activities related to material production, logistics, conversion and end use functions. Material flows downstream from the site of harvest to the end user along the supply chain, with each activity adding value. Material is procured and transformed into intermediate and finished products, which are moved down the chain by logistics systems that include handling, transportation and storage (Goetschalckx, 2011). In addition to material flows, two other flows are critical to efficient and effective supply chains. Information flows back upstream from end users along the chain and can be used to coordinate activities, improve products, advance technologies, increase productivity and reduce costs. Financial transactions between the organizations involved in these activities underpin material and information flows in commercial supply chains. Regardless of the final product, material, information and financial flows are organized and managed to meet the needs of end users.

In the forest biomass example illustrated by the photographs in Figure 2.2, which represents one of many possible supply chain configurations, woody biomass is generated by silvicultural treatments prescribed by forest managers to harvest timber and reduce fire risk in a dry mixed conifer forest. Biomass is field dried in piles, and then collected and ground into a smaller, more uniform material with higher bulk density that can be efficiently delivered to a bioenergy facility by truck. Raw biomass from the forest becomes feedstock when it is processed – in this case biomass is ground into feedstock using a horizontal grinder. At the facility, the feedstock is further reduced in size, screened, dried, and then converted into biochar in a high temperature industrial pyrolysis system that also produces energy gas to fuel a generator providing power to the electrical grid. The biochar is packaged for distribution in 200 liter metal drums and delivered to an abandoned mine site, where it is finally used as a soil amendment for remediation and mine reclamation. Technical details associated with supply chains like this one, including the operations pictured, can be found in case studies throughout this book and also in Anderson et al. (2012, 2013), Keefe et al. (2014), and Kim et al. (2015).

Material flows are a useful way to characterize supply chains, but as described in Section 2.1, a supply chain is best thought of as a network of organizations engaged in activities to meet the needs of end users. Industrial manufacturing supply chains are generally dominated by private firms, businesses and corporations meeting the needs of consumer end users. Because of biochar's close connections to agriculture, forestry and climate change mitigation, and because it can be applied in various socioeconomic contexts around the world, in this case it is important to recognize a broad definition of organization, which includes public agencies, institutions, non-governmental organizations (NGO), family units and other groups.

In the example from Figure 2.2, the end user is a public National Forest in need of biochar for mine reclamation activities. A different public National Forest is the biomass producer, a private logging company is contracted to harvest and grind biomass on site and deliver it to the bioenergy facility, the bioenergy facility further processes the feedstock and carries out conversion, an independent co-located business packages and markets the biochar, and a common carrier freight company delivers the packaged biochar to an environmental engineering firm that has been contracted by the end user to remediate abandoned mine sites on public land. The material, information and financial flows in this example span seven different organizations, two of which are public agencies. It is also important to point out that the supply chains of other products and end uses are part of this network, and include logs that leave the site to be used in products like paper and solid wood products, as well as the co-product of electricity that is delivered from the bioenergy facility to customers over a grid that includes private companies, co-operative business, and public utilities.

Of course, it is possible for a single organization to carry out all of the functions and activities of the biochar supply chain. In fact, many authors have described a simple model of biochar production and application for small-scale agriculture in which farmers process waste biomass from crop residues in on-site small batch conversion systems like charcoal kilns to produce biochar for application to their fields (e.g. Sparrevik et al., 2013). Though simple in structure, in the context of climate change mitigation such supply chains may not be isolated from global markets. For example, Leach et al. (2012) examined the interplay between traditional biochar production and application for small-scale agriculture and biochar supply chains to meet global carbon management objectives through carbon markets.

The process of expanding the operations of an organization upstream or downstream along the supply chain is known as vertical integration, and a farmer who carries out all of the supply chain functions is fully vertically integrated with regards to biochar production and use. Horizontal integration occurs when an organization adds functions that are in a different sector or industry, such as a factory that manufactures charcoal briquettes for retail sale as cooking fuel expanding to develop and market a proprietary biochar soil amendment for home gardening applications. The costs and benefits of integration versus specialization vary widely by industry, but the general purposes of integration are to fill unmet consumer needs, capture value from new operations, and reduce the market leverage of suppliers and distributors. Most supply chains are made up of multiple organizations with varying levels of integration and specialization.

Much of the remainder of this book is devoted to case studies of existing real-world biochar systems and applications, but is it useful here to examine a network of hypothetical organizations. Figure 2.3 is a schematic of two hypothetical biochar supply chains (organizations #1 and #2 together in one chain, and #3 through #17 as another) showing the connections between 17 different organizations engaged in four general functions: biomass production, logistics, conversion and end use. These organizations are connected by material flows for raw biomass, intermediate products and biochar. Organization #1 is an almond (*Amygdalus communis*) orchard producing significant biomass residues in the form of branch trimmings, shells, cull trees and other byproducts. Organization #2 is a co-located company that produces biochar from these residues, as well as processing heat for orchard operations, including a greenhouse. Both companies have logistics capacity to transport, process and store materials using trucks, loaders, chippers, hammer mills, conveyors, bins, dryers, and other equipment. The orchard is the primary end user of the biochar produced, which it uses to improve soils in its orchards and reduce its carbon footprint through carbon sequestration. Like the example of a fully integrated farming operation, structurally this is a very simple supply chain made up of only two organizations, but it includes all of the major supply chain functions.

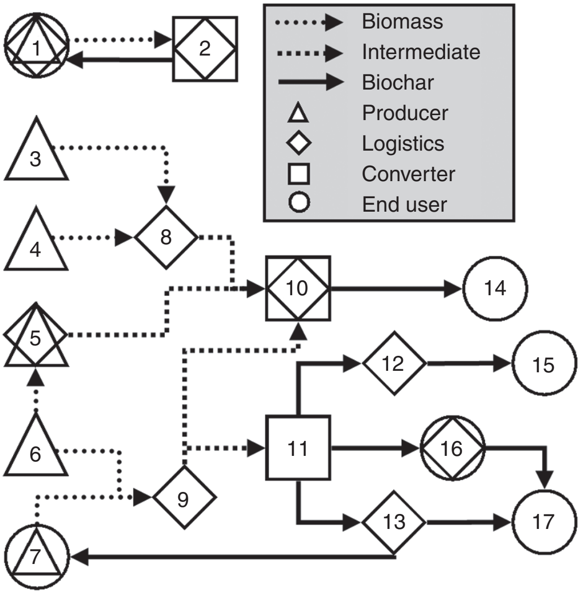

Figure 2.3. A schematic illustrating the interconnectedness of organizations and their functions in a biochar supply chain.

The connections between the remaining 15 organizations in Figure 2.3 are more complex and less vertically integrated. A forest park (#3) and tree plantation (#4) contract with loggers and trucking companies (#8) to chip and deliver woody biomass from forest management operations to a biochar company (#10) that produces, packages and delivers biochar to an organic strawberry grower (#14). A sawmill (#5) not only grinds, screens and delivers a portion of its mill residues to the biochar producer (#10), it also processes and delivers residues from a private industrial forest (#6) that also sells biomass to an equipment operator specializing in biomass harvesting operations (#9), who delivers ground and screened material to two different biochar producers (#10 and #11). One of the customers for this biochar is a forest reserve owned and operated by an environmental NGO (#7) that also provides biomass to both biochar producers (#10 and #11), through the biomass operator (#9). One of the end users (#16) uses biochar in potting mixes for its commercial greenhouse operations, but also sells the proprietary mix to retail customers (#17). Looking at the connections between #6 through #15 in this model, a linear material flow between specialized organizations nicely fits the metaphor of a “chain” for a simple product and single end user. However, as Christopher (2011), Stock and Lambert (2001), and others have pointed out, in reality even relatively simple products actually require complex flows of material, information, and capital in networks of organizations that integrate the supply chains of many different products and end uses.

What do models like these tell us about biochar systems? Over the last decade biochar has experienced a rapid expansion of awareness and interest closely tied to applications in agriculture, forestry, mining and climate change mitigation, some of which have been advocated for by scientists and various government agencies and non-profit initiatives, committees, centers, and other organizations. Compared to activity by these groups and in contrast to other industries in the agricultural and forest sectors, commercial enterprises devoted to the manufacture, marketing and use of biochar and biochar production equipment remain less common. As biochar evolves as a consumer product to meet various needs in diverse markets, we can expect the industry to move toward higher levels of complexity with varying degrees of integration and product differentiation across local, regional and global scales. This is true across a range of economic systems, including informal economies in developing countries for which biochar has been proposed as an accessible alternative to resource-intensive industrial agricultural inputs (Duku et al., 2011). For individuals, organizations and broad associations connected by biochar supply and demand, achieving biochar's potential benefits efficiently will hinge on understanding, organizing, and managing information, resources and materials across the supply chain, moving biochar from a nascent to an established industry.

2.3 Biochar Sustainability, SCM, and LCA

A supply chain framework is also a useful way to organize and analyze the various aspects of biochar production, effectiveness, economics, and environmental impacts that are discussed in detail in subsequent chapters of this book. To a larger extent than most manufactured products, biochar is fundamentally bound to sustainability (Part 2 of this book). This can be traced directly to its feedstocks, end uses, and intended benefits, which leverage environmental benefits from reduced greenhouse gas emissions, better waste disposal, and substitution for more environmentally damaging products. As a result, sustainability must be ingrained in biochar SCM (Section 2.5 of this chapter). Though sustainability is most commonly equated with environmental impacts, it also includes various socioeconomic aspects of production, such as land tenure, indigenous rights, labor rights, safety, legal standards, economic obligations and cultural protections. Most of these are formalized in various sustainability standards and certifications, including those for agriculture, forestry and even biochar specifically (e.g. FSC, 2010; Leonardo Academy, 2012; IBI, 2014).

With regards to quantifying and evaluating environmental impacts, the supply chain model closely parallels the life cycle assessment (LCA) method of evaluating environmental impacts (Chapter 3). The boundary of the biochar system defined and examined in LCA encompasses all of the supply chain functions illustrated in Figure 2.2, from raw material extraction ("the cradle") to end use and disposal ("the grave"), though each stage of the process may be segmented differently in LCA. For example, biomass harvest, collection, and processing may be attributed to raw material extraction rather than biomass production. In addition, the biochar system defined in LCA includes energy offsets and avoided emissions, with detailed accounting for emissions, effluents and waste from the system. As with supply chains, material conversions and logistics feature prominently in LCA, as do flows of materials, energy and capital. Though integration of LCA with SCM has not been without challenges (Hagelaar and van der Vorst, 2002), businesses increasingly view environmental impact, especially carbon footprint, as a key indicator of supply chain performance and value. In fact, formal integration of LCA is becoming a cornerstone of the relatively new field of environmental supply chain management (ESCM), also known as "green" SCM. In this book, LCA and SCM models provide a holistic framework to examine current biochar research with an emphasis on product life cycle and end use.

2.4 Biochar Supply Chains and End Use

As discussed in Section 2.1, biochar supply chains are focused on meeting four general and often overlapping needs of end use consumers (Lehman and Joseph, 2009): soil improvement, waste management, energy production and climate change mitigation. Much of the research on biochar is focused on understanding and quantifying biochar's effects on soil chemical, physical, and biological properties, particularly its impacts on soil chemistry, nutrient cycling, water availability, soil biota, and the nitrogen cycle (see subsequent chapters). In agricultural and forestry settings, beneficial changes to soil properties can be linked to increased productivity with lower inputs of nutrients and water, depending on the specific biochar used and a wide range of site-specific variables, especially soil texture, moisture regime and plant species. Whether for business or subsistence or both, increased productivity and more efficient water and nutrient use translate directly to higher yields at lower cost. These gains can be quantitatively measured against other options that might achieve similar outcomes, such as alternative soil amendments, chemical fertilizers, new irrigation technologies and genetically modified plants. Appropriate metrics for comparison typically include various market and non-market costs and benefits related to alternative financial, social and environmental outcomes.

As with biochar used to improve soil properties and enhance plant growth, the costs and benefits of using pyrolysis to process biomass waste like logging slash, stover, bagasse, nut shells, straw and other materials can be compared to alternative disposal options, including open burning, controlled combustion (i.e. incineration), biochemical conversion (i.e. decomposition or digestion) or burial. Similarly, biochar production systems often produce useable energy co-products in the form of heat, liquid fuels and energy gases (see 2.5.3 and Part 3 of this book), which can be compared to various substitute energy products, including both renewable and non-renewable options. For example, modern combustion and gasification systems that produce heat or combined heat and power (CHP) from biomass are technologically similar to some pyrolysis-based thermochemical conversion systems that produce biochar, and are similarly marketed for a broad range of waste-to-energy applications (Anderson et al., 2013).

Here it is important to distinguish between end use of biochar and its associated co-products from the consumption of final goods. In economics, demand for biochar systems to meet soil, waste and energy needs is derived from demand for various final goods. For example, an integrated forest products company may use wood residues from sawmill

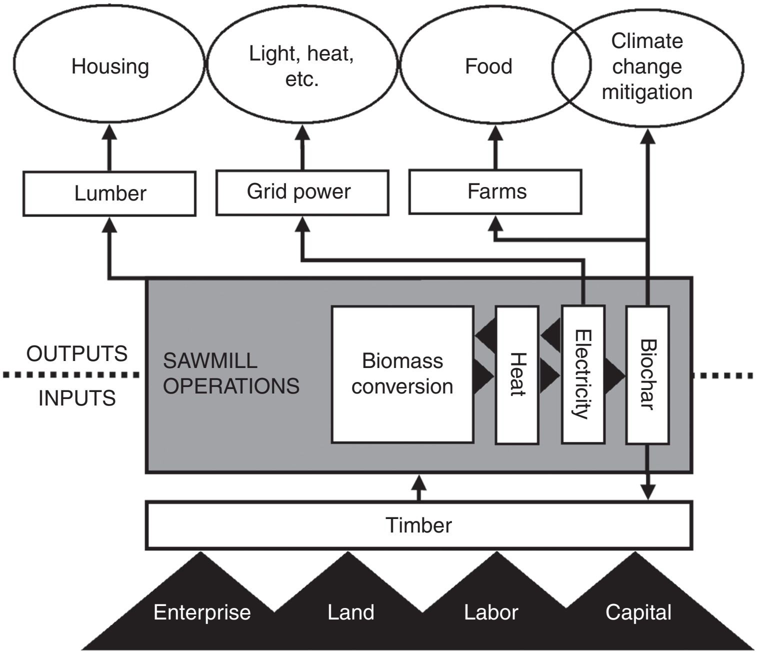

Figure 2.4. For a sawmill using mill residues to produce biochar, heat, and electricity, the demand for these intermediate goods is derived from demand for final goods like housing and food.

operations to produce biochar, heat, and power for on-site processes, and electricity to the grid using a distributed-scale biomass conversion system (Figure 2.4). The biochar may be marketed to local farms and also used to rehabilitate forest roads on company timberlands that have experienced soil compaction and erosion. However, in this example, demand for soil improvement, waste wood disposal, and energy are clearly derived from demand for other final goods, such as houses, home heating and lighting, and food (Figure 2.4). Recognizing that biochar is an intermediate good rather than a final good is important because its supply chains are subject to competition from alternative products that can be substituted for pyrolysis technologies and biochar to meet the same needs. However, climate change mitigation as an end use objective for biochar systems offers another level complexity.

In Figure 2.4, biochar can be used as an input to improve crop and timber production in ways previously described, connecting biochar to food and housing as final goods, for example. However, biochar systems can also be used primarily as a tool to meet climate change mitigation objectives, and in this application biochar can be considered a final good in itself. Section 2.5.5 discusses biochar used for climate change mitigation in more detail, but the direct connection between biochar production and climate change mitigation is closely tied to long-term sequestration of relatively stable carbon in the soil. This characteristic not only imparts potential carbon negative status on biochar and its co-products, depending on the details of the supply chain (Mathews, 2008), but has also distinguished biochar production and application as a potential means for geoengineering global-scale reductions in atmospheric carbon, independent of applications in agriculture, waste management and energy (Downie et al., 2012).

Though each of the four general end uses associated with biochar systems can be pursued independently to some degree, they are obviously bound together. For example, consider a subsistence farmer using a traditional charcoal kiln without energy capture or emissions controls to process crop residues into biochar for her fields. This simple supply chain incorporates soil improvement, waste disposal and carbon sequestration, though increased agricultural productivity from soil improvement is likely to be the main driver of use in this case. However, it should be clear at this point that the greatest net benefits from biochar are likely to occur when all four needs are met simultaneously in supply chains that include multiple products and market substitution for more carbon intensive products and practices. To what extent such benefits are realized rests squarely on the details of a specific supply chain.

2.5 A Closer Look at the Biochar Supply Chain

The generalized biochar supply chain segments and activities shown in Figure 2.2 cut across a wide range of specific feedstocks, logistics, conversion technologies, and end uses. Furthermore, given its close ties to agriculture and forestry, biochar has potential for production and use in diverse settings around the globe at many different scales within all types of economies. Section 2.5 takes a closer look at the range of materials, practices, activities, and technologies associated with each segment of the biochar supply chain, and examines the relationships between organizations that typically carry out critical functions at each stage of production. Subsequent chapters examine the technical details of specific cases, with an emphasis on biomass sustainability, innovative conversion technology, and end uses for soil improvement and climate change mitigation.

2.5.1 Biomass Production

By definition, biochar must be manufactured from biomass. Though pyrolysis of various petroleum and fossil coal products and derivatives can result in char that has similar chemical and physical properties (e.g. Ariyadejwanich et al., 2003), feedstock for biochar production must be derived from live or recently living organisms. Biochar is most often produced from herbaceous and woody plant materials, also known as cellulosic biomass, but it can also be made from algae, food waste, manure, and animal tissue. Though high in biomass content, mixed organic waste streams such as sewage and municipal solid waste (MSW) are generally not seen as viable feedstocks for biochar production because they can contain hazardous materials that contaminate soils (IBI, 2014). The emphasis here is on production of cellulosic biomass.

Biomass used as feedstock for pyrolysis can be a waste product (e.g. manure), a byproduct (e.g. bark), a co-product (e.g. wood chips), or a primary output of a dedicated feedstock production operation (e.g. *Miscanthus* cultivation). Primary products include crops and trees purposely grown as biomass feedstocks, such as switchgrass (*Panicum virgatum*), willow (*Salix* spp.), and hybrid poplar (*Populus* spp.). The difference between a waste, byproduct and co-product is variable by discipline, but SCM provides a relatively clean definition grounded in economics: waste products have disposal costs, byproducts have marginal costs and marginal value relative to primary products and co-products are manufactured jointly, have similar value, and use joint product costing in accounting. The complication with this definition is that the same material can be a waste, a byproduct, or a co-product depending on its value and costs, but it is useful to draw a clear line between waste as a material with net costs, especially for disposal, and production outputs that have market value and the potential to generate revenue.

In both theory and practice, biochar supply chains heavily favor the use of waste biomass as feedstock for several reasons. First, waste materials have disposal costs, generally making them a low cost raw material to procure. Poultry litter, which is a mix of waste bedding, feathers, feed, and excrement, falls into this category. Byproducts typically have some positive market value, but much of the cost of production is borne by some other higher value primary product. This makes them potentially less costly as feedstock, depending on other uses and markets. For example, wood chips and sawdust from lumber manufacturing traditionally have strong markets in areas with demand from pulp mills and wood panel manufacturers, but in areas distant from such facilities these may be good target feedstocks for pyrolysis. Second, waste materials often have disposal options with more damaging environmental impacts than processing via controlled thermochemical conversion. For example, open burning of agricultural and logging residues for disposal is widely practiced throughout the world, and has negative impacts from particulate and greenhouse gas (GHG) emissions (Loeffler and Anderson, 2014). In addition, logging residues are often burned in piles, which can result in long-term damage to the soil, invasion of non-native species, and loss of soil organic matter. Third, the use of waste biomass for biochar is unlikely to directly and negatively affect land use with regards to both conversion of forest to agriculture and transition from food crops to energy crops. Fourth, manufacturing facilities that generate waste and byproduct biomass in large quantities often need heat and power for production processes, which are co-products of some conversion systems.

Unlike waste and byproduct biomass, biomass purposely grown for bioenergy and bioproduct applications using agricultural, coppice, and plantation production systems must bear the full costs of production and feedstock logistics. In general, the trade-off here is between higher cost of production and higher productivity, which may result in lower per unit production costs. As with agricultural crops, this is often expressed as annual production per unit land area. Productivity for energy crops ranges from less than 2.0 megagram (Mg) ha^{-1} yr^{-1} (wheat straw) to 44.0 Mg ha^{-1} yr^{-1} (*Miscanthus*), with economically efficient and environmentally sustainable production systems generally characterized by easily established perennial crops rather than annual crops with high fertilizer, herbicide and pesticide inputs

(Laser and Lynd, 2014). In addition to increasing productivity, dedicated energy crops may reduce transportation and storage logistics costs when production and conversion are co-located and can hedge against feedstock price volatility, especially for vertically integrated firms. Co-locating production and conversion may also provide greater control over feedstock flow and quality, especially moisture content and homogeneity of feedstock physical and chemical properties. This is especially important for conversion systems that use catalysts to produce liquid fuels and chemicals.

The biomass production segment of the supply chain (Figure 2.2) is focused on the cultivation of crops and the silviculture of forests and woodlands. For most cellulosic feedstocks, this applies to biomass from dedicated energy crops, plantations, natural forests, and waste and byproduct biomass in both traditional and industrialized settings. Cultivation and silviculture as components of the supply chain include all aspects of site preparation, establishment, and tending. In agriculture, cultivation may include burning, tilling, fertilization, planting, pest and weed control, crop rotation, irrigation, and greenhouse and nursery operations. Silviculture may additionally include various practices for mechanical soil scarification, thinning, pruning and protection of forest health, such as sanitation cuttings to remove trees infected by insects and disease. The choice to develop and use different varieties of plants, including genetically modified organisms, hybrids and clones, is also included in feedstock production.

Even if the biomass used as feedstock is a waste or byproduct, the biochar supply chain appropriately begins in the field or forest, not with a pile of rice hulls or coconut shells at a processing plant. This has important implications for sustainability, which is the third component of feedstock production. A core concept of sustainability in agriculture and forestry is that sustainable practices do not degrade the long-term potential and productivity of the land, especially with regards to water, soil, and biodiversity. More recently, categorizing and quantifying GHG emissions have become central to assessing the sustainability of manufactured products. Though all segments of the supply chain have environmental impacts, sustainability features most prominently in biomass production because of the high potential for environmental damage due to deforestation, erosion, nutrient runoff, emissions and pollution from poor practices (Part 2 of this book).

2.5.2 Feedstock Logistics

Feedstock logistics includes activities to harvest, handle, collect, process, transport and store biomass from the field or forest to the conversion site. In industrial supply chains, these functions are often facilitated by specialized equipment (Figure 2.5). Waste and byproduct biomass is typically concentrated at the site of processing for primary products, such as a processing plant (e.g. nut shells, hulls, husks and bagasse), a concentrated animal feeding operation (e.g. manure), or at log landings and mills (e.g. logging and mill residues). These materials can also be left behind on field and forest sites in dispersed patterns, as in the case of corn stover, straw, orchard prunings, and some logging residues.

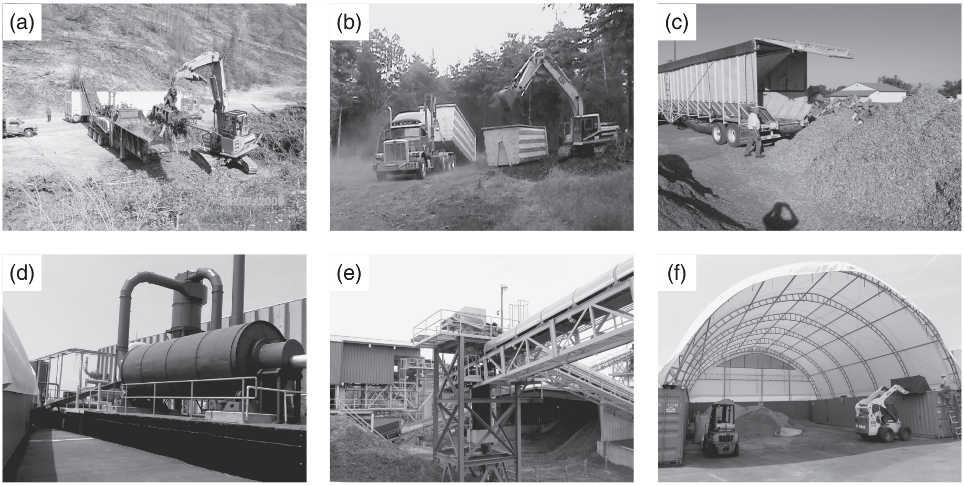

Figure 2.5. Examples of industrial equipment used in woody biomass feedstock logistics, including: (a) a loader and horizontal grinder, (b) excavator and container truck, (c) self-unloading trailer, (d) rotary dryer, (e) feedstock conveyors and (f) a storage tent. Photographs by Nate Anderson. (A black and white version of this figure will appear in some formats. For the colour version, please refer to the plate section.)

Figure 2.6. Six different woody biomass feedstocks produced at a single sawmill (starting at 12 o'clock and running clockwise from left): dry planer shavings, ground wood fuel (also known as “hog fuel”), screened chips, sawdust, pulp chips and screened bark mulch. Photograph by Nate Anderson.

Forest biomass is particularly diverse with regards to concentration, ranging from widely dispersed tops, limbs, and foliage (i.e. "slash") left behind after cut-to-length logging operations, to piles of slash and unmerchantable logs resulting from road-side processing, to large volumes of homogenous sawdust, shavings, and wood chips concentrated at mill facilities (Keefe et al., 2014). Even when woody materials are concentrated as byproducts, the options for feedstock for use in biochar production can be highly variable at a single site (Figure 2.6). Sometimes waste and byproduct biomass can be procured at very low or even zero purchase price, but this should not be confused with the cost of logistics. For example, dispersed logging slash may have a very low purchase price per tonne, but the cost of logistics to harvest, process, and deliver this material to the conversion facility can be quite high – often more than the value of the feedstock once it is delivered (i.e. the "gate price").

Obviously, feedstock concentration is a good thing from a logistics perspective because dispersed feedstocks incur higher costs for collection and transportation, which translates to higher emissions from logistics in LCA. As a result, co-location of conversion systems with biomass production reduces logistics costs and associated emissions. This is true for waste and byproduct feedstocks, as well as dedicated biomass crops and plantations. Co-location can be achieved through integration of on-site biomass conversion, or by locating an independent biomass user at the site of biomass concentration. For example, many large forest industry operations use biomass-fueled combustion boilers for process heat and CHP, and biomass power plants tend to be located near biomass sources. Sometimes feedstock logistics systems feature intermediate concentration sites, such as feedstock silos and concentration yards. Such sites can improve transportation efficiency, product sorting and differentiation and processing (e.g. field drying).

Most conversion systems require some biomass processing prior to pyrolysis. The purpose of processing in feedstock logistics is to make the feedstock more suitable for conversion and more homogenous, which improves mechanized handling and reduces variability in solid, liquid, and gaseous conversion outputs. Specific needs for processing depend on technical specifications for feedstock moisture, particle size, ash content, and other characteristics. Typical processing functions include separation (e.g. debarking), drying, screening, and comminution by grinding, chipping, or hammering. Screening serves not only to narrow particle size distribution, but also to remove contaminants that may have detrimental effects on conversion, such as mineral soil and inorganic debris, like metal fragments from equipment and refuse.

Storage as a component of logistics is also important because it decouples conversion from feedstock production and delivery, allowing conversion to take place independently of feedstock production. This is especially critical when biomass is subject to seasonal availability or disruptions in supply due to weather or market conditions, which is the case for many agricultural and forest biomass resources. For large biomass operations, it is also important to consider systems for managing feedstock degradation, fugitive dust emissions and spontaneous combustion risk, which are all hazards in biomass storage and handling.

2.5.3 Conversion

The conversion segment of the supply chain includes three categories of activities: the chemical and physical transformation of biomass feedstock into biochar via thermochemical conversion, post-conversion treatments to enhance biochar effectiveness for specific end uses, and production of any co-products, including heat, power, energy gas, liquid fuels, and chemicals. Part 3 of this book examines pyrolysis conversion of biomass in detail, but several aspects of conversion are worth highlighting here. More than any other component of the biochar supply chain, conversion hinges on technology. The most striking aspect of biomass conversion from a supply chain standpoint is the diversity of technologies and scales that can be used to transform biomass into biochar. On one end of the spectrum, small traditional charcoal kilns and more modern small batch systems (Odesola and Owoseni, 2010) can be employed by farmers, gardeners, and horticulturalists to process residues into biochar for relatively small-scale, on-site applications, similar to the fully integrated production scenario described in Figure 2.2. On the other end of the spectrum, biochar can be a co-product of biofuel production by large, integrated biorefineries deploying cutting-edge conversion technologies at large scales (Rocke, 2014). In this context, biochar supply chains take on widely differing characteristics depending on the conversion technology employed, with biochar itself being variously a waste, byproduct, co-product or sole primary product, depending on the operation. Common co-products of pyrolysis include heat, bio-oil and gas that can be used as fuel for combustion (e.g. renewable natural gas) or as a raw material in the production of liquid fuels and chemicals via catalysis (e.g. synthesis gas).

Even among relatively comparable technologies, supply chains can be quite variable. For example, mobile and distributed-scale thermochemical conversion systems have received significant attention in recent years, mostly due to their relatively low capital investment and ability to be deployed in forward operations close to feedstocks, thereby producing dense, value-added products from waste biomass and reducing logistics costs (Anderson et al., 2013). Though many of these systems are similar in terms of size and configuration (Figure 2.7), they have different feedstock specifications and their different outputs necessitate significantly different downstream logistics. For example, fast pyrolysis systems that produce bio-oil as a co-product must include systems for liquid fuel handling, storage, transportation and safety, and biochar production cannot be decoupled from bio-oil production, regardless of independent market demand for the two products. Similarly, conversion technologies that capture and use gas for heat and power must include not only gas storage and handling systems, but also be well balanced with on-site energy demand.

Biochar can be used in its raw form to improve soils. However, in many cases, its performance as a soil amendment can be enhanced by post-conversion treatments. Such treatments include inoculation with desirable microbes, treatments to change pH or other chemical characteristics, granularization or pelletization to improve material handling and performance, composting or blending with chemical fertilizers and organics such as

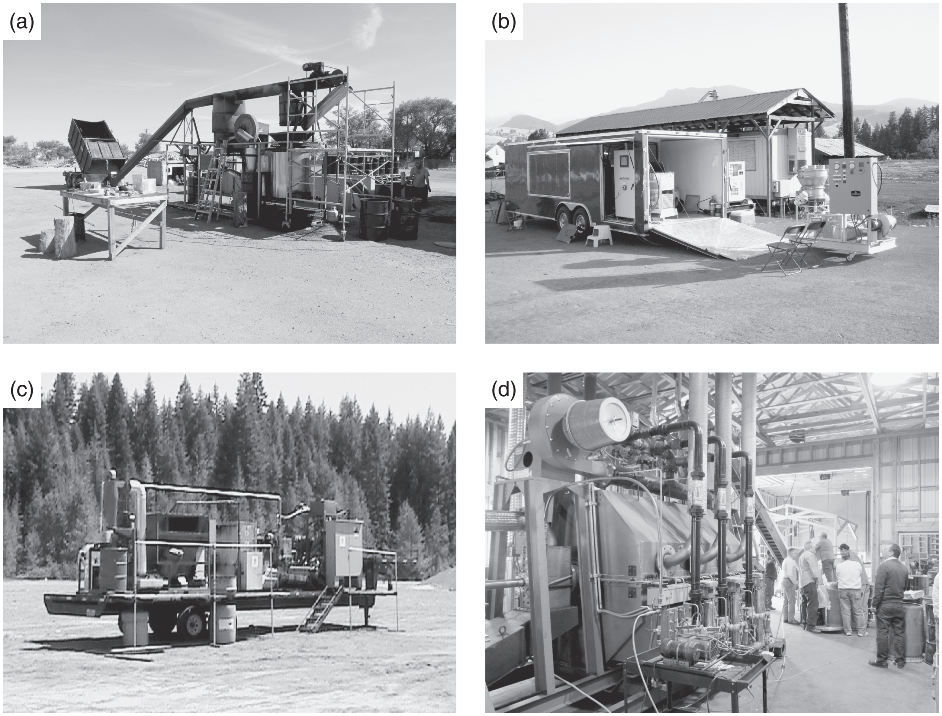

Figure 2.7. Examples of mobile and distributed-scale pyrolysis conversion systems producing co-products with biochar: (a) biochar and heat, (b) biochar with low-energy gas and bio-oil, (c) biochar with low-energy gas and bio-oil and (d) biochar with medium-energy gas. Photographs by Nate Anderson. (A black and white version of this figure will appear in some formats. For the colour version, please refer to the plate section.)

manure, and activation by chemical or physical means to increase surface area and promote ion exchange. In addition to improving product performance, such treatments provide biochar producers with critical opportunities to both diversify their products to better meet the needs of different end users and also differentiate their products from other manufacturers marketing to the same customers.

2.5.4 Distribution Logistics

Distribution logistics includes activities to package, transport, and store biochar from the site of conversion to the site of end use. Depending on the feedstock and conversion method, biochar resulting from pyrolysis can be variously characterized as a fine powder or a coarse charcoal, hydrophobic or hydrophilic, physically stable or friable, and homogenous or heterogeneous in particle size and shape. Biochar may be dry or wet, depending on the cooling method used in production, and has various levels of performance in pneumatic and conveyor handling systems. These characteristics have important implications for distribution. Fine powders can be both difficult and dangerous to store and handle due to combustion risk and risk to health from aspiration of dust particles. Methods of pelletizing biochar to improve handling have proven effective (Reza et al. 2014), but come with added financial costs and energy requirements.

For large-scale applications and wholesale markets, biochar can be transported in bulk by rail or truck in specially designed rail cars and trailers. More commonly, raw biochar and biochar downstream products are packaged for delivery in forklift-able bulk containers, large polyethylene bulk bags (i.e. totes or "super sacks," which are common in agriculture), metal and plastic drums, large multi-ply paper bags, and low-volume plastic bag and bucket packaging for small-scale consumer applications. From a logistics standpoint, bulk packaging can be efficient for producers, but may not meet the needs of end users, especially if specialized equipment such as hydraulic lifts and rolling forklifts are needed for unloading. More broadly, distribution logistics must be well matched to both transportation modes and the capabilities of end users to handle and store the biochar before use.

2.5.5 End Use

In addition to agricultural and forest applications focused on improving soil productivity, several other biochar uses have gained prominence, including uses for mitigation and reclamation of mining sites, seed coating, potting media, storm water filtration, and restoration of soils on burned sites (Dumroese et al., 2011; Fellet et al., 2011; Delaney, 2015). Part 4 and other chapters of this book examine specific end uses of biochar for a variety of case studies.

The end use segment of the supply chain includes not only the application of biochar to soils, but any blending or pre-application processing that may occur at the site of end use. Biochar can be blended mechanically or by hand with soil and other soil additives, such as seeds, manure, compost or chemical fertilizers. Processing can include further grinding or screening, or additions of water or surfactants to improve handling during application. Application can be done by hand, but it is often performed by specialized agricultural and forestry equipment (Figure 2.8). Application generally relies on broadcasting by hand or application using planters, tillers, seeders, and spreaders at various scales and levels of mechanization. Biochar can also be applied using hydroseeding systems that spread a pressurized aqueous slurry of biochar, typically mixed with other additives, such as compost, mulch fertilizer, and tackifying agents to reduce loss of biochar in storm runoff.

As described in Section 2.1, biochar is used as a soil amendment, and biochar systems can meet a broad range of soil improvement, waste management, energy, and climate change mitigation needs. However, the same charcoal classified as biochar in soil applications has potential for use as a fuel and raw material in other applications. Alternative uses include fuel pellets and briquettes, chemicals, feedstock for gasification, gunpowder, pigments and dyes, industrial sorbents, and a precursor in the manufacture of activated carbon (Azargohar and Dalai, 2006; Anderson et al., 2013). In a supply chain context, biochar producers should be aware of alternative uses of charcoal for two reasons. Alternative uses

Figure 2.8. A six-wheeled forwarder, normally configured to carry logs, here mounted with a modified pellet spreader to apply biochar pellets on forested sites developed by the Missoula Technology Development Center, Missoula, MT. Photo by Han-Sup Han. (A black and white version of this figure will appear in some formats. For the colour version, please refer to the plate section.)

provide opportunities to diversify product lines and enter new, complementary markets. They also present the threat of competition from horizontal integration of biochar production and marketing by organizations that are already using biomass to manufacture carbon and charcoal products like solid fuels and activated carbon.

SCM considerations for biochar used primarily to meet climate change mitigation objectives (Section 2.4 and Figure 2.4) can be more complicated than the end uses discussed thus far. Gaunt and Cowie (2009) identified six specific characteristics of biochar that can result in net reductions of GHG emissions attributable to biochar systems: 1) sequestration of relatively stable carbon in the soil; 2) avoided emissions of methane and nitrogen oxides related to alternative disposal methods such as biomass decomposition and combustion; 3) avoided emissions of methane and nitrogen oxides related to changes in soil processes; 4) displacement of carbon intensive agricultural inputs through both direct substitution and increased efficiency; 5) carbon sequestration resulting from higher productivity leading to greater soil carbon; and 6) displacement of fossil fuels from biochar co-products. Only one of these, carbon sequestration in the soil, is a direct effect. The other benefits, though supported by research, are indirect and rely on assumptions about the fate of waste biomass, changes in soil processes and characteristics, and market substitutions for fertilizer, fossil fuels, and other carbon intensive inputs.

In a commercial context, monetizing climate change mitigation effects can turn these benefits from a desirable non-market secondary characteristic of biochar used primarily to improve productivity into a viable end use with potential to generate revenue. Biochar producers and end users may be able to capture value related to carbon sequestration through effective marketing and product differentiation, especially in the context of certification schemes and robust LCA (Section 2.3 and Chapter 3). When produced as a co-product of biofuels, biochar can be critical in meeting renewable fuel standards and capturing value from associated financial incentives (e.g. Wang et al., 2014). Monetizing climate benefits may also be possible through various international, national, regional, and independent frameworks that establish mechanisms to compensate, sell, and exchange net carbon offsets through markets and payments for ecosystem services (Jack et al., 2008; Gaunt and Cowie, 2009). Though these opportunities are closely tied to public policy, they can be incorporated explicitly into biochar SCM, and climate change mitigation can be considered a viable end use for biochar when conditions are favorable.

2.6 Conclusions

A supply chain approach to biochar systems is focused on meeting the needs of end users and emphasizes the interconnectedness of organizations involved in various stages of production, logistics, conversion and end use. It is an effective framework for dissecting and evaluating the economic, social, and environmental dimensions of biochar as a manufactured product used to meet diverse objectives, including improving soils, managing waste, producing renewable energy, and mitigating climate change. As the biochar industry evolves, SCM can be used to organize, coordinate and manage the material, information, and financial flows of the biochar supply chain, allowing organizations to more effectively and efficiently deliver the many potential benefits of biochar systems.

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