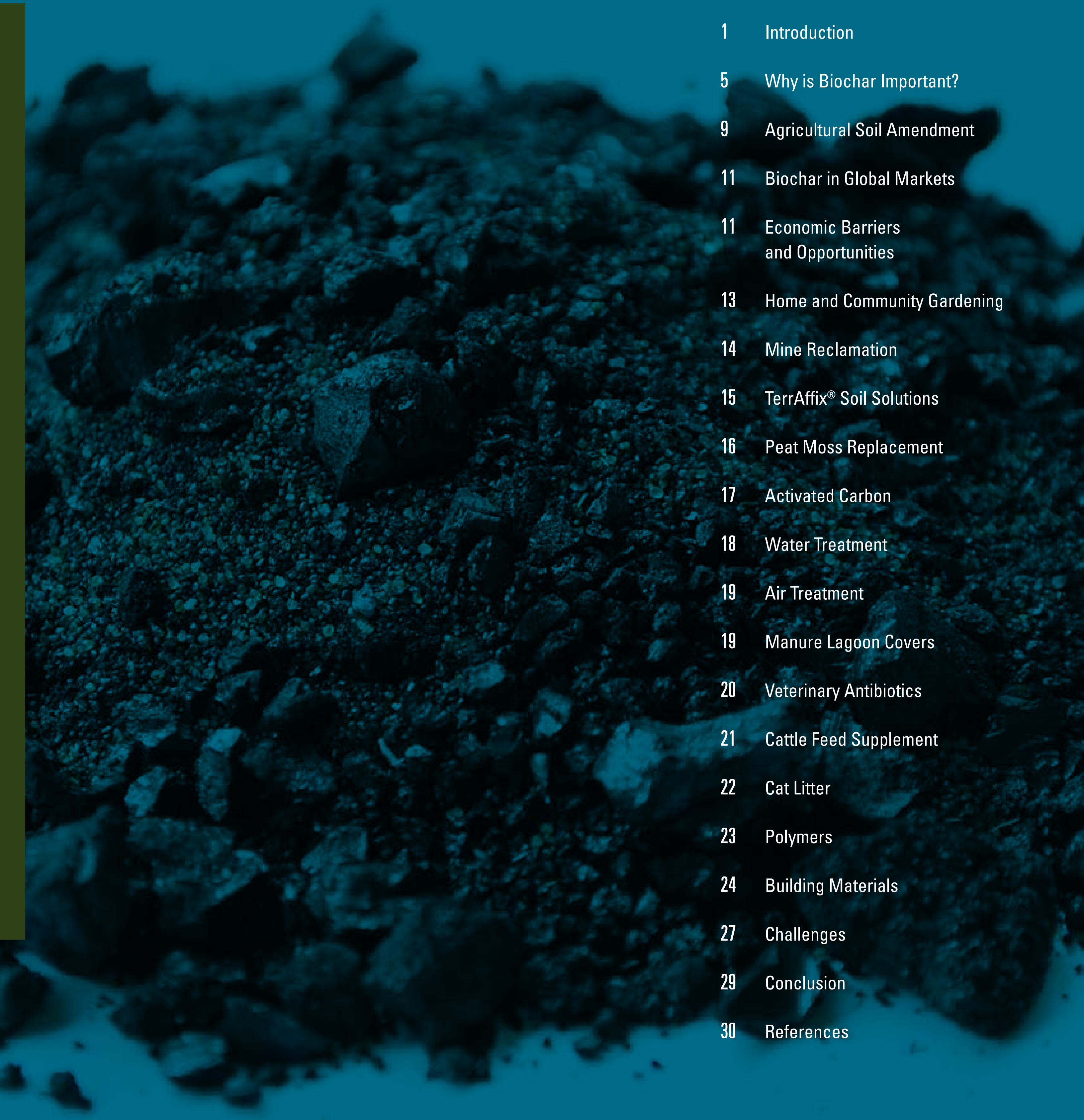
EMERGING MARKETS FOR BIOCHAR

CHALLENGES AND OPPORTUNITIES



Contents

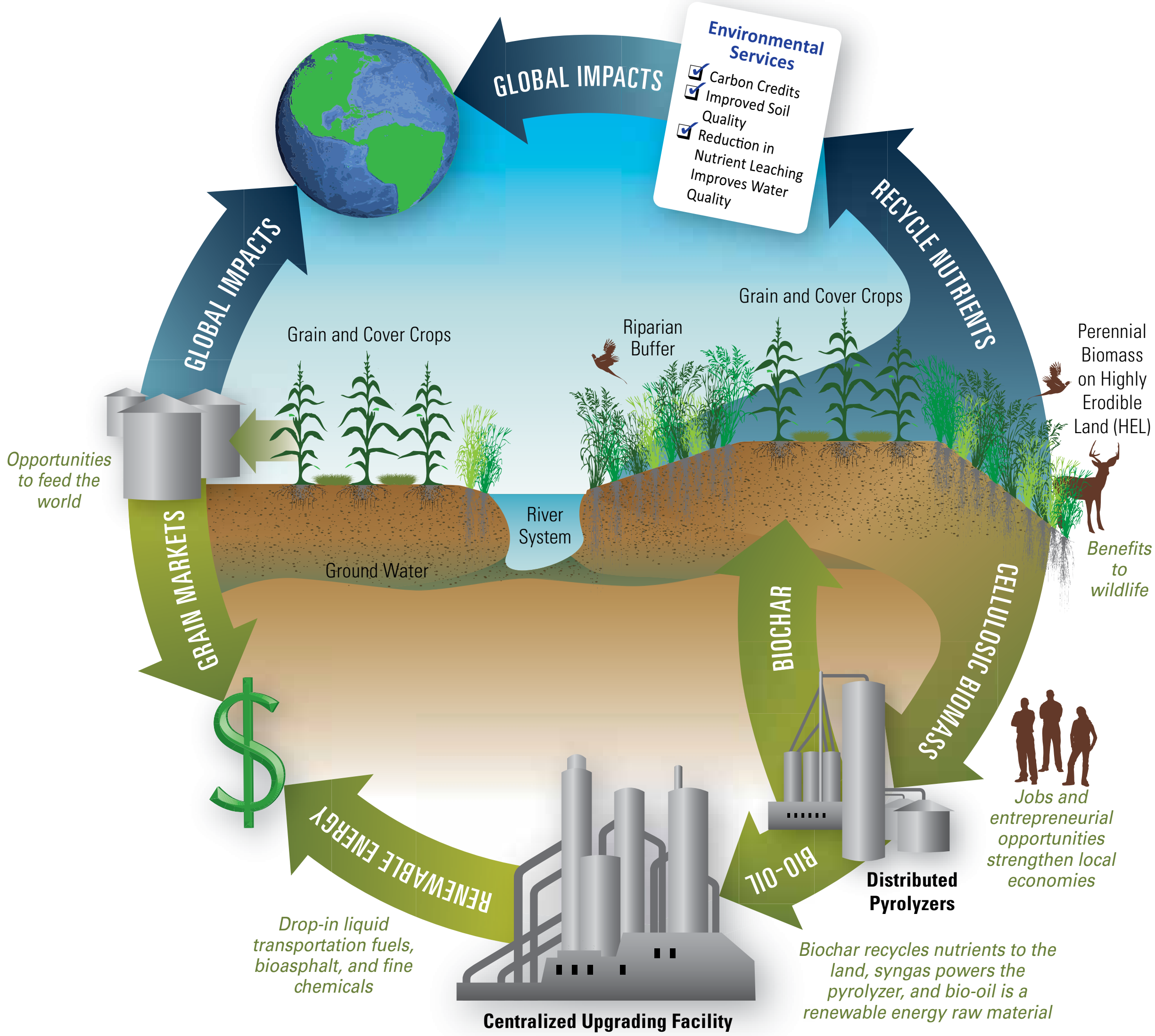


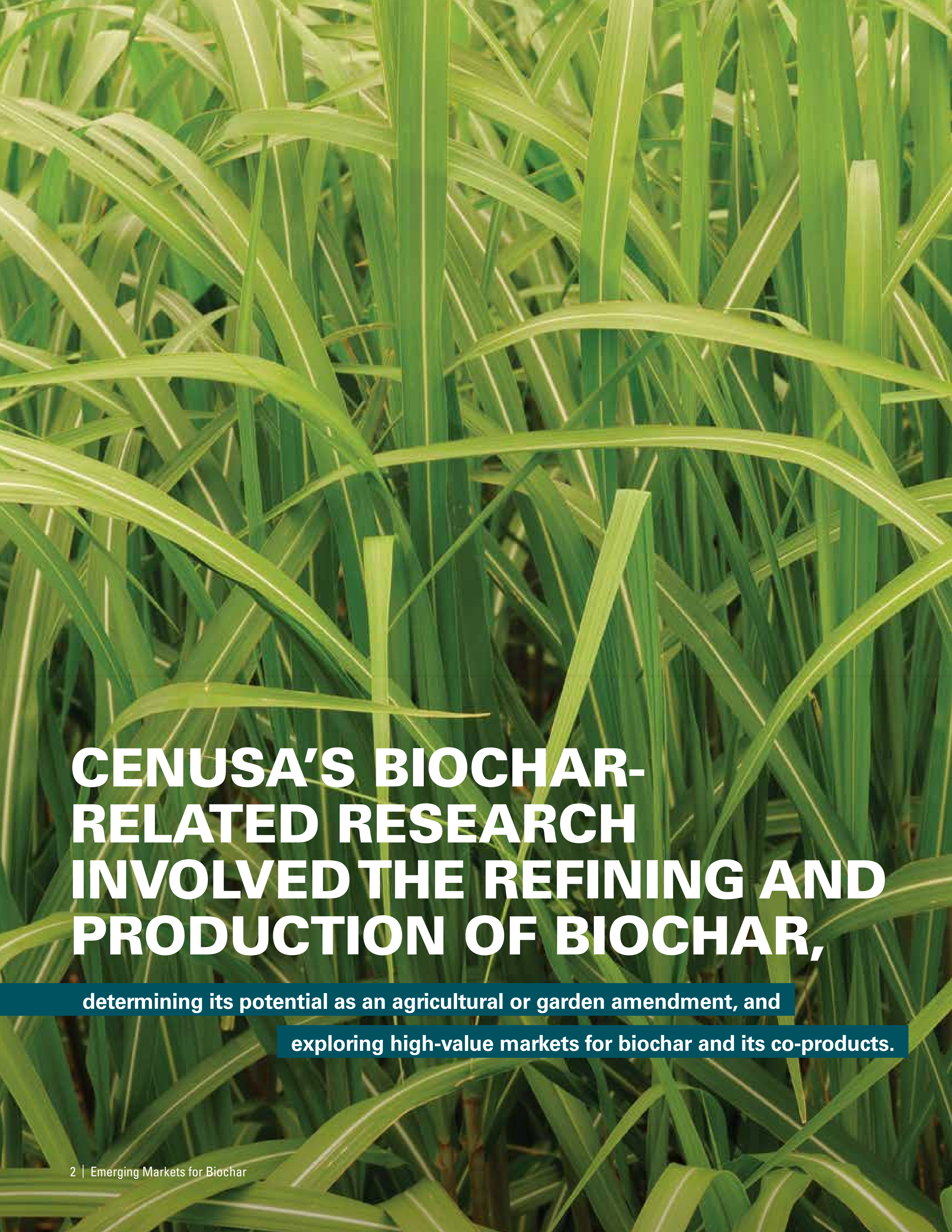
Figure 1. CenUSA Bioenergy Vision

Credit: Chris Hobbs, Hobbs Designs LLC

Introduction

CenUSA Bioenergy: Sustainable Production and Distribution of Bioenergy for the Central USA (CenUSA) **is a USDA National Institute of Food and Agriculture (USDA-NIFA) backed research project with a vision to create a sustainable biofuel and bioproducts system in the US Midwest.[1] Although CenUSA focused heavily on the research and development of perennial grasses that could be used to produce these biofuels and bioproducts, the project also had the objective of improving the sustainability of existing cropping systems by reducing nutrient runoff and soil erosion while increasing carbon sequestration. One method for meeting these sustainability goals is to enhance soil with biochar.**

1 Learn more about the CenUSA Bioenergy vision and work product at www.cenusa.iastate.edu



CENUSA'S BIOCHAR-RELATED RESEARCH INVOLVED THE REFINING AND PRODUCTION OF BIOCHAR,

determining its potential as an agricultural or garden amendment, and

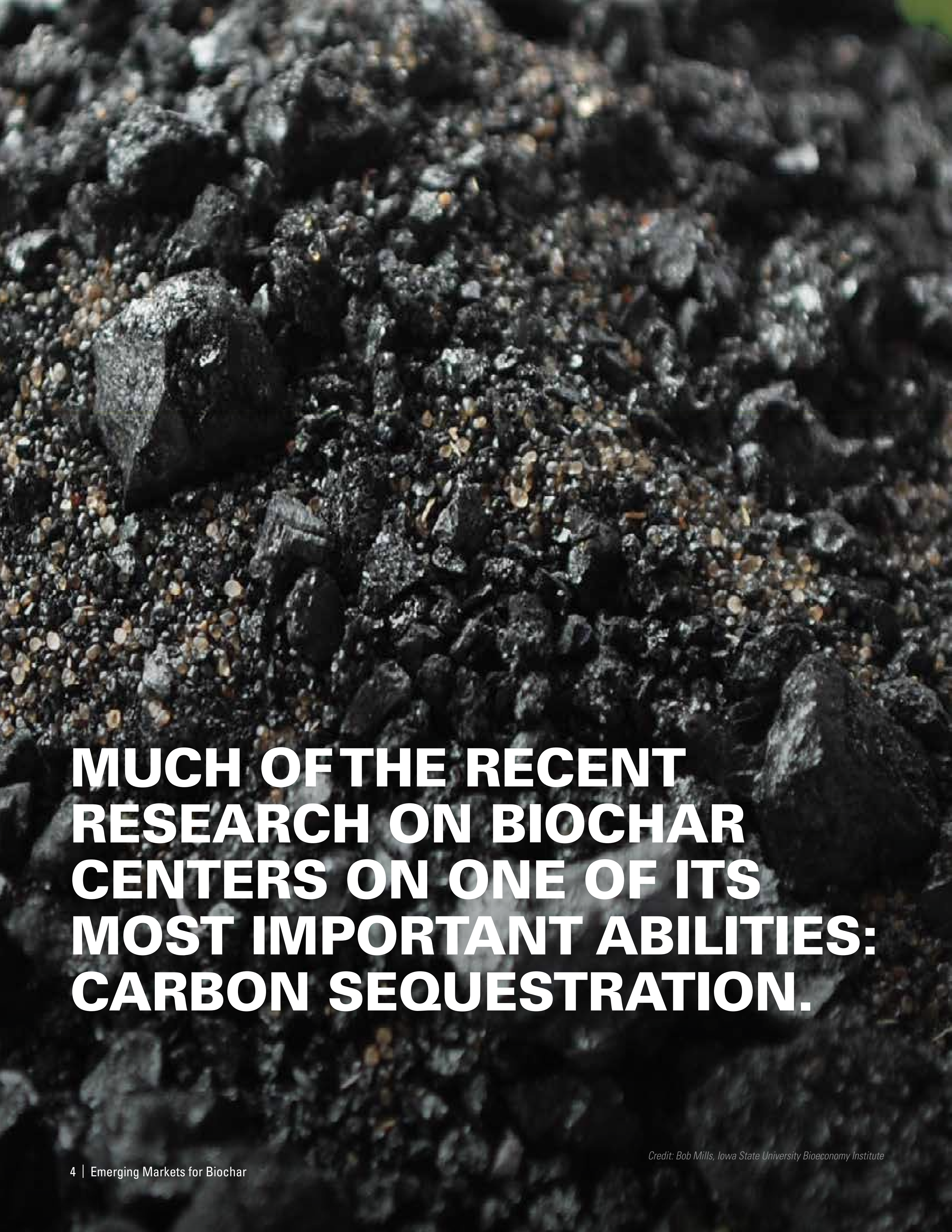
exploring high-value markets for biochar and its co-products.

CenUSA's vision of the bioenergy cycle involves the use of cellulosic biomass, such as perennial grasses, not only being used in biochemical-process ethanol facilities, but also being converted to fuels via pyrolysis. Through pyrolysis, this biomass would generate biochar for land amendment and nutrient recycling, bio-oil for upgrading to liquid transportation fuels, and synthesis gas (syngas). CenUSA's biochar-related research involved the refining and production of biochar, determining its potential as an agricultural or garden amendment, and exploring high-value markets for biochar and its co-products (Porter, 2014).

Biochar, a form of charred biomass similar in appearance and composition to charcoal, is a material with a wide variety of applications. Any biomass source with high carbon content can be used as its feedstock, but currently, the most common source is wood. Biochar is generated by pyrolysis, which is the heating of biomass in the absence of oxygen. As hydrogen, carbon monoxide, and other volatile gases are driven off, a carbon-rich solid product is created (Porter, 2014). The non-condensable fraction of the volatiles is called synthesis gas, or syngas, while the remaining fraction can be condensed into bio-oil (Laird, 2008). In some instances, syngas can be used as fuel for the pyrolizer, meaning no external energy is required for biochar production beyond the biomass itself (Yale E360, 2010). Bio-oil can also be burned to generate heat, or can be further refined for use as transportation fuel (Laird, 2008).

Biochar's properties are heavily influenced by the operating conditions in the pyrolyzer. This is because biochar's adsorption capacity is dependent on its surface charge and surface area, which can vary depending on type of feedstock used, pyrolysis temperature, or pre- and post-pyrolysis treatments. Producing biochar at a low pyrolysis temperature (300 – 400°C) and high pH will result in a high cation exchange capacity. Biochar with high cation exchange capacity are optimized for the adsorption of heavy metals (such as arsenic, lead, and mercury), but not oxyanions (such as nitrate and phosphate). Alternatively, those with high anion exchange capacity can adsorb large quantities of oxyanions. The cation exchange capacity of biochar has been studied extensively, but there are few studies regarding anion exchange capacity (Banik et al., 2018). Lawrinenko and Laird of Iowa State University were the first to study the nature of positively charged functional groups on biochar surfaces, reporting that anion exchange capacity decreases with increasing pH, and increases for biochar's produced in high temperature ranges (700 - 900 °C) (Lawrinenko et al., 2016 and Banik et al., 2018). Because of the variability in feedstocks and pyrolysis methods used to produce biochar, each batch of biochar can have unique characteristics; therefore, different types of biochar may be better suited for different types of markets and purposes.

BECAUSE OF THE VARIABILITY IN FEEDSTOCKS AND PYROLYSIS METHODS USED TO PRODUCE BIOCHAR, EACH BATCH OF BIOCHAR CAN HAVE UNIQUE CHARACTERISTICS; THEREFORE, DIFFERENT TYPES OF BIOCHAR MAY BE BETTER SUITED FOR DIFFERENT TYPES OF MARKETS AND PURPOSES.



MUCH OF THE RECENT RESEARCH ON BIOCHAR CENTERS ON ONE OF ITS MOST IMPORTANT ABILITIES: CARBON SEQUESTRATION.

Credit: Bob Mills, Iowa State University Bioeconomy Institute

Why is Biochar Important?

Biochar began garnering interest after the discovery of carbon rich, highly fertile "terra preta" soils in the Central Amazon. These soils are a result of the slash-and-char cultivation hundreds of years ago, which entailed the charring of wood residue and subsequent mixing of the residue into the soil (Montanarella, 2013). Since the discovery of these soils, researchers have been exploring the effects of charred biomass – i.e. biochar – on soil quality. A multitude of studies have determined that the addition of biochar to soils can improve soil functionality and crop productivity in a variety of ways (Bilgili et al., 2019). Biochar's highly porous structure improves soil physical characteristics by encouraging the formation of macro aggregates, improving soil porosity by reducing soil bulk density, and increasing the water-holding capacity of the soil (Bilgili et al., 2019; Basso et al., 2012). The enhanced physical condition of the soil and increased adsorption of microbial substrates (carbohydrates, lipids, and proteins) improve soil microbial activity, while the high surface area and cation exchange capacity of the char increase nutrient retention in the soil (Bilgili et al., 2019). Biochar amendments have also been shown to reduce soil bulk density and improve aeration (Porter and Laird, 2014).

Much of the recent research on biochar centers on one of its most important abilities: carbon sequestration. Biochar's ability to sequester carbon is beneficial to soil health – when incorporated into soils, biochar can increase soil carbon content, thus increasing fertility (Sudmeyer, 2018). However, it may also have implications in the global fight against climate change. The biochar pyrolysis system has the potential to act as a carbon sink, meaning it takes more carbon out of the atmosphere than it puts back in. This is because plant matter emits carbon dioxide (CO2) as it decays. Other plants then absorb this CO2, later decay, and the cycle continues. Depending on the biomass used and pyrolysis conditions to produce biochar, up to 50% of the original carbon in the biomass feedstock is stored in the char. Biochar stores carbon in a stable form that prevents leaking, so when plant matter is pyrolyzed to create biochar rather than allowed to oxidize and decay, the carbon it contains that would otherwise be discharged into the atmosphere as CO2 is instead sequestered in the biochar for hundreds or potentially thousands of years (Levitan, 2010).

Figure 2: Biochar in the emerging agricultural economy

Credit: David Laird, Iowa State University

IF BIOCHAR USE BECOMES COMMONPLACE, ITS ABILITY TO ENHANCE SOIL NUTRIENT RETENTION AND CYCLING, RETAIN WATER, AND SEQUESTER CARBON

may be able to make a substantial difference in some of humankind's most pressing issues.

Credit: Bob Mills, Iowa State University Bioeconomy Institute

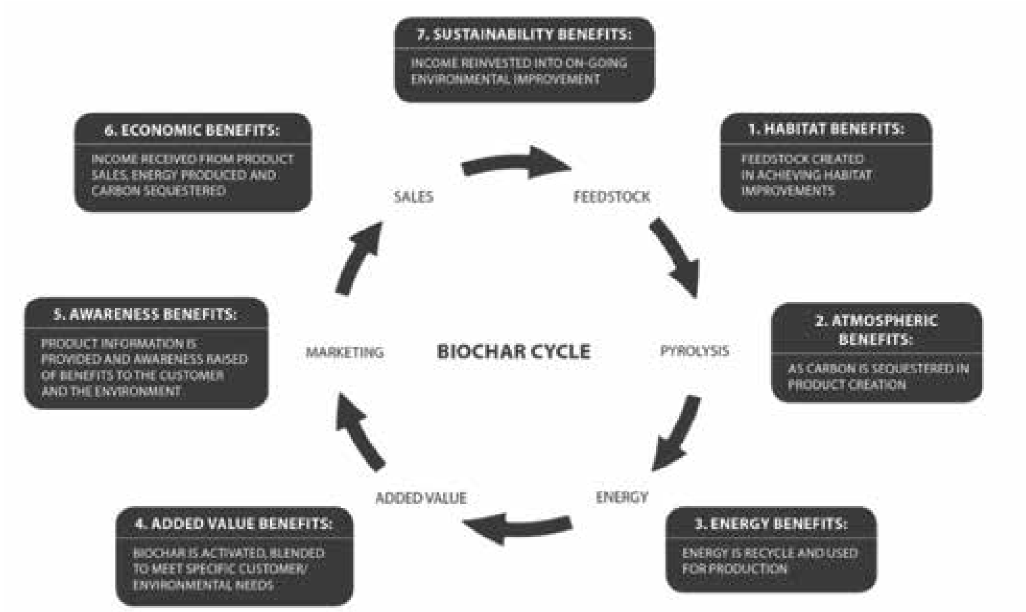


Figure 3: Biochar Cycle

Source: TerrAffix® Soil Solutions

A 2013 study backed by the USDA-ARS set out to find if biochar could significantly mitigate carbon, methane, and nitrous oxide emissions from soils. Researchers created biochar by pyrolyzing oak pellets at 550 °C. Four temperate soils were supplemented with this biochar at five rates: 0%, 1%, 5%, 10%, and 20% (weight/weight). The group found that in all soils, CO_2 emissions increased linearly while N_2O emissions decreased exponentially with increasing biochar addition rates. Emission measurements were taken over the course of two years; even though the soils respired CO_2 over the course of the study, they still emitted less than the volatile carbon content sequestered in the biochar itself (4%). All in all, the group concluded that all greenhouse gas emissions were small in comparison to total soil organic carbon sequestered in the biochar, making biochar generation a carbon-negative process (Stewart et al., 2013). This emission reduction capability has caused many to back biochar as a possible strategy for climate change mitigation. One group estimates that biochar could offset 2% of global greenhouse gas emissions, but only if the biomass is obtained from non-food sources. Another evaluation found that pyrolyzing and burying 10 percent of the world's biomass waste could sequester five gigatons of carbon annually (Cooper, 2016).

Well over 300 peer-reviewed papers were published on the carbon-sequestering ability of biochar in 2013 alone, establishing a consensus that biochar amendments can effectively remove CO_2 from the atmosphere (Porter, 2014). Studies performed across a range of cropping systems have also shown that biochar-amended soils release between 44 and 66% less nitrous oxide – a greenhouse gas 310 times more potent than CO_2 – in comparison to un-amended soil (Edwards et al., 2018; USBI, 2019). This research demonstrates that soil carbon sequestration by way of biochar amendment may be a feasible tool for reducing greenhouse gas emissions.

Improving the efficiency of food production, limiting water consumption in agriculture, and reducing greenhouse gas emissions are becoming increasingly important. If biochar use becomes commonplace, its ability to enhance soil nutrient retention and cycling, retain water, and sequester carbon may be able to make a substantial difference in some of humankind's most pressing issues. The bulk of biochar-related research centers around its ability to improve soils; as a result, some only see biochar's potential in the soil amendment market. However, there are a myriad of other possible niche markets and uses for biochar. If these niche markets and the larger soil amendment market are explored and utilized to their full capacity, the biochar generated may be able to store immense amounts of carbon. At the same time, biochar could replace products and feedstocks that cause environmental damage or require large amounts of energy to produce. In the remainder of this white paper, we will discuss the various markets that biochar can be used in, the properties that make biochar applicable to these markets, and the challenges associated with establishing global markets for biochar. In doing so, we hope the reader will gain an understanding of the challenges and opportunities facing this unique material.

Robert C. Brown and Santanu Bakshi are part of a team looking for ways to make biochar more useful and valuable to agriculture.

Credit: Christopher Gannon.

"THIS MIGHT CHANGE HOW FARMERS APPLY FERTILIZER TREATMENTS."

Robert C. Brown, director of Iowa State's Bioeconomy Institute

Agricultural Soil Amendment

As mentioned above, most biochar-related research centers around its ability to be used as a soil amendment – but much of the farmland in the United States already consists of productive soils, and farmers may not be eager to purchase and apply biochar to lower-value, high-yielding crops such as corn or wheat (Voth, 2013). However, according to Jonah Levine (Voth interview), a biochar salesman associated with the Colorado-based companies Biochar Solutions and Biochar Now, biochar can find a place in "functional niches".

These niches lie in high-value crops that have a long-term payback, such as fruit and nut trees. For example, a Midwest corn grower may have no need for the carbon sequestration provided by biochar, but trees can greatly benefit from the increased water-holding capacity it provides. A ponderosa pine tree will die if soil moisture falls below 7%; Levine claims that he has had success holding moisture above 10% when a 5% biochar amendment is applied to soil (Voth, 2013).

Jim Ippolito, a USDA-ARS soil scientist based at Colorado State University, believes that reducing irrigation and water use could be a long-term feat of biochar (Voth interview). By increasing soil water holding capacity, there's a possibility that the same crop yield could be produced with less water applied overall (Voth, 2013).

Biochar is even being evaluated as a tool for nutrient runoff reduction. There are two reasons for this. The first is that if biochar amendment improves soil quality, it could reduce the need for fertilizer, in turn reducing the amount of harmful runoff. The second reason is that if biochar-enriched soils increase productivity, it's possible that fewer acres would need to be in production overall, which could reduce nutrient loading (Porter, 2014).

Although much of the research relating to biochar as an agricultural soil amendment appears promising, predicting exact soil and crop response to biochar can be difficult. Different biochar production methods lead to different chemical and physical properties of the biochar, and soil properties are highly variable depending on location and other environmental factors. Ultimately, these variables can affect plant response to biochar. A 2013 literature analysis conducted by Dr. Lori Biederman and Dr. Stanley Harpole of Iowa State University found that the addition of biochar to soil resulted in increased aboveground productivity, crop yield, and total soil nutrient (N, K, and P) content. Meanwhile, variables such as belowground productivity, plant tissue nitrogen and phosphorous concentration, and soil inorganic nitrogen did not demonstrate any clear effect from biochar addition. The researchers also found that in some instances, adding greater quantities of biochar reduced productivity, while in others, productivity increased after increasing biochar application rates (Biederman & Harpole, 2013).

A more recent literature review compiled by researchers from South Korea, Egypt, Oman, Germany, Pakistan, New Zealand, and the United States also acknowledge that the impact of biochar application depends heavily on both the biochar and soil type; however, they have recommendations for maximizing biochar's economic viability. To lower the cost of biochar application, a valid minimum application rate should be identified. Thus, they believe future experiments should be geared toward studying low application rates. Furthermore, they recommend designing suitable biochar types for different soil properties. Ultimately, the group believes that standardization of biochar application – knowing the exact rate and type of biochar will suit each type of soil fertility issue – is the key in making biochar an affordable soil amendment solution (El-Naggar et al., 2019).

There are also modifications that can be made to biochar that allow it to perform better as a soil amendment. In a recent experiment, Robert C. Brown and Santanu Bakshi of the Iowa State University Bioeconomy Institute determined that biochar's sponge-like properties make it an effective slow-release fertilizer. This is because when biochar is pre-treated with iron sulfate (an inexpensive byproduct of steel manufacturing) it can adsorb phosphate at 12 times the rate of untreated biochar. Biochar then releases this phosphate at a rate that can supply the necessary phosphorous to crops. Bakshi calculated that the biochar releases 18 milligrams of phosphorous per kilogram of soil after three hours of leaching with water – this is nearly equal to the 22 milligrams of phosphorous per kilogram of soil recommended for crop growth. However, it is less soluble in water than conventional fertilizer, and is therefore less likely to be washed away by rain or leeched into groundwater. The researchers believe that these results could have big impacts on agriculture around the nation, as Brown said, "This might change how farmers apply fertilizer treatments."

BIOCHAR COULD PLAY AN IMPORTANT ROLE IN AGRICULTURE ON A GLOBAL SCALE,

particularly in countries with low-quality soil.

Biochar in Global Markets

Biochar could play an important role in agriculture on a global scale, particularly in countries with low-quality soil. The European Union Soil Thematic Strategy ("the Strategy", a report aimed at establishing common practices for the sustainable use of soil, mentions the constant decline of soil organic carbon as one of the largest threats to soil in the European Union. The Strategy also identifies soil's role as a carbon sink as one of its most important function. For these reasons, biochar is garnering attention in Europe for the positive influence it may have on field capacity, nutrient availability, and fertilizer efficiency. However, under EU regulation, biochar is considered a waste product, and the majority is thus blocked from agronomic utilization. The small percentage of biochar that is not blocked is subject to regulations that were designed for sewer sludge and other amendments (Montanarella, 2013).

Despite the lack of legislation, some progress has been made in recent years regarding the regulated use of biochar. Existing laws regulating the use of traditional wood charcoal have offered a point of contact to create voluntary biochar standards in Europe and the United States. Groups such as the British Biochar Foundation and the International Biochar Initiative have created their own quality standards that provide users and producers with guidelines to follow (Meyer et al., 2017). This progress is promising, but the EU will need to further investigate the change in heavy metals in soil, pesticide sorption, and introduction of metal contaminants that may come about as a result of biochar amendment in the long term in order to create science-based policies. If they can bridge these knowledge gaps, biochar could provide a huge benefit to European agriculture by offering a solution to their lack of soil carbon (Montanarella, 2013).

Economic Barriers and Opportunities

There are economic barriers to widespread biochar use in agriculture as well. Despite the fact that biochar has been shown to increase crop yield, some studies show the increase in yield and resulting increase in revenue may not be enough to offset the price of biochar. To evaluate the economic viability of biochar in agriculture, researchers at Justus Liebig University in Germany performed a review of literature regarding field application of biochar. By extracting 507 yield differences from literature, the group concluded that the average increase in crop yield resulting from 3 Mg/hectare biochar addition is approximately 10%. This yield increase would have to continue on for 10 years for farmers to realize a profit; however, roughly two thirds of the data points reviewed were based on 1-year trials. Those that reflected a longer time period did show that yield affects continue for several years after application, but at very low levels in comparison to the first year. As a result, if only the agronomic value of biochar is considered, purchasing biochar to be used as a soil amendment may not be profitable for farmers. However, this review did not consider the possibility of farm-owned biochar production. If farmers produced their own char using their own biomass and a small kiln located on their property, they may find it much easier to turn a profit (Bach, Wilske & Bruer, 2016).

The economic viability of biochar's use as an agricultural soil amendment is hard to predict, but there are potential future policy changes that could greatly accelerate its production and use in agriculture. Carbon taxes and emissions markets may provide a secondary outlet for farmers to generate profit from biochar. Carbon markets are based around the concept that some businesses may prefer to pay other businesses to reduce greenhouse gas emissions rather than make the reduction themselves. These markets trade in carbon credits; each credit is equivalent to one ton of CO2. If an emissions regulation needs to be met, a business has the choice to reduce their greenhouse gas emissions, or purchase carbon credits from someone who already has. Because greenhouse gas emissions are not capped in North America, the carbon trading market is voluntary (Powers, Schulte, and Stowell, 2009).

Though most carbon offset schemes trade in emission reductions, a different type of carbon market may soon become carbon: CO2 removal. Puro is the first online marketplace in Europe for the buying and selling CO2 removals. Their CO2 removal certificates are awarded based on 1 ton of CO2 removed from the atmosphere by one of their certified removal methods – biochar is one of these methods. The certificates are verified and tradeable, and after the first few online Puro auctions, the average price of the removal certificates being bought and sold was €26.92 ($30.47). Because this carbon market depends on the removal

Source: Iowa State University Extension and Outreach

of carbon from the atmosphere rather than a reduction in emissions, it could provide a higher environmental benefit while exposing business owners and individuals to the benefits of generating and using biochar (Puro, 2019). Systems such as Puro may also pave the way for the concept of carbon removal to be integrated into existing markets, such as the carbon cap-and-trade program in California. Farmers who want to utilize biochar for its soil health benefits could use biochar to improve their yield, and subsequently sell their carbon removal credits on a carbon market. Biochar may also be applicable in a carbon tax system. With a carbon tax, a fee is charged per ton of carbon emitted (Union of Concerned Scientists, 2019). If mandatory carbon taxes are to exist in the future, carbon removal by way of biochar could offer a way for industries or individuals to offset their emissions and therefore reduce the amount they pay in fees.

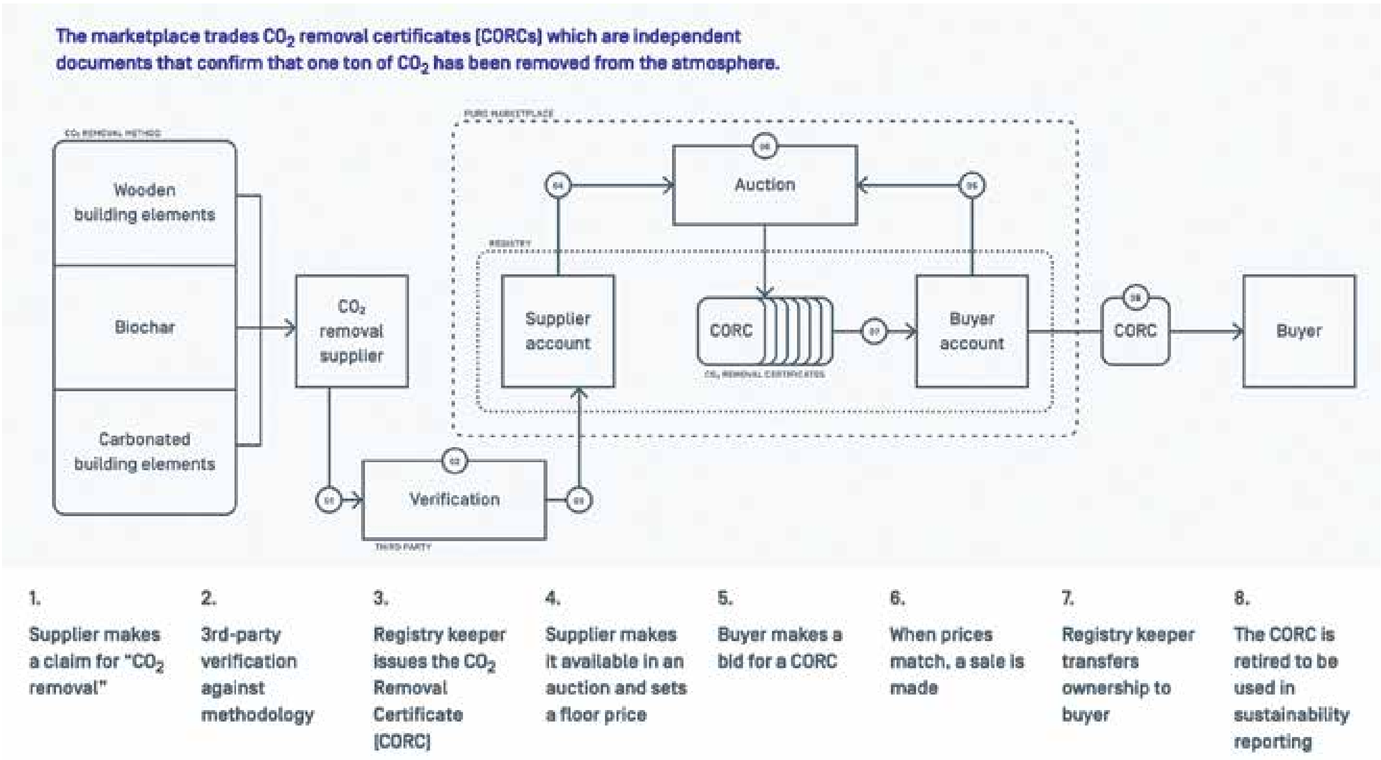


Figure 4: Puro Carbon Marketplace.

Credit: Puro Carbon Marketplace https://Puro.earth

Home and Community Gardening

Between 2012 and 2015, CenUSA collaborated with The University of Minnesota Extension Master Gardeners and the Iowa Extension Master Gardener projects to determine if biochar has value as a soil amendment in home gardens. The overarching project goal for these "citizen science" teams was to determine if biochar could be sold commercially in the horticulture market. Researchers from both teams planted, maintained and monitored three biochar demonstration over the course of the study. The three-year analysis showed a few improvements between the control soil and the biochar-amended soil. Soil organic matter content increased, and the soil tilth – a measure of aggregate formation, moisture content, and aeration – improved in each biochar plot. However, other measures of plant health remained inconclusive: the harvest weight for some vegetables (kale, potatoes, green peppers) went up, while certain plant varieties, such as basil and cucumber, experienced a decrease in harvest weight. Researchers concluded that given the inconsistency of the data and the variety of factors other than biochar that could influence plant growth patterns, it could not be determined if there were measurable benefits when using raw biochar as a soil amendment in a typical home garden (Davenport-Hagen et al., 2017).

Another study that analyzed the plant growth effects of biochar in gardens focused on how mixing biochar with organic amendments affected the growth of lettuce (Lactuca sativa L.). The study, conducted by university researchers in Italy, used nine non-pyrolysis organic amendments (NPOAs) and ten different types of biochar, resulting in 90 combinations (Bonanomi et al., 2017). The results of this study found that certain combinations, like nitrogen rich materials, were very conducive to the lettuce growth and root health. Other combinations, such as wood materials, resulted in negative growth impacts on the plants. With these results, the outcome of a certain mixture is able to be predicted based on the chemical interactions common between the two materials used. One note from the researchers was that "the positive properties of specific NPOA-biochar combinations far outweigh the growth promotion observed when their component were used separately" (Bonanomi et al., 2017). They suggest developing guidelines to ensure that the mixture performance matches or exceeds the cost of the amendment.

Although raw biochar may be unpredictable in its effects on home gardens, some are finding ways that biochar can be modified to turn it into a marketable soil supplement. Cool Planet, a company based in Colorado, processes raw biochar to create a more reliable soil amendment. Their treatment process involves detoxifying the biochar by removing hydrocarbon residues and other substances, bringing the pH to a neutral state, and conditioning biochar pores to better retain water, nutrients, and beneficial microbes. They call the end result Cool Terra®, and report that based on 100 independent studies conducted on the product, growers can expect a 12.3% average yield increase and a 3:1 return on investment when using their product (Cool Planet, 2019). Cool Planet is not the only company curating biochar-based soil conditioners: Wakefield BioChar, Oregon Biochar Solutions, and many other U.S. based companies sell biochar soil enhancement products, demonstrating that for the time being, there may be more value for biochar in the home gardening market rather than in agriculture.

Frongoch Lead and Zinc Mines post capping. *Source: Terraffix Soil Solutions*

Mine Reclamation

Biochar's ability to enhance soil health has additional applications outside of agriculture and horticulture. There are hundreds of thousands of abandoned mine sites worldwide, and roughly 500,000 sites in the United States alone (Cui, 2019). The soils at these locations leech acidic and metal-rich material into water sources, degrading water quality and harming aquatic life. To prevent transport of these pollutants, vegetation must be established on-site, but the soil is often so damaged that this can often be difficult. Using biochar as a soil amendment in mine reclamation is one way to improve soil health, sorb heavy metals, and accelerate the revegetation process (Peltz and Harley, 2016). Biochar can assist in the reclamation process in a variety of ways. It has been shown to increase soil and waste rock pH, cation-exchange capacity, water-holding capacity, organic matter content, nitrate concentration and biological nitrogen. These changes encourage the establishment of vegetative cover while reducing concentrations of heavy metal concentration in the soil (Cui, 2019).

As evidence of biochar's soil-enhancing abilities accumulates, a series of case studies have been performed analyzing the application of biochar to reclaim mine-affected lands. In one study in San Juan County, Colorado, in an area that was mined extensively between 1871 and 1991, soil was amended with biochar at a 30% volume in the first six inches of depth. Researchers found that water retention increased, bulk density decreased, and leachate concentrations of iron and aluminum decreased. A second study focused on the Hope Mine, also in Colorado, where a cover comprised of biochar, erosion control webbing, compost, and hydromulching was applied to the deteriorated land. The biochar was applied at varying rates of 6.2 to 49.4 tons per hectare. Vegetation establishment in the first growing season was excellent, and researchers determined that a 12.5% volume/volume biochar-compost mixture was optimal for plant growth (Peltz and Harley, 2016). A third study done by researchers at the University of Colorado, USEPA, and USDA analyzed the effects of biochar derived from Miscanthus, a perennial grass, on spoiled mine soils. They found that combining a biochar treatment with lime reduced concentrations of leachable metals in the soils, while biochar on its own reduced dissolved organic carbon leaching from the soil (Novak, 2018). By analyzing the results of these case studies and the properties of biochar, it appears that biochar can condition soil in a way that reduces erosion, improves water conservation and quality, and facilitates vegetation establishment at both abandoned and active mine sites (Peltz and Harley, 2016).

LEARN MORE ABOUT THE EFFECTS OF MIXING BIOCHAR WITH OTHER ORGANIC AMENDMENTS IN BIOCHAR AS PLANT GROWTH PROMOTER: BETTER OFF ALONE OR MIXED WITH ORGANIC AMENDMENTS?, CHECK OUT THE STUDY AT HTTPS://WWW.FRONTIERSIN.ORG/ARTICLES/10.3389/FPLS.2017.01570/FULL

TerrAffix® Soil Solutions

One United Kingdom company is capitalizing on biochar's ability to reclaim highly-degraded soils. TerrAffix® Soil Solutions manufactures biochar-based soil remediation solutions that are specifically engineered to improve the health of and establish vegetation on hard-to-reclaim lands.

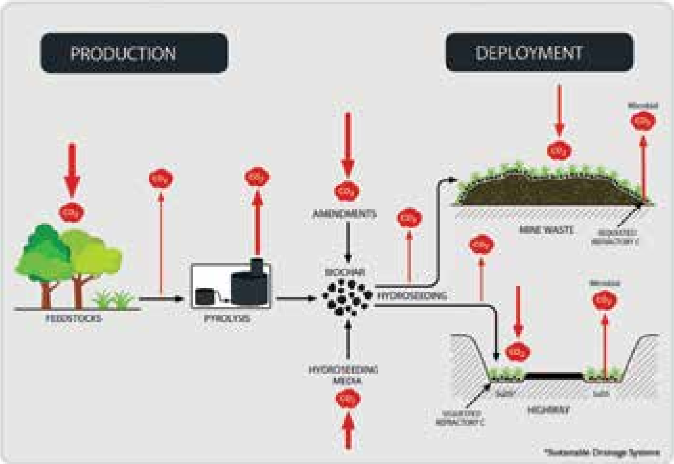


Figure 5. TerrAffix®- Carbon Sequestration Cycle.

Source TerrAffix® Soil Solutions

TerrAffix®- Mine is a matrix of biochar augmented with nutrients and minerals specifically targeted at acidic soils – when sprayed on impaired soils, TerrAffix® claims that the slurry increases water and nutrient retention, decreases mobilization and bioaccumulation of harmful heavy metals, and prevents pollutants from leaching into water bodies. The company offers additional biochar-based products for ecological recovery in other applications: The company also markets products geared for vegetation establishment on railway embankments, vegetated drainage swales for roadsides and attenuation purposes, and bank stabilization for slopes with weak soils. Like TerrAffix®-Mine, these products are slurries intended to be sprayed over soils requiring remediation to encourage rapid vegetation establishment and reduce pollutant mobilization into waterways. TerrAffix® has conducted case studies analyzing the effects of their product on mine sites and roadside swales, finding that a thorough vegetation cover was established 3 – 5 weeks after product application. The products can cost anywhere from $1.43 - $6.87 per square meter of land treated, depending on the product, additives, and number of layers required at the reclamation site. The company also claims that a genuine carbon sequestration and climate benefit value can be calculated for the material applied (TerrAffix®, 2019).

One major benefit of establishment of vegetative cover is the erosion control that it provides – vegetated cover can reduce erosion by up to 99% when compared to bare soil. Because of this, there is an extensive market for erosion control products to be used in the construction industry and beyond (Minnesota Stormwater Manual, 2019). The biochar slurries sold by TerrAffix® may be able to find a foothold in the construction erosion field, while concurrently selling into soil remediation and reclamation markets posing an opportunity for biochar in two promising markets.

Peat bricks drying.

Peat Moss Replacement

Biochar may be able to offset carbon emissions in ways other than soil sequestration. It can serve as a potential replacement for peat moss, a common component of soil-free potting mixtures in greenhouse operations (UIUC, 2018). The horticultural value of peat moss lies in its ability to retain moisture and oxygen while still being lightweight. However, harvesting peat moss requires mining of peat bog ecosystems, consisting of peat soil and the wetland habitat that grows on its surface. These bogs serve as a global carbon sink, storing roughly a third of the world's soil carbon (Higgins, 2017). When peat is extracted for horticulture, the bog is drained, cleared of vegetation, and leveled. This process increases peat moss decomposition on site, thus increasing CO_2 emissions, and removes living biomass from the surface, therefore eliminating any carbon fixing occurring in the ecosystem. Eventually, when the extracted peat is used as a potting component, it is decomposed by bacterial and fungal activity at a rate significantly higher than what is observed in natural peatlands, generating CO_2 and CH_4 (Cleary et al., 2005).

In an effort to lessen the carbon emissions generated by the peat moss industry, Andrew Margenot of the University of Illinois and colleagues at the University of California, Davis investigated biochar as a potential replacement for peat moss in potting mix. The group used softwood biochar as a peat substitute in a conventional 70:30 (volume/volume) peat: perlite mixture at 10% volume increments. The substrate was tested on marigolds; the pH of one group was left as-is, while the pH of another group was adjusted using pyroligneous acid (PLA), a biochar byproduct. They found that the pH-adjusted substrates inhibited seed germination for 50-70% biochar volume, but that seed germination was not altered for the un-adjusted pH group. The substitution did not negatively impact marigold biomass or flowering, and at substitution rates of 10-30%, marigold biomass was greater than that of the control group. This allowed the group to conclude that softwood biochar can be a considered a full replacement of peat in conventional peat-perlite substrates, and that in the case of marigold production, a pH adjustment for biochar is not required (Margenot et al., 2018).

The idea of using pyrolyzed biomass in soil-free substrates has been around for decades; studies investigating the use of charcoal for substrate improvement date as far back as 1956. However, as research on biochar continues to accumulate, scientists may be able to engineer biochar production to target specific benefits of substrates by altering the way the material is pyrolyzed or the feedstock that is used. Nursery plants can benefit from biochar-based substrates in a variety of ways, from increased water holding capacity to pathogen and pest suppression. For these reasons, Margenot and his team encourage additional research regarding biochar as a full replacement for peat moss. Considering that peat moss expense is expected to climb in the years to come due to production costs and competing use, biochar has the potential to be an improved substrate for the horticulture industry both environmentally and economically (Margenot et al., 2018).

Activated Carbon

Although biochar has immense market potential globally as a soil enhancement, the soil enhancement market is still a market in its nascent stage. However, the high adsorption and cation exchange capacity of biochar may allow it to edge into smaller markets currently dominated by activated carbon. Activated carbon is charcoal generated by pyrolysis of coal, wood, or other materials of plant origin. This charcoal is then physically or chemically treated to creates micro-fissures, significantly increasing its adsorptive surface area (Jackson, 2014 and McLaughlin, 2016). Activated carbon is a well-established market with roughly one million tons of production worldwide each year (McLaughlin, 2016) – with an average cost of $5.60 per kg, this amounts to a market size of over $5 billion (Alhashimi and Aktas, 2017). Biochar and activated carbon have similar properties; their ability to sorb heavy metals makes them helpful amendments for several markets such as wastewater treatment and soil remediation (Hagemann et al., 2018). However, biochar has environmental and economic advantages that may give it an edge in markets currently dominated by activated carbon (Alhashimi and Aktas, 2017).

The production and fate of activated carbon used for toxin removal in water, air, and soil may result in life cycle emissions that do more harm than good. Alternatively, studies have demonstrated that the life cycle of biochar removed more CO2 equivalent from the atmosphere than it puts in. A 2016 literature analysis of 84 types of biochar and activated carbon by researchers at the University of New Haven found that nearly all studies related to the life cycle of biochar found that it had a negative global warming potential, with average emissions of -0.9 kg CO2 eq/kg. Literature regarding activated carbon reported average emissions of 6.6 kg CO2 eq/kg. There was also a large disparity in energy demand required throughout production – biochar production requires 6.1 MJ/kg on average, while activated carbon requires 97 MJ/kg (Alhashimi and Aktas, 2017).

Reported values for both biochar and activated carbon prices are highly variable. The commercial price of biochar ranges between $0.8 – $18 per kg, while activated carbon prices obtained from literature range from $0.34 – $22 per kg. The resulting average costs as determined by the New Haven researchers for activated carbon and biochar are $5.60 and $5.00 per kg, respectively. However, the International Biochar Initiative reported the average commercial biochar price to be $3.08 per kg in 2014 based on the prices of 54 products. For either estimate, it appears that biochar is a more economical option when compared to activated carbon. Because the market potential of both products depends on their ability to sorb heavy metals, the researchers acknowledge the necessity of comparing cost per kilogram of contaminant removed by each material. It is important to note that the variability in biochar production introduces inconsistencies to these comparisons and thus, more research is required regarding biochar's ability to sorb specific metals and the corresponding cost. Despite the knowledge gap, biochar's significantly lower environmental impact and promising economic position demonstrates that it could be a feasible replacement in the industries where activated carbon currently dominates (Alhashimi and Aktas, 2017).

Animal waste lagoon on a modern dairy farm.

Water Treatment

Biochar may be able to enter into a portion of the industrial water treatment market, where activated carbon is frequently used to adsorb organic compounds, odor compounds, and synthetic organic chemicals (EPA, 2007). The use of Biologically Activated Carbon (BAC) trickling filters is a common practice in wastewater treatment. BAC filters are efficient and allow for potential resource recovery, but can only handle low influent concentrations of organic matter, else they foul quickly. Because of this, their use is most practical in tertiary wastewater treatment, a point in the process where much of the high organic loading has already been removed. To overcome the challenge of high concentrations of organics, carbon materials that experience slower rates of fouling could expand the potential applications of these trickling filters (Huggins et al., 2015).

BAC trickling systems are made up of granular activated carbon packed into columns. As water seeps through the column, contaminants are adsorbed to the surface of the carbon material. Once these adsorption sites have reached capacity, treatment efficiency of these systems depreciates. This is because granular activated carbon materials are comprised mostly of micropores, which are clogged easily by suspended solids in wastewater. Concentration of contaminants traveling through the filter, flowrate, and adsorption capacity of the carbon all affect filter lifespan. As a result, selecting a carbon material with the highest adsorption capacity could save costs, including labor associated with replacing the material. Biochar generated from lignocellulosic biomass, such as switchgrass, shows particular potential as a replacement for activated carbon. This is because pyrolyzed lignocellulosic biomass will retain its interconnected structure containing a distribution of pore sizes, from large pores to nano-pores. As mentioned above, it is also less energy intensive to manufacture than Granular Activated Carbon ("GAC") (Huggins et al., 2015).

To determine if biochar could save costs and effort in the water treatment industry, Tyler Huggins and his team at the University of Colorado Boulder compared the efficacy of biochar to that of activated carbon for contaminant treatment. Polyethylene tubes were either packed with biochar prepared from lodge pole pinewood, or with granular activated carbon manufactured from coal. Tubes were shaken for 24 hours to reach equilibrium concentration before adsorption capacity was measured. The team found that biochar had a higher removal rate for chemical oxygen demand (COD), ammonia (NH4), phosphate (PO4), and total suspended solids (TSS) (Huggins et al., 2015).

This higher treatment efficiency can be attributed to the larger macrospores possessed by biochar. Bacteria range from 0.4 μm to 4 μm in size; granular activated carbon loses all macrospores larger than 1 μm during the activation step in manufacturing, while biochar made from lignocellulosic biomass retains many different pore sizes. This provides biochar with the advantage of using more surface area for adsorption than GAC. Although biochar has a history of land application, its low cost and high treatment efficiency may be able to earn it a place in the wastewater industry (Huggins et al., 2015).

Air Treatment

In the same way the adsorption properties of biochar make it applicable in water treatment, it may be able to effectively sorb harmful compounds from the air as well. In some highly urbanized areas of the world, degraded air quality is a public health concern (Khan et al., 2018). Volatile organic compounds (VOCs) are a source of pollution in both indoor and outdoor air quality, as they can be released from fuel combustion and industrial emissions as well as from household products such as aerosols, paints, and bug repellants (EPA, 2017).

Biochar's sorption capabilities may have global implications in the growing struggle to increase air quality in urban areas. Researchers in South Korea, which has the worst air quality among the 35 richest countries as of 2018, have taken an interest in biochar as an option for air treatment (Lee, 2018 and Khan et al.,2018). A 2018 study conducted by a group at Hanyang University in Seoul set out to find if biochar could effectively remove gaseous benzene from the air. Benzene, a gasoline component known by the CDC to cause leukemia (CDC, 2018), is hazardous even at low concentrations when airborne. The study found that biochar produced from a mixed feedstock made up of woodchips, food waste, and chicken manure and treated with potassium hydroxide had a similar treatment capacity to that of GAC, demonstrating the feasibility of biochar for air quality management (Khan et al., 2018).

Manure Lagoon Covers

Aside from posing a health hazard, some air pollutants also cause an odor nuisance. Livestock manure lagoons, which are a commonly utilized for storing livestock waste until it can be field-applied as fertilizer, emit odor-causing compounds such as ammonia, sulfides, and fatty acids, as well as greenhouse gasses such as methane, carbon dioxide, and nitrous oxide. Leaking waste and ammonia emissions can also cause nutrient pollution within the watershed. Researchers have long been testing the practice of adding biocovers to these lagoons to mitigate gas and nutrient emissions; covers made from straw, corn stover, vegetable oil, and woodchips have been evaluated, but none are currently used on a broad scale (Dougherty et al., 2017).

Though manure lagoon biocovers have not yet been accepted as standard practice, Brian Dougherty and his colleagues at Oregon State University have found that floating biochar covers on waste lagoons can lower odor intensity, reduce ammonia emissions, and adsorb nutrients. The group found that biochar pyrolyzed at 600˚C from a mixture of Douglas fir bark and center wood was able to reduce ammonia concentration in the headspace above the lagoon by 72 – 80%. Ammonia is a contributor to ground-level air pollution and odor, and can also intensify eutrophication of water bodies, so emission reduction could pose a benefit to the public as well as the environment. Though the results of the study were promising, the experiment also underscores the importance of choosing a feedstock and production method for biochar that will fit the desired use – biochar made from gasification

of Douglas fir chips at 650 ˚C did not demonstrate significant ammonia reduction (Dougherty et al., 2017). However, sorption of ammonia to biochar is pH dependent; adjusting the pH of biochar to a range of 6 – 7.5 could potentially make less-promising feedstocks, such as Douglas fir, much more effective at retaining ammonia (Fidel, Laird, and Spokas, 2018).

Because of the multiple feedstock and production options, further research must be done to determine which biochar type will result in the highest net benefit when used as a lagoon cover. Biochar is also more expensive than straw, a more conventional method for lagoon covering, but Dougherty is optimistic. He has a life cycle vision for biochar similar to that of CenUSA's: Biochar could be generated from excess farm residue on-site, and energy from the pyrolysis process could be used to heat buildings or water throughout colder months. The biochar generated could then be used as a lagoon cover, and subsequently be spread on fields, allowing the nutrients sorbed from manure to be repurposed as fertilizer (American Society of Agronomy, 2017).

Veterinary Antibiotics

There has been growing concern in recent years regarding the overuse of antibiotics in agriculture. In the past, farmers were able to supplement animal feed with small, "subtherapeutic" doses of antibiotics as a means of pathogen suppression and growth improvement. Animals go on to excrete these antibiotics, turning manure into a reservoir of antibiotic resistant bacteria. Because manure is often land-applied as fertilizer, these bacteria are dispersed to the environment, thus increasing the risk of antibiotic resistance development in humans (Heuer, Schmitt, & Smalla, 2011). Increased regulation now prevents farmers from administering medically-important antibiotics to animals at subtherapeutic doses in certain regions of the world, including the United States and Europe (USDA, 2017) As a result, there is a need to identify alternative methods of feed supplementation that confer the same disease prevention and growth benefits as antibiotics (Willson et al., 2019).

A group of researchers at Queensland University in Australia evaluated the effect of dietary inclusion of biochar in poultry feed. Doses of 1%, 2%, and 4% biochar were included in layer diets on a weight/weight basis in an effort to determine the optimal inclusion level of biochar as an anti-pathogenic additive for laying hens. The biochar, sourced from Pacific Pyrolysis Pty Ltd in Sydney was pyrolyzed from woody green waste. Cloacal samples were taken from live birds to analyze the microbial communities of control birds as well as those fed 1%, 2%, and 4% biochar. The researchers concluded that the best anti-pathogenic effects on intestinal microbiota occur at inclusion rates up to 2% w/w, after which the benefit either decreased or remained the same (Willson et al., 2019).

The biochar-fed birds were found to have significantly lower levels of campylobacter bacteria in their microbiota; this includes a reduction in campylobacter hepaticas, the cause of spotty liver disease in chickens (Willson et al., 2019). Spotty liver disease is an emerging problem in the poultry industry. Although it's been identified for over 60 years, the disease has become a severe problem in the poultry industry over the last decade (Moore et al., 2018). Outbreaks can reduce egg production by 35% and increase layer mortality by 15%

(Courtice et al., 2018). A second research group at Queensland University saw a reduction in Campylobacter jejuni – a bacterium that causes inflammation of the digestive tract in humans when consumed – in the microbiota of biochar-fed chickens (Prasai et al., 2016). As antibiotic regulation continues to increase, biochar may be a promising alternative for poultry producers who hope to safeguard their flocks from pathogens.

Biochar may even be able to reduce the spread of antibiotic resistance at its source. A study done in collaboration by researchers from China, the United States, and Belgium found that when biochar was applied during the composting of pig manure, the abundance of 8 antibiotic resistance genes was reduced by 26 – 85%. This reduction can likely be attributed to a shift in the bacterial community brought about by the biochar, and demonstrates that this method can be used to reduce the health risks associated with ARGs in livestock manure, effectively making it safer to utilize livestock manure as fertilizer (Qian et al., 2019).

A handful of studies have also examined the effects of biochar supplementation on performance characteristics of poultry. A different group of Queensland, Australia researchers fed chickens a fungal-contaminated diet to decrease their egg production, then assigned them a treatment diet of 1%, 2%, or 4% biochar. They found that egg production significantly improved, particularly on the 2% biochar diet. The group believes that this is a result of the biochar acting as a detoxifier and improving digestion, therefore improving feed conversion ratio (Prasai, 2017). Because it is no longer legal to administer many types of antibiotics at small doses for growth promotion, biochar may be able to serve as a less harmful substitute.

Some poultry farmers are finding that they can take their chicken litter – a mixture of manure, feathers, and bedding – and process it into biochar on site. They can then apply the biochar as fertilizer or sell it at a significantly higher profit than would could be obtained from raw litter (Cox, 2018). Researchers at Brown University found that the poultry manure-derived biochar acts as an effective slow-release fertilizer. The biochar was tested in both silt-loam soils and sandy soils for a 2-year period. At the conclusion of the study the biochar addition had increased soil carbon and nitrogen storage, improved nutrient retention, and positively affected soil fertility overall (Clark et al., 2019). These results are exciting for regions containing watersheds that have become impaired due to field-application of manure. The conversion of manure into biochar could help break the cycle of pollution caused by the manure, while providing farmers with an effective fertilizer if they choose to land-apply their biochar, or alternatively, an extra source of profit if they choose to sell it (Cox, 2018).

Cattle Feed Supplement

Biochar has exciting applications in the poultry industry for disease prevention and management, but researchers have found use for it in the cattle industry as well. There is evidence that feeding biochar to cattle can decrease the amount of methane they release. Methane contributes to 14% of total greenhouse gas emissions worldwide, and agriculture accounts for the majority of this emission; of the methane emitted by agriculture, 62% derives from the digestive processes of ruminant animals such as cows (Toth et al., 2016).

Throughout the last decade, researchers have started investigating the possibility of mitigating methane emissions from cattle with biochar. A 2012 study out of the University of Copenhagen supplemented cattle diets with biochar at a high rate – 9% of feed dry matter – and then tested the cows for methane production. Biochar-fed cows produced 11 – 17% less methane than the control group. A second study done at Souphanouvong University in Laos gave 0.6% biochar feed to young cattle. They found that live weight gain increased by 25% compared to controls – indicating that biochar may also encourage growth promotion in cattle. The methane measured in the cattle's exhaled gasses decreased by 22%. When biochar was added to diets in combination with potassium nitrate, methane reduction increased to 41%. The mechanism behind this property may be that biochar limits the activity of methanogens, which are methane producing bacteria (Toth et al., 2016). Although the North American carbon credit market is still in its nascent stages, this method of greenhouse gas reduction may present an opportunity for livestock farmers to make a profit on the carbon market – especially considering the fact that one ton of methane is equivalent to 21 tons of carbon dioxide (Powers, Schulte, and Stowell, 2009).

Researchers in India found that goats were given feed that was supplemented with activated charcoal, the goats produced milk that was five times lower in aflatoxin compared to goats that were not. Aflatoxins are naturally occurring toxins produced by fungi, and are often generated in grain that is later fed to cows. Aflatoxins cost the U.S. dairy industry an estimated $200 million per year; biochar's ability to serve as a replacement for activated charcoal means that supplementing cattle feed with biochar could reduce both methane emissions and aflatoxin contamination (Finger Lakes Biochar, 2017).

Cat Litter

Biochar has applications in the pet industry as well. One Ohio-based company called OurPets® manufactures cat litter made from biochar and switchgrass. Conventional cat litter is made from clay; it is non-biodegradable, it creates dust, and is heavy. According to OurPets®, a 10 lb bag of the switchgrass blend provides the same amount of litter box material as a 25 lb bag of conventional litter. A 10 lb bag of the OurPets® litter sells for around $13.50, and while the price of conventional cat litter is highly variable depending on the brand, a 25 lb bag of conventional litter from one popular brand, Fresh Step, sells for $13.00 - $14.00 (chewy.com pricing). Not only is OurPets® cost competitive, but market trends have also shown that consumers in the pet market have a growing interest in natural products. Sales growth of regular cat litter increases at a rate of about 2% annually, a rate proportional to the increase in cat ownership. The natural cat litter market, on the other hand, has seen a 15% annual expansion or higher in recent years (Caley, 2016). Biochar is highly absorbent, and does not result in paw marking. When used in combination with switchgrass, the substances absorb odor and act as a filter, whereas clay litter relies on the physical entrapment of odor instead of filtration (Kinzel, 2017 and Caley, 2016). The effectiveness of OurPets® litter and the rapid expansion of the natural litter sector may offer an exciting niche opportunity for biochar in the $2.5 billion cat litter industry (Kinzel, 2017).

Polymers

Researchers in Italy have begun taking an interest in using biochar as an environmentally-friendly filler in epoxy resin. Epoxy resin is a type of polymer used in a variety of applications, including industrial coatings, general purpose adhesives, plastics, paints, and cement binding. A number of materials have been investigated for use as epoxy fillers, but each has its own electrical and mechanical properties, which alter the properties of the polymer overall. One group of researchers analyzed the difference between supplementing epoxy with two different materials: high-tech carbon nanotubes, and biochar. The group found that supplementing with 2% biochar by weight resulted in a remarkable improvement in mechanical properties – such as tensile strength and strain loading capabilities – even more so than the nanotubes. In addition, carbon nanotubes require high energy inputs to create. Conversely, biochar is low-cost, eco-friendly, and renewable (Khan, 2017).

A second study analyzed the effect of maple tree-derived biochar as a filler in epoxy resin. The research group found that at very low weight percent of biochar addition, the materials became stiffer. However, at 2% biochar addition, the resin became less fragile and more ductile, experienced up to a 63% increase in ultimate tensile strength, and had a tensile toughness 11 times higher than the pure resin control. This research is significant because conventional epoxy production produces considerable amounts of CO2. By replacing some of this material with biochar, which requires very little energy input to produce, overall emissions and energy requirements for the industry could be considerably lowered. The epoxy industry amounts to more than $5 billion in North America and $15 billion worldwide. If biochar is used as an epoxy filler, even at a low weight percent, this market could pose a huge commercial opportunity for biochar (Giorcelli, 2018).

RESEARCHERS AT TUSKEGEE UNIVERSITY IN ALABAMA HAVE COMPOUNDED BIOCHAR WITH RECYCLED PET (POLYETHYLENE TEREPHTHALATE) PLASTIC DERIVED FROM DISPOSED WATER BOTTLES TO CREATE BIOCHAR/PET COMPOSITE FILAMENTS FOR 3D PRINTING. THE RESULTING COMPOSITE MATERIAL HAD IMPROVED MECHANICAL, THERMAL, AND DYNAMIC PROPERTIES WHEN COMPARED TO PET ALONE. JUST A 5% WEIGHT ADDITION OF BIOCHAR RESULTED IN A 60% INCREASE IN TENSILE STRENGTH (IDREES ET AL., 2018).

Building Materials

Biochar has extremely low thermal conductivity and an ability to absorb water up to six times its weight. Because of these two properties, biochar is exceptional for use as an insulation material and a humidity regulator. With these facts in mind, The Ithaka Institute for Carbon Strategies, based in Switzerland, devised a way to restore and refurbish wine cellars using a biochar-clay mixture. Maintaining optimal humidity in wine cellars is important, as too much moisture promotes the growth of harmful microbes, while too little moisture leads to particulate pollution and wine evaporation. The group sprayed the biochar mixture on old cellars in a 10 cm thick layer, and found that the machine-sprayed mixture is able to keep cellar humidity at a constant 60 – 80% year-round, which greatly reduces the development of unwanted

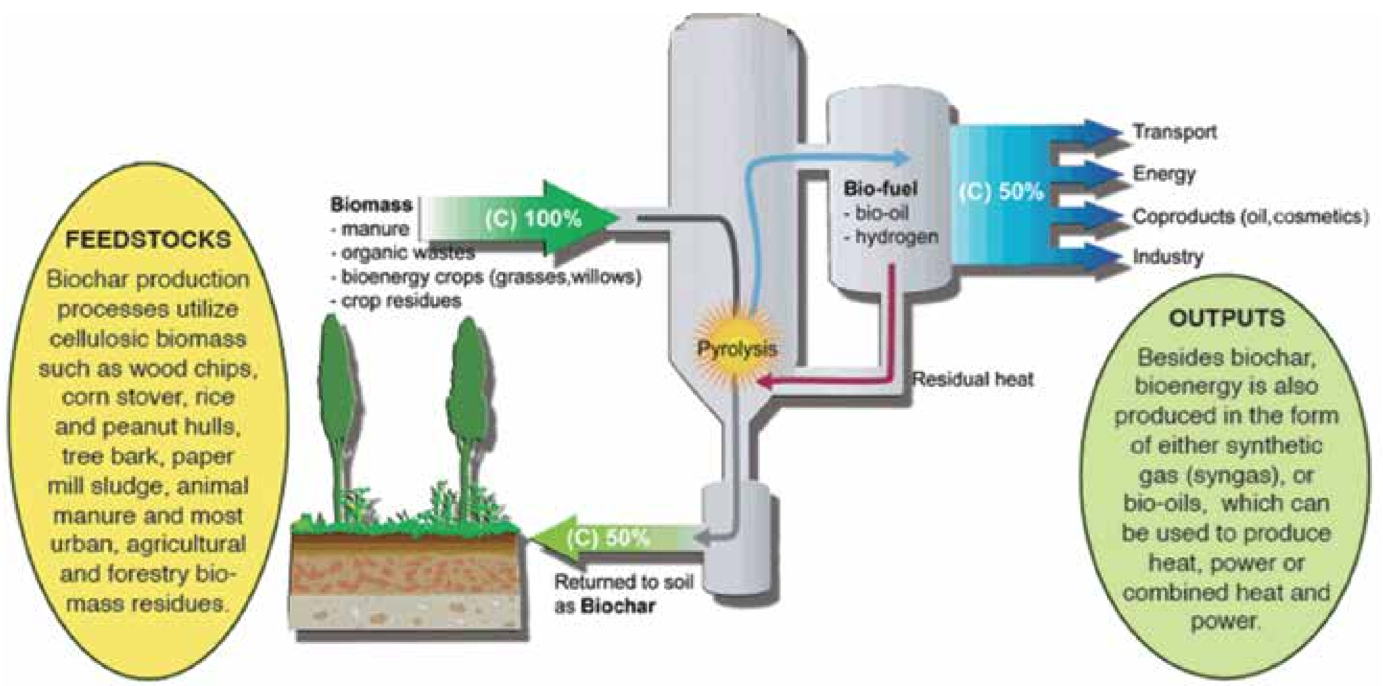


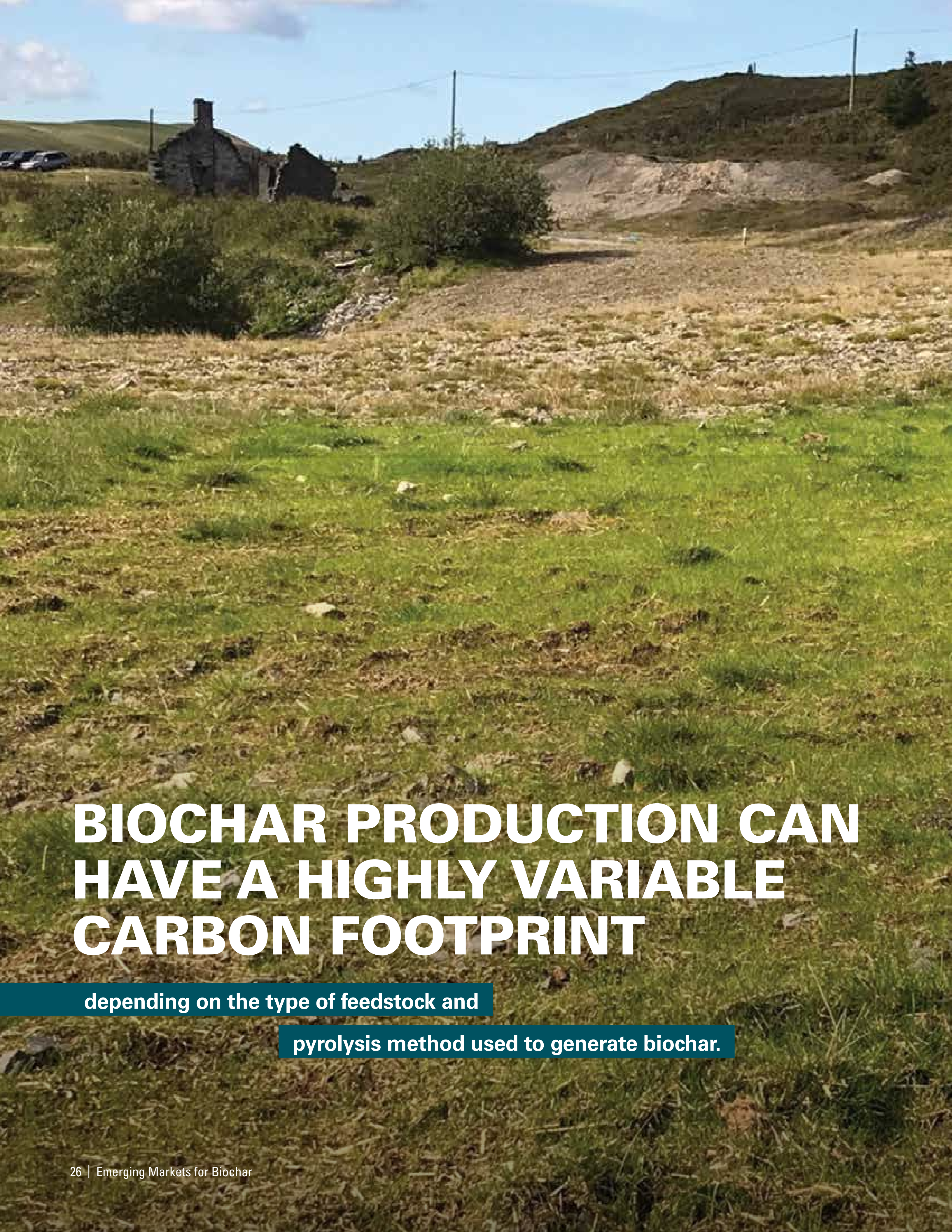
Figure 6: Biochar Production System

Source: International Biochar Initiative (https://biochar-international.org/biochar-technology)

mold and microbes in the cellar. In addition, the high porosity of the biochar allows it to absorb contaminants and toxins while binding the gases produced throughout the wine fermentation process (Schmidt, 2013).

The Ithaka Institute hopes that this process catches on as natural way of optimizing a cellar's climate; they also claim that this technology would be effective for food storage, animal housing, warehouses, or even homes and offices as a substitute for Styrofoam insulation (Schmidt, 2013). Others are even experimenting with the use of biochar in brick making; trials have demonstrated that biochar can be used as an additive for brick and concrete elements at a ratio of up to 80% (Ithaka Institute, 2013). By using biochar-based building materials, houses can become long-term carbon sinks while providing a healthier indoor climate. In addition, if one of these houses were to be demolished later on, the biochar mixtures could be used as a compost supplement instead of becoming hazardous waste (Schmidt, 2013).

BIOCHAR NOW, A COMPANY MANUFACTURING BIOCHAR FROM BEETLE-KILLED PINE TREES IN COLORADO, SELLS BIOCHAR TO OIL AND GAS EXTRACTION COMPANIES. THE BIOCHAR SERVES AS A BONDING MATERIAL FOR TOXIC SUBSTANCES, CAPTURING AND SEQUESTERING HYDROCARBONS AND VOLATILE ORGANIC COMPOUNDS FROM THE CONTAMINATED WELL CUTTINGS. THE COMPANY ALSO SELLS BIOCHAR FOR WATER FILTRATION PURPOSES ON THESE JOB SITES, EFFECTIVELY REMOVING POLLUTANTS FROM PRODUCTION WELL WATER BEFORE IT IS DISCHARGED INTO THE SURROUNDING WATER SUPPLY (BIOCHAR NOW, 2016).



BIOCHAR PRODUCTION CAN HAVE A HIGHLY VARIABLE CARBON FOOTPRINT

depending on the type of feedstock and pyrolysis method used to generate biochar.

Challenges

Biochar shows promise in a wide variety of industries; however, there are questions that need to be asked when analyzing how realistic it is to expect long-term, lucrative markets to be established in each of these fields. At this point in time, it would be nearly impossible to quantify the size of the biochar soil amendment market. This is because there is insufficient research regarding the quantity of biochar that would be required in the home gardening and agricultural industries. If biochar can be purchased and applied to soil at a single time point, and the producer sees benefits in the soil as a result of the biochar for years following the amendment, then there would be little incentive for the producer to repurchase biochar regularly – on the other hand, if benefits only occur for one or two years following application, there may not be enough financial incentive for growers to keep repurchasing biochar.

Very few studies comparing biochar effect on yield come from long-lasting, longitudinal experiments. Results from these studies indicate that yield results tend to continue for several years following application, but at lower rates in compared to the first few years (Bach et al., 2016). Because of this uncertainty, commercial biochar producers may end up relying on markets that require consistent biochar production – such as water treatment, peat moss replacement, or livestock feed supplement – to make a consistent profit for the time being.

Determining realistic benefits that would result from widespread biochar use may also prove to be difficult. Biochar's carbon sequestration abilities have caused many to tout it as a climate change mitigation method; others are not as confident that biochar production could have a meaningful impact on emissions. Some studies have shown that biochar application to land creates a "priming effect", where the rate of organic matter composition increases, thus increasing microbial output and plant matter decomposition rates. There is some thought that this increased decomposition could result in carbon emissions from decaying matter that exceed the amount of carbon biochar is able to sequester, negating the net-negative impact that biochar has on the environment (Cooper, 2016). A study out of the University of Sydney found that biochar may cause positive priming or negative priming depending on soil type and soil temperature (Fang, 2015). Questions remain in regard to a priming effect and further research is required before conclusions can be drawn. Because biochar composition and properties as well as soil composition can vary so heavily, soil microbe response is highly variable as well. This is why, as described above, biochar will accrue more benefits in some soils than others. Additionally, biochar production can have a highly variable carbon footprint depending on the type of feedstock and pyrolysis method used to generate biochar (Porter, 2014). Until more research is done, it will be hard to quantify an emission reduction benefit caused by biochar.

Another significant barrier to global biochar use is the lack of a 'biochar regulatory scheme". As mentioned previously in this paper, the European Union is not yet prepared to regulate the production and application of biochar. At present, the word "biochar" has not been mentioned by name in any European or national legislation. However, voluntary biochar quality standards have been established for Europe, the United Kingdom, and the United States by independent organizations. Furthermore, existing legislation regarding fertilizers, soil improvers, and wood charcoal have allowed biochar producers and users in certain European countries to fit their product within existing national regulations. One obstacle to creating science-based biochar policies in these countries is the lack of study replication; studies regarding the properties and effects of biochar must be reproduced to build a policy framework around them. To get to this point, involvement from biochar producers in the form of funding further research may be required (Meyer et. al, 2017).

BIOCHAR'S CARBON SEQUESTRATION ABILITIES HAVE CAUSED MANY TO TOUT IT AS A CLIMATE CHANGE MITIGATION METHOD; OTHERS ARE NOT AS CONFIDENT THAT BIOCHAR PRODUCTION COULD HAVE A MEANINGFUL IMPACT ON EMISSIONS.

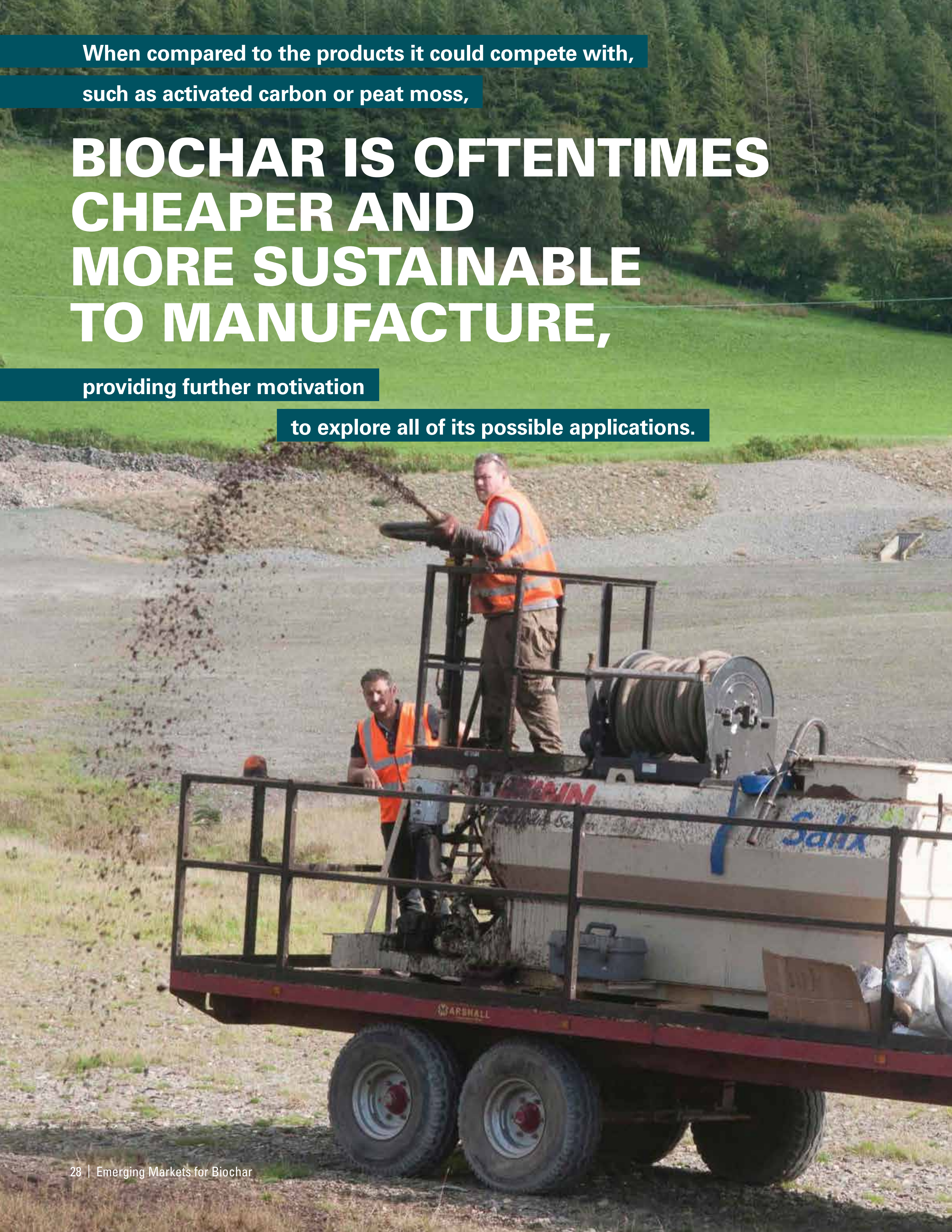
When compared to the products it could compete with,

such as activated carbon or peat moss,

BIOCHAR IS OFTENTIMES CHEAPER AND MORE SUSTAINABLE TO MANUFACTURE,

providing further motivation

to explore all of its possible applications.



BY IMPROVING SOIL FERTILITY AND WATER HOLDING CAPACITY IN AGRICULTURAL SOILS WITH BIOCHAR AMENDMENTS, FOOD PRODUCTION AND WATER USE EFFICIENCY COULD BE IMPROVED ON A GLOBAL SCALE.

Conclusion

Researchers around the world have been studying biochar for decades, but there is still more work to be done if we are to thoroughly understand its properties, limitations, and potential applications. The multitude of feedstocks and production methods means that predicting the way different batches of biochar will perform in different markets will be a difficult task. Some biochar batches may be well suited to absorbing toxins in air and water treatment applications; others may function best as a livestock feed for growth promotion, disease prevention, and methane reduction; still others may perform well in manufacturing polymers or building materials. Determining which types of biochar are best suited to each purpose or product type will require time and extensive research; as time goes on, we may find that biochar is very well suited to some markets and not practical for use in others.

Despite the unknowns, it is in our best interest to explore every avenue for carbon sequestration. If biochar can store carbon in soil for millennia, reduce soil emissions of other greenhouse gasses such as nitrous oxide, reduce methane production in livestock, and at the same time improve soil properties, there are reasons to continue investigating the best ways to produce and utilize it. In addition to humankind's fight against climate change, we face growing problems in food production and water scarcity as well. By improving soil fertility and water holding capacity in agricultural soils with biochar amendments, food production and water use efficiency could be improved on a global scale.

As research demonstrating the benefits and applications of biochar accumulates, biochar's global market size has steadily expanded. According to a survey done by the International Biochar Initiative, as of 2018, more than 100 companies were producing roughly 45,000 tons of biochar annually in the United States alone (Cox, 2018). With an average consumer end retail price of $3.08 per kg, this translates to a 2018 market size of $125 million. As society seeks out new and innovative ways to meet its needs while meeting the needs of the planet, it's likely that this number will only continue to grow. When compared to the products it could compete with, such as activated carbon or peat moss, biochar is oftentimes cheaper and more sustainable to manufacture, providing further motivation to explore all of its possible applications. As our understanding of biochar production and properties becomes more comprehensive, we may begin to see expansion of its use in the soil amendment market as well as in smaller niche markets. Ultimately, the widespread use of biochar could improve agricultural production and provide an affordable, sustainable feedstock for a variety of niche markets while aiding in the reduction of harmful emissions.

References

Alhashimi, Hashim A., and Can B. Aktas. "Life Cycle Environmental and Economic Performance of Biochar Compared with Activated Carbon: A Meta-analysis." *Resour., Conserv. Recycl.* no. 118 (March 2017): 13-26. doi:10.1016/j.resconrec.2016.11.016.

American Society of Agronomy. "Biochar Shows Benefits as Manure Lagoon Cover. *Phys.org - News and Articles on Science and Technology*, August 9, 2017. Accessed March 04, 2019. https://phys.org/news/2017-08-biochar-benefits-manure-lagoon.html.

Bach, Martin, Burkhard Wilske, and Lutz Breuer. "Current Economic Obstacles to Biochar Use in Agriculture and Climate Change Mitigation." *Carbon Manage.* 7, no. 3-4 (July 2016): 183-90. doi:10.1080/17583004.2016.1213608.

Banik, Chumki, Michael Lawrinenko, Santanu Bakshi, and David A. Laird. "Impact of Pyrolysis Temperature and Feedstock on Surface Charge and Functional Group Chemistry of Biochars." *J. Environ. Qual.* 47, no. 3 (April 2018): 452. doi:10.2134/jeq2017.11.0432.

Basso, A. S., F.E. Miguez, D.A. Laird, R. Horton, and Mark Westgate. "Assessing potential of biochar for increasing water-holding capacity of sandy soils." *GCB Bioenergy* 5, no. 2 (March 2013): 132-143. doi:10.1111/gcbb.12026.

Bilgili, Ali Volkan, Salih Aydemir, Osman Altun, Ebru Pınar Sayğan, Hamza Yalçın, and Robert Schindelbeck. "The Effects of Biochars Produced from the Residues of Locally Grown Crops on Soil Quality Variables and Indexes." *Geoderma* 345 (July 2019): 123–133. doi:10.1016/j.geoderma.2019.03.010.

"Biochar Market – Global Demand Analysis and Opportunity Outlook 2027." May 2019. https://www.researchnester.com/reports/biochar-market/1093.

Biochar Now. "Oil and Gas Filtration and Cleanup." Accessed May 21, 2019. http://www.biocharnow.com/index.php/applications/oil-and-gas.

Biochar Now. "Biochar Can Beneficially Change The World" Accessed February 8, 2019. http://biocharnow.com/index.php.

U.S. Biochar Initiative. "Biochar Slows Climate Change." Accessed May 21, 2019. http://biochar-us.org/biochar-slows-climate-change.

Ridge to Reefs. "Bioreactors & Biochar: What's a Woodchip Bioreactor?" 2017. Accessed April 19, 2019. http://www.ridgetoreefs.org/bioreactors--biochar.html.

Bonanomi, Giuliano, Francesca Ippolito, Gaspare Cesarano, Bruno Nanni, Nadia Lombardi, Angelo Rita, Antonio Saracino, and Felice Scala. "Biochar As Plant Growth Promoter: Better Off Alone or Mixed with Organic Amendments?" *Front. Plant Sci.*, 8 (September 2017):1570. doi:10.3389/fpls.2017.01570.

Centers for Disease Control and Prevention. "Emergency Preparedness and Response: Facts About Benzene." April 4, 2018. Accessed March 04, 2019. https://emergency.cdc.gov/agent/benzene/basics/facts.asp.

Clark, Mahalia, Meredith G. Hastings, and Rebecca Ryals. "Soil Carbon and Nitrogen Dynamics in Two Agricultural Soils Amended with Manure-Derived Biochar." *J. Environ. Qual.* 48, no. 3 (May 2019): 727-734. doi:10.2134/jeq2018.10.0384.

Cleary, Julian, Nigel T. Roulet, and Tim R. Moore. "Greenhouse Gas Emissions from Canadian Peat Extraction, 1990–2000: A Life-cycle Analysis." *Ambio*: 34, no. 6 (August 2005): 456. doi:10.1639/0044-7447(2005)034[0456:ggefcp]2.0.co;2. http://www.geog.mcgill.ca/faculty/roulet/Published%20Manuscript%20pdfs/Cleary%20et%20al.%20Ambio%202005.pdf

Cool Planet. "Biochar-Based Soil Health Solutions. Accessed February 8, 2019. https://www.coolplanet.com/.

Cooper, Jennifer, "Carbon Trading 101: What Is It — How Does It Work?" *Native Energy*. February 25, 2018. Accessed June 11, 2019. https://nativeenergy.com/2018/02/how-does-carbon-trading-work/.

Cooperman, Yoni. "Biochar Carbon Sequestration: Sequestering Carbon in the Soil Using Biochar." *Solution Center for Nutrient Management ANR Blogs*. September 30, 2016. https://ucanr.edu/blogs/blogcore/postdetail.cfm?postnum=22224.

Cox, Jeremy, "Biochar could be the hot new thing in addressing Bay's poultry litter." Bay Journal. November 26, 2018. Accessed April 19, 2019. https://www.bayjournal.com/article/biochar_could_be_the_hot_new_thing_in_addressing_bays_poultry_litter.

Courtice, Jodi Maree, Layla Khalid Mahdi, Peter John Groves, and Michael Kotiw. "Spotty Liver Disease: A Review of an Ongoing Challenge in Commercial Free-range Egg Production." *Vet. Microbiol.* no. 227 (December 2018): 112-118. doi: 10.1016/j.vetmic.2018.08.004.

Davenport-Hagen, Lynne, Weisenhorn, Julie, Meyer, Mary H., Xiaoye Su, Luna. University of Minnesota Extension Master Gardener CenUSA Biochar Demonstration Gardens 2012 – 2015. CenUSA Bioenergy. 2017.

Dougherty, Brian, Myles Gray, Mark G. Johnson, and Markus Kleber. "Can Biochar Covers Reduce Emissions from Manure Lagoons While Capturing Nutrients?" *J. Environ. Qual.* 46, no. 3 (2017): 659-666. doi:10.2134/jeq2016.12.0478.

Edwards, Joseph D., Cameron M. Pittelkow, Angela D. Kent, and Wendy H. Yang. "Dynamic Biochar Effects on Soil Nitrous Oxide Emissions and Underlying Microbial Processes during the Maize Growing Season." *Soil Biol. Biochem.* no. 122 (July 2018): 81-90. doi:10.1016/j.soilbio.2018.04.008.

Environmental Protection Agency. "Drinking Water Treatability Database: Granular Activated Carbon, February 05, 2007. Accessed February 26, 2019. https://iaspub.epa.gov/tdb/pages/treatment/treatmentOverview.do?treatmentProcessId=2074826383.

Environmental Protection Agency. "Indoor Air Quality: Volatile Organic Compounds' Impact on Indoor Air Quality,". November 06, 2017. Accessed March 01, 2019. https://www.epa.gov/indoor-air-quality-iaq/volatile-organic-compounds-impact-indoor-air-quality.

Fidel, Rivka B., David A. Laird, and Kurt A. Spokas. "Sorption of Ammonium and Nitrate to Biochars Is Electrostatic and PH-dependent." *Sci. Rep.* 8, Article number: 17627 (December 2018). doi:10.1038/s41598-018-35534-w.

Finger Lakes Biochar. "One big benefit of adding biochar to livestock feed: healthier milk." March 12, 2017. Accessed June 23, 2019. http://fingerlakesbiochar.com/one-big-benefit-of-adding-biochar-to-livestock-feed-healthier-milk/.

Gerlach, Henning and Hans-Peter Schmidt. "Biochar in poultry farming." *Ithaka Journal viticulture ecology climate-farming* 1 (2012): 262–264. http://www.ithaka-journal.net/pflanzenkohle-in-der-geflugelhaltung?lang=en.

Giorcelli, Mauro, Aamer Khan, Nicola M. Pugno, Carlo Rosso, and Alberto Tagliaferro. "Biochar as a Cheap and Environmental Friendly Filler Able to Improve Polymer Mechanical Properties." *Biomass Bioenergy*, 120 (January 2018): 219-223. doi: 10.1016/j.biombioe.2018.11.036.

Hagemann, Nikolas, Kurt Spokas, Hans-Peter Schmidt, Ralf Kägi, Marc Böhler, and Thomas Bucheli. "Activated Carbon, Biochar and Charcoal: Linkages and Synergies across Pyrogenic Carbon's ABCs." Water 10, no. 2 (February 2018): 182. doi:10.3390/w10020182.

Heuer, H., H. Schmitt, and K. Smalla. "Antibiotic resistance gene spread due to manure application on agricultural fields." *Curr. Opin. Microbiol.*, 14, no. 3 (June 2011): 236 –243. https://doi.org/10.1016/j.mib.2011.04.009.

Higgins, Adrian, "Is This Popular Gardening Material Bad for the Planet?" *The Washington Post*, May 11, 2017. Accessed March 29, 2019. https://www.washingtonpost.com/lifestyle/home/should-sustainable-gardeners-use-peat-moss/2017/05/09/1fc746f0-3118-11e7-9534-00e4656c22aa_story.html?noredirect=on&utm_term=.880b5fb4073a.

Huggins, T. M., A. Haeger, J.C. Biffinger, and Z. J. Ren. "Granular biochar compared with activated carbon for wastewater treatment and resource recovery." *Water Research* 94 (May 2016): 225-232. doi: 10.1016/j.watres.2016.02.059.

Idrees, Mohanad, Shaik Jeelani, and Vijaya Rangari. "Three-Dimensional-Printed Sustainable Biochar-Recycled PET Composites." *ACS Sustainable Chemistry & Engineering* 6, no. 11 (September 2018): 13940-13948. doi:10.1021/acssuschemeng.8b02283.

Ithaka Institute for Carbon Intelligence. "Biochar as a Building Material." Accessed May 13, 2019. https://www.ithaka-institut.org/en/ct/97.

Jackson, Ron S. *Wine Science: Principles, Practice, Perception*. Amsterdam: Academic Press, an Imprint of Elsevier. 2014.

Khan, Aamer, Patrizia Savi, Simone Quaranta, Massimo Rovere, Mauro Giorcelli, Alberto Tagliaferro, Carlo Rosso, and Charles Jia. "Low-Cost Carbon Fillers to Improve Mechanical Properties and Conductivity of Epoxy Composites." *Polymers* 9, no. 12 (2017): 642. doi:10.3390/polym9120642.

Khan, Azmatullah, Jan E. Szulejko, Pallabi Samaddar, Ki-Hyun Kim, Botao Liu, Hubdar Ali Maitlo, Xiao Yang, and Yong Sik Ok. The Potential of Biochar as Sorptive Media for Removal of Hazardous Benzene in Air. *Chem. Eng*. J. 361, no. 1 (April 2019): 1576-585. doi: 10.1016/j.cej.2018.10.193.

Kinzel, Anne. "Switchgrass: Newest Product in the $2.5 Billion Cat Litter Market?" *CenUSA Bioenergy Blades Newsletter*, Jan. 2017. Accessed June 10, 2019. http://blades-newsletter.blogspot.com/2017/01/switchgrass-newest-product-in-25.html.

Kleinman, P., K.S. Blunk, R. Bryant, L. Saporito, D. Beegle, and K. Czymmek, et al. 2012. "Managing manure for sustainable livestock production in the Chesapeake Bay watershed" J. *Soil Water Conserv.* 67, no. 2 : 54A–61A. doi:10.2489/jswc.67.2.54A. . http://udel.edu/~inamdar/nps2007/Kleinman.pdf.

Laird, David A. "The Charcoal Vision: A Win–Win–Win Scenario for Simultaneously Producing Bioenergy, Permanently Sequestering Carbon, While Improving Soil and Water Quality." *Agron.* J. 100, no. 1 (January 2008): 178-181. doi:10.2134/agronj2007.0161.

Lawrinenko, Michael, David A. Laird, Robert L. Johnson, and Dapeng Jing. "Accelerated Aging of Biochars: Impact on Anion Exchange Capacity." *Carbon* 103 (July 2016): 217–227. doi:10.1016/j.carbon.2016.02.096.

Korea Country Commercial Guide. "Korea - Air Pollution Control: Korea Air Pollution Control Industry overview, best prospects, trade shows and contacts." September 6, 2018. Accessed March, 04, 2019. https://www.export.gov/article?id=Korea-Air-Pollution-Control.

Levitan, Dave. "Refilling the Carbon Sink: Biochar's Potential and Pitfalls." *Yale School of Forestry and Environmental Studies*, December 9, 2010. Accessed March 07, 2019. https://e360.yale.edu/features/refilling_the_carbon_sink_biochars_potential_and_pitfalls.

Manyuchi, M., C. Mbohwa, and E. Muzenda. "Potential to use municipal waste bio char in wastewater treatment for nutrients recovery." *Physics and Chemistry of the Earth*, Parts A/B/C 107 (October 3018):92-95. doi: 10.1016/j.pce.2018.07.002.

Margenot, Andrew J., Deirdre E. Griffin, Bárbara S.q. Alves, Devin A. Rippner, Chongyang Li, and Sanjai J. Parikh. "Substitution of Peat Moss with Softwood Biochar for Soil-free Marigold Growth." *Ind. Crops Prod*. 112 (February 2018): 160-169. doi: 10.1016/j.indcrop.2017.10.053.

McLaughlin, Hugh. "An Overview of the Current Biochar and Activated Carbon Markets." *Biofuels Digest*. October 11, 2016. Accessed February 22, 2019. https://www.biofuelsdigest.com/bdigest/2016/10/11/an-overview-of-the-current-biochar-and-activated-carbon-markets/.

Meyer Sebastian, Lorenzo Genesio, Ines Vogel, Hans-Peter Schmidt, Gerhard Soja, Edward Someus, Simon Shackley, Frank G. A. Verheijen, and Bruno Glaser. "Biochar standardization and legislation harmonization" J. Environ. Eng. & Landscape Manage. 25 no. 2 (January 2017): 1-17. doi:10.3846/16486897.2016.1254640.

Minnesota Stormwater Manual. "Erosion Prevention Practices – Temporary Seeding and Stabilization." April 4, 2019. Accessed May 09, 2019. https://stormwater.pca.state.mn.us/index.php?title=Erosion_prevention_practices_-_temporary_seeding_and_stabilization.

Montanarella, Luca and Emanuele Lugato. "The Application of Biochar in the EU: Challenges and Opportunities." *Agronomy 3*, no. 2 (May 2013): 462-473. 10.3390/agronomy3020462.

Moore, Robert, Peter Scott, and Hao Van. "Spotty Liver Disease in Laying Hens." *Poultry Hub*, May 7, 2018. Accessed April 12, 2019. http://www.poultryhub.org/spotty-liver-disease-in-laying-hens/.

Nora Caley,. "Cleaning Up with Natural Litter." *Pet Business*. Nov. 27, 2018. Accessed Nov. 21, 2018. http://www.petbusiness.com/October-2016/Cleaning-Up-with-Natural-Litter/.

Novak, Jeffrey M., James A. Ippolito, Thomas F. Ducey, Donald W. Watts, Kurt A. Spokas, Kristin M. Trippe, Gilbert C. Sigua, and Mark G. Johnson. "Remediation of an Acidic Mine Spoil: Miscanthus Biochar and Lime Amendment Affects Metal Availability, Plant Growth, and Soil Enzyme Activity". *Chemosphere* 205 (August 2018): 709-718. doi: 10.1016/j.chemosphere.2018.04.107.

Peltz, Christopher D., Andrew Harley, M. Guo, Z. He, S.M. Uchimiya. "Biochar Application for Abandoned Mine Land Reclamation." In *Agricultural and Environmental Applications of Biochar: Advances and Barriers,* edited by Mingxin Guo, Zhongqi He, and Sophie Minori Uchimiya. SSSA Special Publication No. 63, 2016. doi:10.2136/sssaspecpub63.2014.0047.5.

Porter, Pam and David Laird. Biochar: Prospects of Commercialization. October 31, 2014. Accessed February 8, 2019. https://cenusa.iastate.edu/files/cenusa_2019_018.pdf

Powers, Crystal A., Dennis D. Schulte, and Richard R. Stowell. "Carbon Credits from Livestock Production." *University of Nebraska-Lincoln Extension, Institute of Agricultural and Natural Resources*. 2009. Accessed June 12, 2019. http://extensionpublications.unl.edu/assets/pdf/g1962.pdf.

Prasai, T. P., K. B. Walsh, D. J. Midmore, and S. P. Bhattarai. Effect of Biochar, Zeolite and Bentonite Feed Supplements on Egg Yield and Excreta Attributes. *Anim. Prod. Sci.* 58, no. 9 (April 2017): 1632-1641. doi:10.1071/an16290.

Puro. "Puro – The World's First Marketplace to Buy and Sell CO2 Removals." 2019. Accessed June 11, 2019. https://puro.earth/#section-solution.

Ridge to Reefs. "What is a Woodchip" . Accessed April 19, 2019. http://www.ridgetoreefs.org/bioreactors--biochar.html.

Schmidt, Hans-Peter. "Biochar as Building Material for Optimal Indoor Climate." *Ithaka J. for Ecology, Winegrowing, and Climate Farming*. February 8, 2013. Accessed May 13, 2019. http://www.ithaka-journal.net/pflanzenkohle-als-baustoff-fur-optimales-raumklima?lang=en.

Stewart, Catherine E., Jiyong Zheng, Jorin Botte, M. Francesca Cotrufo. "Co-generated Fast Pyrolysis Biochar Mitigates Greenhouse Gas Emissions and Increases Carbon Sequestration in Temperate Soils." *GCB Bioenergy* 5, no. 2 , 2012: 153-64. doi:10.1111/gcbb.12001.

Sudmeyer, Rob. "Carbon Farming: Applying Biochar to Increase Soil Organic Carbon." *Agriculture and Food*. November 8, 2018. Accessed May 29, 2019. https://www.agric.wa.gov.au/soil-carbon/carbon-farming-applying-biochar-increase-soil-organic-carbon.

TerrAffix Soil Solutions Ltd. "About Us." 2019. Accessed May 09, 2019. Last modified 2019. https://terraffix.co.uk/about-us/.

Toth, John D., Zhengxia Dou, M. Guo, Z. He, and S.M. Uchimiya. "Use and Impact of Biochar and Charcoal in Animal Production Systems." In *Agricultural and Environmental Applications of Biochar: Advances and Barriers*, edited by Mingxin Guo, Zhongqi He, and Sophie Minori Uchimiya. SSSA Special Publication No. 63. 2016. doi:10.2136/sssaspecpub63.2014.0043.5.

University of Illinois at Urbana-Champaign. "Biochar Could Replace Unsustainable Peat Moss in Greenhouse Industry." Phys.org., February 08, 2018. Accessed March 29, 2019. https://phys.org/news/2018-02-biochar-unsustainable-peat-moss-greenhouse.html.

Union of Concerned Scientists. "Carbon Pricing 101." Accessed June 23, 2019. https://www.ucsusa.org/global-warming/reduce-emissions/cap-trade-carbon-tax.

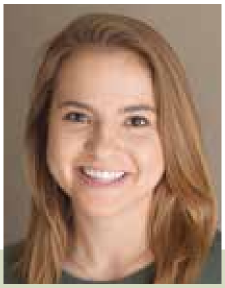
U.S. Food and Drug Administration. "Medicine. FACT SHEET: Veterinary Feed Directive Final Rule and Next Steps." *USDA Center for Veterinary Medicine*. October 13, 2017. Accessed June 12, 2019. Last modified October 13, 2017. https://www.fda.gov/animal-veterinary/development-approval-process/fact-sheet-veterinary-feed-directive-final-rule-and-next-steps.

Voth, Kathy. "Biochar Part III – Can Even the Best Char Salesman Sell Carbon to a Farmer?" On Pasture. October 01, 2013. Accessed March 26, 2019. https://onpasture.com/2013/09/30/biochar-part-iii/.

Willson, Nicky-Lee, Thi T. H. Van, Surya P. Bhattarai, Jodi M. Courtice, Joshua R. Mcintyre, Tanka P. Prasai, Robert J. Moore, and Kerry Walsh, and Dragana Stanley. "Feed Supplementation with Biochar May Reduce Poultry Pathogens, including Campylobacter Hepaticus, the Causative Agent of Spotty Liver Disease." *Plos One* 14, no. 4, (April 2019): . doi:10.1371/journal.pone.0214471. Open Access: https://www.researchgate.net/publication/332201577_Feed_supplementation_with_biochar_may_reduce_poultry_pathogens_including_Campylobacter_hepaticus_the_causative_agent_of_Spotty_Liver_Disease.

Breanna Dykstra

Bre Dykstra is a CenUSA Bioenergy Undergraduate Research Intern and a co-author of this paper. Bre is a Biological Systems Engineering major at Iowa State University. After graduation, she is interested in pursuing a career in product development and food quality.



Alyssa Iverson

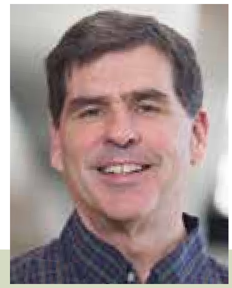
Alyssa Iverson is a CenUSA Bioenergy Undergraduate Research Intern and a co-author of this paper. Alyssa is studying biological systems engineering at Iowa State University and after graduation, she will be pursuing her Masters with a focus in water resources engineering.

Keri Jacobs

Dr. Keri Jacobs served as a faculty advisor for this publication. She is an associate professor of economics and extension economist at ISU. Dr. Jacobs is a Co-PI on the CenUSA project, primarily investigating the market barriers to production of dedicated biomass and exploring the conditions and incentives necessary to achieve commercial-scale production.

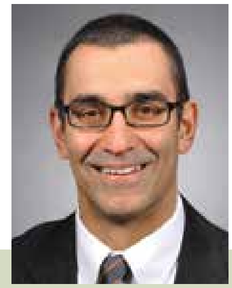
Anne Kinzel

Anne Kinzel supervised the development of this paper as is the CenUSA Bioenergy COO and Assistant Director of the Iowa State University Bioeconomy Institute.



Ken Moore

Ken Moore is the Project Director of CenUSA Bioenergy and a Charles F. Curtiss Distinguished Professor in Agriculture and Life Sciences at Iowa State University.



Raj Raman

D. Raj Raman served as a faculty advisor for this publication. He is a Morrill Professor of Agricultural and Biosystems Engineering (ABE) Department at Iowa State *University. Dr*. Raman is a Co-PI on the CenUSA project, directing the Education Objective.

cenusa bioenergy

This project is supported by Agriculture and Food Research Initiative Competitive Grant N0. 2011-68005-30411 from the National Institute of Food and Agriculture.

We would like to acknowledge the contributions of our Advisory Board (Tom Binder, Albert (Bert) Bennett, Christopher Clark, Denny Harding, Jerry Kaiser, Bryan Mellage, Scott Rempe, LaVon Schiltz, Thomas G. Shannon, David Stock, Jay Van Roekel, John Weis, and Eric Zach) and Dr. William Goldner (USDA-NIFA National Program Leader, Division of Sustainable Bioenergy of the Institute of Bioenergy, Climate and Environment) to the success of CenUSA Bioenergy. **Learn more at** *www.cenusa.iastate.edu*.