The Economics
of
Biochar Carbon Sequestration
in
Massachusetts

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Executive Summary

Biochar is the charcoal residue produced by biomass pyrolysis, or heating of biomass (e.g. wood) with insufficient oxygen for complete combustion. Biochar has long been used to improve productivity of agricultural soils, especially in the humid tropics. Because biochar persists in soil for centuries to millennia, its production represents a way to sequester carbon drawn from the atmosphere by some form of biomass (e.g. trees). We estimate the cost in Massachusetts of using biochar from forest biomass to sequester carbon. This cost represents a possible indicator of the social cost of carbon, i.e. the cost of reversing current carbon emissions.

To estimate net carbon sequestration cost, we first review the agricultural benefits of biochar and estimate their value. While there is much anecdotal evidence that biochar increases crop yields, and some experimental evidence of this from other places, we find few published studies of biochar yield effects in Massachusetts, indicating one research need. For agricultural value estimates, we assume that biochar could increase Massachusetts crop yields by 10%, a figure consistent with other studies.

We next consider the potential quantity of biochar that could be produced in Massachusetts. Based on a previous study of sustainable biomass supply, we estimate the sustainable supply of biochar to be about 270,000 tons per year. We also estimate potential land areas for biochar application including cropland and pasture land, though biochar could also be applied to non-commercial farmland, forestland, and grass turf areas of Massachusetts. At least in in the short run, application potential greatly exceeds sustainable production capacity. The stable carbon portion of biochar production represents about 1% of current Massachusetts greenhouse gas emissions. While biochar is thus not a complete solution for climate change mitigation, we demonstrate how it could be used to greatly expand existing forest carbon sinks.

There is a great variety of methods used to produce biochar. We present six possible production paths, five of which are currently used in Massachusetts. Potential scale varies greatly between the methods, along with associated capital and labor costs. Because the technologies use different pyrolysis methods, the biochar proportions of biomass and biochar qualities also vary.

Finally, we estimate the cost of carbon sequestration for the five technology pathways currently used in Massachusetts. While the technologies differ, final sequestration costs are similar, ranging from \$82 to \$119 per ton of CO_2, with a mean of \$102/ton CO_2 for the four commercial-scale technologies. While greater than some other estimates for the social cost of carbon, our estimate is perhaps more reliable, in that it reflects the actual cost of reversing a small quantity of current greenhouse gas emissions.

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1.0 Introduction: Biochar for Carbon Sequestration

Climate change may be the world's most urgent environmental problem, and given world dependence on fossil fuels, one of its most intractable problems. Renewable energy sources in the form of solar, wind, hydro, geothermal, and biomass energy must ultimately replace fossil-fuel combustion. Energy obtained by combustion of biomass (plant matter produced in the recent past) is perpetually renewable, and is ultimately carbon neutral—carbon dioxide released in combustion is ultimately absorbed by new plant growth. Biochar production is a variation of biomass energy, where plant matter is only partially combusted for energy, leaving biochar as a charcoal residue. The carbon in this biochar is highly resistant to further decay, so that when applied to agricultural soils, a portion of the original biomass carbon is effectively sequestered for decades, centuries, or even millennia. Biochar is thus a potentially carbon-negative energy resource, producing energy while simultaneously sequestering carbon. Given the difficulty of the climate change problem, biochar appears to represent a promising technology.

The International Biochar Initiative (IBI) defines biochar as:

> "a solid material obtained from the thermochemical conversion of biomass in an oxygen-limited environment. Biochar can be used as a product itself or as an ingredient within a blended product, with a range of applications as an agent for soil improvement, improved resource use efficiency, remediation and/or protection against particular environmental pollution, and as an avenue for greenhouse gas (GHG) mitigation" (IBI, 2015).

As the IBI definition suggests, biochar is of interest not only for its carbon sequestration potential, but also for its other attributes, including increasing the productivity of agricultural soils. This use of biochar has a long history, as exemplified by the Terra Preta soils of the South American Amazon region. These biochar-enriched soils are still more productive today than nonenriched soils, centuries after biochar application (Wiedner & Glaser, 2015). Modern approaches to biochar production and application promise similar long-run agricultural benefits. In this report we consider only agricultural uses for biochar, though biochar also has applications in filtration, environmental remediation, etc.

Biochar is produced by pyrolysis, where biomass is heated in the absence of sufficient oxygen for complete combustion, driving a variety of gases and liquids from a biomass feedstock, and leaving solid biochar as a residue (Brown, del Campo, Boateng, Garcia-Perez, & Masek, 2015). Pyrolysis temperature and duration affect the proportion and qualities of the biochar produced, as well as proportions and qualities of the gaseous and liquid coproducts. Coproducts include energy-rich fuels, as well as hydrocarbons with other potentially useful properties. There is a wide variety of biochar and coproduct characteristics, and the term "biochar" actually describes a family of related products rather than a single homogeneous product.

In this study, our main research question is the cost of sequestering carbon in Massachusetts using biochar technology. Several other studies have considered biochar economics (Galinato, Yoder, & Granatstein, 2011; Roberts, Gloy, Joseph, Scott, & Lehmann, 2009; Woolf, Lehmann, & Lee, 2016), but to our knowledge no previous studies focus on Massachusetts or estimate the net cost of carbon sequestration with biochar. Besides being of direct interest for reducing atmospheric carbon levels, this cost of carbon sequestration may have a greater significance in representing a social cost of carbon, i.e. a cost of reversing current carbon emissions. The social cost of carbon has great importance in the economics of climate-change mitigation, indicating which of a broad range of renewable-energy and energy-efficiency technologies are economically optimal to implement. To determine the net cost of biochar carbon sequestration, we first estimate direct costs of biochar production through several different technological pathways, then subtract the agricultural value of biochar and values of any other pyrolysis coproducts.

In addition to evaluating the cost of biochar in Massachusetts, we estimate the possible quantity of carbon that could be sequestered with biochar using Massachusetts forest biomass. Though forests are not the only source of biomass for biochar, they are likely the largest source in Massachusetts, and previous studies have quantified the extent of the Massachusetts forest biomass resource. The carbon sequestration estimate is based on both forest biomass production and likely biochar application rates for land uses including crop land, pasture land, and forest land. Together, these biochar production and use estimates indicate the minimum potential scale of a biochar industry in the Commonwealth (with non-forest biomass sources—not estimated in this report--likely increasing that scale).

We base our findings on a review of the biochar literature, on data from publicly available sources like the USDA Census of Agriculture, and on interviews with current biochar producers and experts. In general, we find evidence to support the feasibility of biochar for both carbon sequestration and soil improvement in Massachusetts (and do not evaluate other potential uses of biochar). The scale of potential biochar carbon sequestration in Massachusetts is modest relative to current carbon emissions—biochar is clearly not a complete solution to the problem of climate change, but could complement other approaches. We also find significant gaps in research on Massachusetts biochar. Published empirical evidence of biochar improving Massachusetts crop yields is sparse and weak. Especially important is more research on biochar soil improvement value for poor soils, where it could be expected to provide the greatest benefits. More research is also needed on the extent to which biochar benefits correlate with specific biochar properties, which as described below, vary with biomass feedstock and pyrolysis technology used in biochar production.

Section 2 describes and presents estimates of biochar value for Massachusetts agriculture, and in section 3 we estimate a maximum scale of agricultural biochar use. In section 4 we assess the supply of woody biomass potentially available for biochar production in Massachusetts. Section 5 presents case studies of five technologies currently used in Massachusetts biochar production, followed by cost estimates for each of these technologies in section 6. Section 7 takes a closer look at long-run carbon dynamics and values associated with biochar, with final observations and conclusions in section 8. Appendices 1-3 provide GIS maps of Massachusetts soil pH, soil water-holding capacity, and Massachusetts land uses suitable for biochar application.

While results of this study are limited to Massachusetts, findings should be relevant in areas with similar forest and agricultural conditions (e.g. the New England region), and the methodology of the report should be replicable anywhere.

2.0 Biochar agricultural use and value

Biochar interactions with agricultural crops are complex, and not completely understood. The porous structure of biochar allows it to adsorb other chemicals and minerals (such as nitrogen), preventing these nutrients from leaching out of soil and making them more available for plant use. Biochar is also a liming agent, making soil less acidic by raising its pH. And biochar can increase beneficial microbial activity in soil. While there is abundant anecdotal evidence for crop growth increases from biochar use, results from rigorous testing are mixed. As described above, biochar produced under different conditions has different properties, which can be expected to have different agricultural effects. Likewise, soil conditions vary greatly, with biochar clearly being more beneficial in some situations than others. And biochar preparation and application practices also affect results.

Biochar has many properties that may affect crop yields. The IBI requires testing and reporting of key biochar characteristics (IBI, 2015), including:

- moisture, an indicator of total biochar content of material purchased (as compared to water content);
- organic carbon, the main component of interest for biochar;
- the ratio of hydrogen to organic carbon, an indicator of carbon stability over time;
- total ash, to distinguish biochar content from ash content;
- total nitrogen, an important crop nutrient;
- pH, an indicator of biochar potential to change soil pH;
- liming (for pH above 7), another indicator of potential to change soil pH;
- electrical conductivity, correlated with a number of important soil properties (Grisso, Alley, Holshouser, & Thomason, 2009) and,
- particle size distribution, associated with biochar application and performance.

For soil application, biochar is often mixed with compost and other soil amendments. Biochar can also be incorporated in animal feed, where it can provide a number of benefits for livestock growth and health, as well as becoming a component of animal-manure fertilizer (Gerlach & Schmidt, 2012; S. Joseph et al., 2015). Though in this report we only consider direct soil application of biochar, including biochar in animal feed is another promising use with applications in Massachusetts. In this section we review properties of biochar relevant to crops, describe situations where biochar is most likely to benefit crops, and present case studies of biochar use on crops in Massachusetts.

2.1 Mechanisms of Biochar Effects on Crops

There are a number of ways in which biochar may have beneficial effects on crop yields.

2.1.1 Nutrient Retention and Addition

The availability of soil nutrients is a key factor in crop productivity. While there is minimal nutrient value in biochar made from woody biomass (the focus of this report), in the soil it can effectively increase nutrient availability. For example, many biochars contain little or no N, yet biochar can still improve N levels in soil (Jeffery, Abalos, Spokas, & Verheijen, 2015). Biochar has a porous structure that expands by several thousand-fold during pyrolysis (Ippolito, Spokas, Novak, Lentz, & Cantrell, 2015). To the extent that N occurs in a soil (or is added), the porous structure of biochar can retain N and prevent the N-leaching that is typical in many soils. This N-retention thus improves N availability to plants, as well as increasing the benefits of future N applications (Jeffery et al., 2015). Biochar's porosity allows for a variety of nutrients to be stored.

Cation Exchange Capacity (CEC) is biochar's "ability to electrostatically sorb or attract cations" and is developed when the feedstock is exposed to water and oxygen, creating an oxygenated surface (Ippolito et al., 2015). Biochar tends to increase soil CEC, which allows a soil to hold more plant nutrients, especially calcium, magnesium, and potassium (Cornell Cooperative Extension, 2007). This increased CEC also reduces the concentration of iron and aluminum, which makes phosphorous more available to plants (Jeffery et al., 2015). This is just one example of the dynamic relationship between biochar and different nutrients and minerals in the soil.

Based on data from approximately 80 articles, biochar's ability to increase nutrient availability is inversely related to pyrolysis temperatures (Ippolito et al., 2015), and slow pyrolysis (accomplished at lower temperatures) is associated with greater nutrient retention than fast pyrolysis for nitrate (NO_3), phosphorus (P), potassium (K), calcium (Ca), and magnesium (Mg) (Ippolito et al., 2015). Increasing pyrolysis temperatures have been observed to cause a decrease in CEC. As a result, high-pyrolysis-temperature biochar may have lower nutrient retention capability, at least in the short run (Ippolito et al., 2015). As biochar breaks down in the soil over time, differences in CEC between biochars produced at different temperatures diminish. This calls for attention to temporal changes in biochar-altered soils that may not be addressed in studies of only a few growing seasons. In addition to differences in CEC based on pyrolysis temperatures, differences in biochar between different biomass feedstocks also partly explain varying nutrient retention among biochars.

While biochar often does not have high nitrogen content, biochar and associated ash do contain other useful minerals. Biochar potassium (K) has shown high availability to plants (Ippolito et al., 2015). Phosphorus (P), can also be available in significant quantities, depending on biomass feedstock (Ippolito et al., 2015). Such nutrients are likely more available in biochars made from feedstocks like dairy manure, but less so from woody biomass feedstock.

The variability of nutrients in biochar implies that different conditions—including feedstock and pyrolysis temperature—may optimize nutrient availability for different crops. For example for corn in South Carolina, optimal P levels would require 145 Mg/ha of softwood biochar but only 20 Mg/ha of turkey litter biochar, which contains seven times more available P (Ippolito et al., 2015). Another major difference was found in average available K concentrations in hazelnut and paper mill waste biochars, which contained 890 and 20,8000 mg K per kg biochar, respectively (Ippolito et al., 2015). In the field, this would result in dramatically different levels of biochar use to achieve the same level of K addition.

However, not all nutrients held by a biochar are necessarily fully available for crops to utilize. Because of biochar's nutrient-holding ability, it is normally applied with a nutrient-adding agent such as manure, compost, etc. When used with a fertilizer, biochar retains fertilizer nutrients for crops to use later (Chan, Van Zwieten, Meszaros, Downie, & Joseph, 2008). One of the lessons learned through research and trials is that uncharged or raw biochar should not be added directly to soils, as it has been shown to adsorb nutrients from the soil, rendering them less available to plants in the short run. This may change as biochar ages and makes more of its held nutrients available to crops (Lehmann et al., 2015b).

2.1.2 Liming Effect

In areas with acidic soil, such as Massachusetts, lime is often used to raise soil pH to a level suitable for crops. Biochar can serve as a liming agent, or as a substitute for incorporating limestone in soils (Berek, Hue, & Ahmad, 2011). For the purpose of this economic analysis, raising soil pH also has a clear market value—replacing the cost of applied limestone. As shown in Table 2-1 Massachusetts crops typically prefer soil pH between 5.0 and 7.0 pH, however there is variation, and cranberries, potatoes, and blueberries are notable exceptions that prefer acidic soils.

The natural pH found in soils across Massachusetts ranges widely from 3.5 to 7.3, with the most acidic soils found in areas of the South Shore, Cape, and Islands, and the most alkaline soils found in far western Massachusetts (see maps in Appendix 1). However, pH varies greatly across short distances within the state. The liming effect of biochar is of course most beneficial on acid soils. On a global scale, 30% of the total land area is considered acidic while up to 50% of arable land is acidic (Jeffery et al., 2015). Staple crops such as corn, prominent in Massachusetts, often require a liming agent to increase production.

A typical assumption is that biochar can be substituted for lime at a 3:1 biochar-to-lime rate in terms of mass (Van Zwieten et al., 2010). However, this ratio is highly variable. Biochar from hardwood feedstock is less substitutable for lime than biochar from feedstocks such as corn straw, which has a higher pH (Chen et al., 2011). The liming effect of biochar, as measured by calcium carbonate equivalency (CCE), increases with pyrolysis temperature (Ippolito et al., 2015), and steam-activated biochar pyrolysis can have a greater pH effect than non-activated biochars (Ippolito et al., 2015). In sandy soil, Collins (2009) found soil pH could be raised by one unit with either 1.35 Mg/ha of lime or 42.5 Mg/ha of biochar, a 31:1 ratio of biochar to lime (much greater than the commonly accepted ratio), though the study noted that biochar also has value in addition to raising pH. It is not known whether there is any difference in the duration of pH changes from biochar and lime (Jeffery et al., 2015).

Table 2-1. Recommended pH Levels for Common Massachusetts Crops

Crop	Acres in MA	Recommended pH	Likely Benefit from Biochar?[10]
Hay (Dry, including Alfalfa)[1,2]	64,257	6.6-7.0	Yes
Corn[1,2]	14,682	5.8-6.2	Yes
Cranberries [1,3]	14,070	4.0-5.0	No
Grass Silage[1,2]	10,430	5.8-6.2	Yes
Sweet Corn[1,2,4]	4,985	6.0-7.0	Yes**
Fruits (Apples, Peaches, Pears)[1]	4,123	Varies	Varies
Potatoes[1,5]	3,898	4.8-5.5	No
Christmas Trees[1,6]	2,770	6.0-6.5	Yes
Pumpkins[1,5]	1,854	5.8-6.8	Yes
Berries (excluding cranberries)[1,7] Blueberries	1,657	6.2-6.8 4.2-4.8	Yes No
Squash (all) [1,5]	1,575	5.8-6.8	Yes
Soybeans [1,2]	751	6.6-7.5	Yes
Tomatoes[1,5]	685	6.0-6.8	Yes
Dry Beans[1,8]	669	6.5-7.0	Yes
Peppers (incl. Bell)[1,5]	579	6.0-6.5	Yes
Tobacco [1,9]	413	5.8-6.2	Yes
Cucumbers and Pickles [1,5]	391	6.0-6.5	Yes
Lettuce (all) [1,5]	300	6.2-6.8	Yes

1. USDA (2014)
2. Cornell Cooperative Extension (2005)
3. UMaine Cooperative Extension (2017)
4. UMass Extension (2012)
5. Cornell Cooperative Extension (2017)
6. Heckman and Vodack (2012)
7. Pritts (2012)
8. Myers (2011)
9. NC State Extension (2017)
10. Assuming that biochar benefits crops requiring a pH range of at least 6.0

Assuming the typical biochar-lime ratio, Table 2-2 shows an example of the liming value of biochar, based on sweet corn production in Massachusetts. Biochar liming value of

$12.00/ton is approximately 21% of the central $57/ton agricultural value of biochar that we estimate in section 3.3 below. Note that application cost of biochar is excluded in this example (assuming that biochar would be applied for other reasons).

While biochar additions have shown greater improvements in crop productivity on acid soils (Jeffery et al., 2015), biochar additions can affect soil salinity (soluble salt changes). In particular, ash-heavy biochars can lead to salinity issues in some soils and for some crops, but not others (Jeffery et al., 2015), which may partly explain differences in crop-yield results with identical biochars. Plant species have unique interactions with biochar applications that may be difficult to identify.

Table 2-2. Example of Biochar Lime-Replacement Value

Lime cost per ton, applied[1]	$36.00
Application rate per acre, Massachusetts sweet corn[1]	0.75
Application cost per acre, Massachusetts sweet corn	$27.00
Biochar-lime ratio[2]	3.0
Biochar application needed to replace lime, tons/acre	2.3
Biochar liming value per ton	$12.00

1. UMass Extension (2013)
2. Van Zwieten et al. (2010)

2.1.3 Water Retention

Another property of biochar that is important for crop production is retaining soil moisture for use by plants, thus promoting crop growth and/or reducing the need for irrigation. Biochar water adsorption is the adhesion of a thin layer of water molecules to the surface of biochar. As with nutrient retention, the porous structure of biochar promotes water adsorption (Kizito et al., 2015). An indicator of plant water stress is content of leaf proline (an amino acid), which has been shown to be reduced in plants grown in biochar-amended soils (Kammann & Graber, 2015).

Some studies have demonstrated that biochar application mitigates water stress for multiple growing seasons after a single application, with increased effects for subsequent applications. But in other cases biochar application rates were not correlated with water-stress amelioration effects (Baronti et al., 2014; de Melo Carvalho et al., 2014). A limitation of many such short-term studies is that soil and water interaction effects may appear over the course of multiple years—biochar adsorption, and its ability to both hold water and to make this water available to plants likely changes over time (S. D. Joseph et al., 2010).

As with other biochar properties, biochar water adsorption is dependent on both the biomass feedstock and the biochar pyrolysis temperature. In the case of apple wood, one study found that biochar is hydrophilic (adsorbs water) at pyrolysis temperatures exceeding 400˚C (Kinney et al., 2012). The same study found magnolia leaf biochar to be highly hydrophobic (had no attraction to water and would not adsorb it).

Appendix 2 shows water-holding ability of Massachusetts soils. Given that biochar helps with water adsorption and retention, the areas that are lightest (least water available for crop growth) are therefore good candidates for biochar application. With 80% of worldwide agriculture relying on rainfall for water, the water-holding capacity of biochar could lead to less vulnerability to droughts (Jeffery et al., 2015), which could increase global food security.

2.1.4 Biological Factors

In addition to its other benefits, the porous structure of biochar is also inviting to microbial activity (Thies, Rillig, & Graber, 2015). Biochar can promote a beneficial, self-sustaining soil biota, which also discourages plant-antagonistic organisms and pathogens (Thies et al., 2015). Soil biological activity, including the quantity, diversity, and activity level of soil microbes, affects soil productivity for crops (Cassman, 1999). One study determined that biochar supported more microbial activity than pumice or activated-charcoal biochar, due in part to a higher water-holding capacity (Pietikäinen, Kiikkilä, & Fritze, 2000).

Given the differences in biochars, including porosity, pH, and nutrient content, the type of microbial development and its ability to thrive likely varies between biochars (Thies & Rillig, 2009). Further research is needed on how biochar differences affect microbial activity, and how microbial activity in turn affects soil properties, crop yields, and carbon sequestration.

2.2 Potential Yield Improvements

Biochar has been found to improve crop yields enhance fertilizer effectiveness with varying degrees of success (Zimmerman & Gao, 2013). In a meta-analysis of biochar application rates, Jeffery et al. (2015) found a general trend toward greater yields as application rates increased, but there was large variation in the methods and results of the studies analyzed. In one study, tomatoes experienced a 20% crop yield increase when biochar was mixed with fertilizer, compared to fertilizer only (Hossain, Strezov, Chan, & Nelson, 2010). In another study with peppers, it was found that biochar application could raise whole-plant yield up to 66.4% against the control plant (Graber et al., 2010). The grand mean crop yield change in a 2011 meta-analysis was found to be positive at 10% (Jeffery, Verheijen, Van Der Velde, & Bastos, 2011), an estimate which we use below to estimate biochar carbon sequestration cost. However Gaskin et al. (2010) also concluded that studies in greenhouses—under ideal conditions—show greater yield increases than those observed in the field. One instance of an explicitly negative response from sewer-solid biochar was found in a meta-analysis, but the original source is unpublished, so the reason for the negative response is unclear (Jeffery et al., 2011). A biochar expert suggests that a problem with biochar metastudies is that the understanding of biochar best practices has changed over time. For example, some early studies used additions of raw biochar (without fertilizers or other inoculants), which are now known to have negative yield effects in the short run (Draper, 2017).

Biochar yield variance among crops may not be related to crop type at all, posit Jeffery et al. (2015), because there is a selection issue with regard to where crops are planted. High-value crops are likely to be planted in better soils, and therefore have little to gain from biochar additions, because soil deficiencies do not exist to begin with. Low-value crops may be planted in poor soils, which would have much more to gain from biochar, though low crop values may not appear to warrant biochar investments. It appears that more research is needed, especially studies that measure yield improvements in poor soils.

Given the variability of biochar's impact, which is affected by biomass feedstock, pyrolysis temperature, and other factors, it has been suggested that biochar may be produced based on the needs where it will be utilized (Novak, Cantrell, Watts, Busscher, & Johnson, 2014). That is, changes in biochar production, application rates, and biochar-fertilizer mixtures could be customized. If the goal is to sequester carbon, wood-based biochar might be the best feedstock. If the biochar is made with the goal of maximizing crop productivity, a feedstock such as corn stover might be better. Soils that lack certain nutrients could get biochars designed to fill those needs. This method of biochar production and utilization may be more likely to provide satisfactory results than treating biochar as a single homogeneous product.

2.3 Massachusetts Agricultural Biochar Studies

In this section we report on Massachusetts biochar field trials for which we were able to find written accounts. In general we do not find strong evidence for biochar benefits, though the number of studies is small.

2.3.1 Emily Cole Dissertation Research, Deerfield, Massachusetts

Research was done in 2015 by Dr. Emily Cole at the University of Massachusetts Amherst for her dissertation on the effects of hardwood biochar in university fields. The study spanned three years of testing sweet corn on soil defined as "prime farmland" (Cole, 2015). The area of study was twenty-five 3x6 meter plots with 1.5 meter buffers between plots, each having five replications. The plots were plowed and disked in preparation for the application of one inch of compost, which was added with a manure spreader. The plots had five application rates of biochar, a control of 0 tons/acre, 18.1, 36.2, 54.2, and 72.3 tons/acre (0%, 2%, 4%, 6%, and 8% on a weight-to-weight basis). Biochar was applied to the research plots by hand and disked into the soil (Cole, 2015). The biochar was created using sugar maple feedstock in a Missouri Kiln, which had a maximum pyrolysis temperature of 400° C. Mean pH of the biochar was 8.1, raising the pH from below 6 to 6.8 at the highest application rate of 72.3 tons/acre. Biochar-amended soils were tested both with and without additions of nitrogen fertilizer.

Cole's study found statistically insignificant increases in yields of sweet corn at the lower biochar application rates in the second year of the trial, with slight and insignificant decreases at higher application levels. In the third year, corn yields were slightly but significantly reduced at all levels of application with no nitrogen application, and slightly but insignificantly reduced with nitrogen. Cole notes that “soils in this study do not have significant fertility issues, thus it is logical that a biochar amendment in these soils would have muted effects on the yield of field crops” (Cole, 2015; p. 77).

Soil biotic activity was also measured in the study with an easy-to-sample common worm population as an indicator of bio-environmental health. Nematode (roundworm) populations were stable with the 18.1 tons/acre and 36.2 tons/acre applications, whereas the population of nematodes decreased in the 72.3 tons/acre plots (Cole, 2015).

The study concluded: “Considering the lack of major growth-retarding deficiencies in the soil, no more than 2% [18.1 tons/acre] biochar application rate would be recommended for application to this field site” (Cole, 2015; p. 79).

2.3.2 Clark and Tang 2015 Study, South Deerfield, Massachusetts

In a 2015 study, Mahalia Clark and Jim Tang evaluated the impact of long-term nitrogen storage in soil amended with wood-based biochar, hypothesizing that biochar-amended soils would have higher levels of carbon and nitrogen. The study took place at the University of Massachusetts Amherst farm in South Deerfield, Massachusetts (same site as the Cole study in section 2.3.1), as well as sites in Delaware and Pennsylvania.

The added biochar had 1.2% N content, which was the equivalent of adding 490 kg N/ha at the 18.1 tons/acre (2%) biochar application rate (Clark & Tang, 2015). Subsequent soil analysis indicated no significant difference in NH_4 levels between biochar-amended and control soils, but a significant increase in NO_3 corresponding to increased biochar application. Organic N was found to be greater in biochar-amended soils at the Delaware and Pennsylvania sites, but not in Massachusetts. The analysis also showed statistically significant increases in C levels at all three sites, consistent with expectations from past research. The authors concluded that biochar does increase long-term nitrogen storage in soils. It was also found that the addition of biochar improves the structure of the soil (Clark & Tang, 2015).

2.3.3 New Harmony Farm Biochar/Basalt Study, West Newbury, Massachusetts

New Harmony Farm is conducting a long-term study using a combination of basalt powder and biochar to measure yields of beets and radishes on a “highly fertile” site (Goreau et al., 2014). The biochar used in the study was produced primarily from oak and pine biomass by New England Biochar in Eastham, Massachusetts, and underwent pyrolysis at approximately 450 degrees Celsius. Biochar was applied by raking in a mix with a 50:50 ratio of compost and biochar. Plots were given 0, 20, or 40 pounds of the biochar-compost mix, as well as 0, 10, 20, or 30 pounds of basalt dust. Two control plots were maintained with no input amendments. In the first crop with biochar amendments and no basalt, yield decreases were found for beets, with little change in yield for radishes. Basalt applications resulted in greater yields. These are preliminary results in an ongoing study (Goreau et al., 2014).

2.3.4 IIT Feasibility study on biochar system for Orange, Massachusetts

In the spring semester of 2011, the Town of Orange in Massachusetts contracted a research group from the Illinois Institute of Technology (IIT) to conduct an economic feasibility study on the purchase, installation, and use of a biochar pyrolysis system for managing waste in the town. IIT's conclusion was that solid organic waste management with biochar would be profitable if run as a side project of an existing private business, where labor to maintain the system would already exist. The alternative of a new system run by the town itself was not found to be cost effective, and a private solution was recommended. It was also proposed that the town could subsidize and sell biochar production technology to local farmers (Adejinle et al., 2011).

3.0 Scale of Potential Massachusetts Biochar Agricultural Use

In this section we consider the upper limits of biochar use in Massachusetts agriculture. Together with estimates of potential biochar production in section 4 below, this information provides an indication about the potential quantity of carbon sequestration that could be accomplished by biochar production and use in the Commonwealth. We also estimate a possible value for biochar used in Massachusetts agriculture, for use in the estimates of carbon sequestration cost in section 6.

3.1 Candidate Biochar Application Locations

For this study we assume that the main land-use type for biochar application is cropland, where typical farm equipment and soil management practices such as manuring and plowing allow easy incorporation of biochar into farm soils. A secondary application land-use type is pastures, which like croplands are accessible to farm equipment, where biochar can be applied at the surface by broadcasting. There are also examples of biochar application in forest (H. Wang, Lin, Hou, Richardson, & Gan, 2010). However, to our knowledge forest biochar application must be performed manually, and can only be placed on the surface of forest soils. Biochar can also be applied to grass turf as found on golf courses and other recreational areas, though we do not quantify the extent of such lands in this report.

Table 3-1 shows the acres of each land-use type on Massachusetts farms, based on the USDA Census of Agriculture. Appendix 3 provides a Massachusetts land-use map, indicative of potential biochar application areas. Note that the total state acreage of each land-use type shown in Appendix 3 is greater than shown in Table 3-1, since the Census of Agriculture only includes land uses for entities defined as active farms.

Table 3-1. Massachusetts Farmland Acres for Biochar Application

Farmland Use Type (2012)	Acres	Percent of total farmland acres	Percent of farms with each land type	Possible tons of biochar application at 18 tons/acre
Cropland	160,789	30.7%	67.7%	2,640,942
Permanent pasture & rangeland	62,234	11.9%	44.9%	1,120,212
Woodland	209,111	39.9%	54.2%	
Farmsteads, buildings, livestock facilities, roads, wasteland, etc.	91,383	17.5%	73.5%	
Total Acres & Tons of Biochar	**523,517**	**100%**	**-**	**3,761,154**

Source: Table 8, USDA Agricultural Census 2012

3.2 Potential Biochar Application Rates

Application rates in biochar studies have ranged from 0.5 ton/acre to 73 tons/acre (1 to 150 Mg/ha) (Jeffery et al., 2015). The goals that drive biochar use influence the appropriate application rate. For example, Cole's western Massachusetts study found that for increasing crop production on existing prime agricultural land, no more than 18.1 tons/acre should be applied (Cole, 2015). This is greater than a figure of 7.3 tons/acre (15 Mg/ha) suggested by Jeffery et al. (2015) for optimizing crop productivity. However, in a study of maximum carbon sequestration, Woolf et al (2010) assumed a global application rate of 24 tons/acre (50 Mg/ha).

As shown in Table 3-1, if Massachusetts applies biochar at a rate of 18 tons per acre, the state can eventually apply approximately 3.8 million tons of biochar to cropland and pastures. This greatly exceeds the estimate of 312,000 tons maximum biochar production in Massachusetts shown in section 4 below—about 12 years of maximum production would be needed for 3.8 million tons of application. And even greater application quantities are possible, for example if greater than 18 tons per acre are applied, if forestland is included, if farmland not included in the USDA Census of Agriculture is used (land not currently farmed commercially), and if grass turf areas are included. At plausible application rates, Massachusetts land areas can absorb some decades of maximum Massachusetts biochar production.

3.3 Biochar Application Value

In this section we estimate an agricultural value of biochar for the economic analysis in section 6, assuming an application rate of 18 tons/acre While biochar's precise value in agriculture is impossible to know, an approximation can be based on the total value of Massachusetts agriculture and yield increases found in other studies. As noted above, we assume a yield increase of 10% based on a meta-study of biochar yield results (Jeffery et al., 2011). A 10% yield increase is also comfortably within the range of results reported in Jeffrey et al. (2015) for a biochar application rate of 18 tons/acre, i.e. with this level of application, yield improvement has generally been greater than 10%.

Jeffrey et al. (2015) also review a study by Woolf (2010), and observe that a global application rate of 24 tons/acre “would generate mean yield increases of 18 percent, if random biochars were indiscriminately applied globally.” We take a similar approach in this study. But note that based on yield improvements, agricultural value will be much greater for crops that have high values per acre than for low-value crops. Also, if biochar has the potential to improve crop yields on poor soils, it has the potential to increase the underlying value of agricultural land (which is based in part on agricultural productivity).

To approximate the effect on Massachusetts agricultural value, we start with a USDA Census of Agriculture estimate of $117 million market value for Massachusetts crops that might make use of field-applied biochar (USDA, 2014), as shown in Table 3-2. Crop value excludes short-rotation woody crops, other crops and hay, livestock value, maple syrup production, aquaculture, greenhouse and nursery crops, and other agricultural sales that we would not expect to be affected by biochar application on farm soils. We also subtract the value and acreage of cranberries (substantial in Massachusetts), which as described above, are not necessarily good candidates for biochar application because of their pH requirements. But anecdotally, there is evidence of biochar benefits even for crops that prefer low pH (Wells, 2017).

Table 3-2 shows values of yield increases at 5%, 10%, and 15% levels, all within the range of previous studies. Because biochar benefits are expected to last many years, and because farmers must wait to receive these benefits, we discount yield increases in future years. Finally, we sum the present value of yield increases for 25 years, then divide by the quantity of biochar applied to obtain these increases, resulting in a biochar value estimate of $56.76 per ton for the 10% yield increase.

Note that while biochar applications in excess of 18 tons/acre are generally not harmful to crops, unless such applications result in significantly greater yields, the value per ton of biochar applied falls with additional biochar application. And as shown in section 6, reducing the agricultural value of biochar results in greater net carbon sequestration cost. Applications of greater than 18 ton/acre may thus result in greater carbon sequestration, but at greater cost per ton sequestered.

In addition to agricultural use, biochar has a number of applications including filtration, environmental remediation, disposal of sewage sludge, reducing volume of organic waste in landfills, etc. Some of these applications may have greater value than the agriculture use considered here. Where this is the case, carbon sequestration cost would be less than estimated in this analysis.

Table 3-2. Possible Value of Biochar in Massachusetts Agriculture

2012 Census of Agriculture, value of relevant MA field crops[1]		$117,270,000	
Discount rate for future year increases		6%	
Present value of yield increases (excluding cranberries)			
Year	5% Yield Increase	10% Yield Increase	15% Yield Increase
1	$5,531,604	$11,063,208	$16,594,811
2	$5,218,494	$10,436,988	$15,655,482
3	$4,923,108	$9,846,215	$14,769,323
4	$4,644,441	$9,288,882	$13,933,324
5	$4,381,548	$8,763,097	$13,144,645
6	$4,133,536	$8,267,072	$12,400,608
7	$3,899,562	$7,799,125	$11,698,687
8	$3,678,832	$7,357,665	$11,036,497
9	$3,470,597	$6,941,193	$10,411,790
10	$3,274,148	$6,548,296	$9,822,443
11	$3,088,819	$6,177,637	$9,266,456
12	$2,913,980	$5,827,960	$8,741,940
13	$2,749,038	$5,498,075	$8,247,113
14	$2,593,432	$5,186,863	$7,780,295
15	$2,446,634	$4,893,267	$7,339,901
16	$2,308,145	$4,616,290	$6,924,435
17	$2,177,495	$4,354,991	$6,532,486
18	$2,054,241	$4,108,482	$6,162,722
19	$1,937,963	$3,875,926	$5,813,889
20	$1,828,267	$3,656,534	$5,484,801
21	$1,724,780	$3,449,560	$5,174,341
22	$1,627,151	$3,254,302	$4,881,453
23	$1,535,048	$3,070,096	$4,605,145
24	$1,448,159	$2,896,317	$4,344,476
25	$1,366,187	$2,732,375	$4,098,562
Total present value of 25 harvests:	$74,955,209	$149,910,418	$224,865,627
Total acres for application[2]	146,719	146,719	146,719
Tons biochar applied (at 18 tons/ac)	2,640,942	2,640,942	2,640,942
Average agricultural value per ton	$28.38	$56.76	$85.15

1. Relevant field crops groups include grains, vegetables, fruits and berries (less cranberries), and tobacco, and exclude greenhouse and nursery crops, short-rotation woody crops, other crops and hay.
2. Acres include all cropland except cranberry land, and omit pasture and hay land.

4.0 Massachusetts Woody Biomass Supply for Biochar

In addition to the question of how much biochar could be utilized in Massachusetts, the question of how much biochar could be supplied is also relevant. In this section we provide estimates of maximum biochar production, assuming that all sustainably-harvested forest biomass (not including saw log production) could be used for biochar production. While 100% utilization of forest biomass for biochar is of course unlikely, it is useful to have an upper bound on forest production possibilities. Forestland accounts for 62% of total Massachusetts land area (Kelty, D'Amato, & Barten, 2008), and is thus a major source of net primary production and resulting biomass. In addition to forest biomass, Massachusetts has biomass from landscaping operations, agricultural waste, animal and human wastes, etc. All of these could potentially be converted to biochar, but to our knowledge, there is no comprehensive inventory of biomass sources in Massachusetts, and we thus restrict our analysis to forest biomass.

4.1 Maximum Forest Harvest

Kelty et al. (2008) prepared a report for the Massachusetts Sustainable Forest Bioenergy Initiative in which they described how much forest biomass could be sustainably harvested for biomass energy. Since our objective is the same, with the exception of exploring biomass use for both biochar and energy, we rely heavily on the Kelty (2008) report. A minimum requirement for sustainable forest harvest is that annual forest harvest not exceed annual forest growth. Kelty (2008) estimated Massachusetts sustainable forest harvest quantities using net forest growth as a starting point, but applying additional screens to reflect the likelihood of actual forest harvest for biomass.

The Kelty (2008) study used data from the U.S. Forest Service’s Forest Inventory and Analysis (FIA) to estimate areas of public forestland, and from Kittredge (2008) to estimate private forestland area. Land areas were divided into the five most common forest types, three site-quality types, and two ownership classes (public and private), for a total of 30 combinations of land types. To determine forest growth rates, Landscape Management Software (LMS) from the U.S. Forest Services was used to estimate 50-year growth rates for each 30 land-type combinations. The study then removed areas that were deemed unlikely to be harvested (as described below). Finally, remaining (likely harvested) acres were multiplied by estimated growth rates per acre to arrive at central estimates of Massachusetts forest biomass production.

In 2015 public ownership (by local, state, and federal governments) accounted for 36% of Massachusetts forestland (less than in some other parts of the country), with 64% of the forestland in Massachusetts owned by private owners (USDA Forest Service, 2015). Most of the private ownership—54% of all forestland—is owned by non-industrial private owners (Alerich, 2000). Many of these non-industrial private forestland owners do not have timber or biomass harvest as their primary interest, but rather aim for nature conservation, recreation, privacy, and maintaining scenic areas on their lands. And some private owners harvest only enough timber or forest to meet the cost of property maintenance, or to be eligible for the property tax reduction program for forest lands

(Kelty et al., 2008). Based on surveys of Massachusetts woodland owners by Kittredge (2008), the Kelty (2008) report excluded 30% of the private land, the proportion of landowners estimated to be unwilling to harvest timber. Since small acreages are unlikely to ever be harvested (and larger areas more likely), the study included only parcels of greater than 10 acres, and reported separately on land area including only parcels larger than 100 acres.

The Kelty (2008) study removed an additional 7% of land due to operational constraints, including steep slopes, wetlands etc. Also removed were forest reserves on 50,203 acres of public land, which were judged unlikely to be harvested. The remaining harvestable forest acres were then multiplied by growth rates to find potential wood production. Of this total, 36% of wood was estimated to be suitable for timber use, and this wood was removed from consideration for biomass energy. The result is an estimate of 890,843 dry tons of sustainably harvested biomass per year, as shown in Table 4-1.

Table 4-1. Maximum Massachusetts forest biomass harvest

	Private Land	Public Land	Total Land[1]
Timberland total acres	2,404,942	554,200	2,959,142
Acres in private ownerships > 10 acres	1,647,685	554,200	2,201,885
Acres less private non-harvesters	1,153,380	554,200	1,707,580
Acres less operational constraints	1,072,643	515,406	1,588,049
Acres less forest reserves (partial)	1,072,643	465,203	1,537,846
Biomass growth rates, dry tons/acre/year	0.89	0.94	
Timberland wood production, tons	954,652	437,291	1,391,943
Tons less timber production = potential tons for biomass energy	610,977	279,866	890,844

Source: Kelty et al. (2008)

1. Since private and total timberland is not given in Kelty (2008), we use FIA 2005 data for total acres, and calculate private acres by subtracting public acres.

As noted above, maintaining harvest levels less than growth rates is only a minimum condition for sustainability—there are potentially many other sustainability criteria. The Kelty (2008) also considered soil nutrient retention, potential soil damage from harvesting operations, possible negative effects on stream water quality, wildlife habitat, and forest fire risks. Recommendations for best management practices were made to address these sustainability issues. In addition, the report noted that removal of full biomass production likely requires some clearcutting, a forest management practice that has not been favored in Massachusetts, and which has the potential to exacerbate some sustainability problems, including soil erosion.

4.2 Maximum Biochar Production and Carbon Sequestration

To estimate an upper bound on biochar production we assume that all harvested biomass could be converted to biochar. As described above, sustainable harvest from public and private forestland is 890,844 dry tons per year of biomass. Given the assumptions shown in Table 4-2, this results in an estimated total of 267,253 metric tons of biochar that could be produced annually in Massachusetts, if all sustainably harvest forest biomass were converted to both energy and biochar.

Table 4-2. Maximum Massachusetts biochar production from forest biomass

Tons less timber production = potential tons for biomass energy (from Table 4-1)	890,844
Biochar yield, proportion of biomass dry weight[1]	30%
Biochar production, tons	267,253
Carbon content of biochar[2]	79%
Recalcitrant portion biochar carbon[3]	97%
Long-run carbon sequestration, U.S. tons C	204,615
Long-run carbon sequestration, metric tons CO_2[4]	682,049
Million metric tons (MMT) CO_2	0.68
MA 2014 emissions, MMT CO_2	74.60
Biochar long-run carbon sequestration, percent of 2014 emissions	0.91%

1. Greatest biochar yield reported in case studies (section 5)
2. Mean of 271 biochar samples from woody biomass (UCD Soil Chemistry, 2017)
3. Wang et al. (2016)
4. Converting U.S. tons C to metric tonnes CO_2

With 2014 total Massachusetts greenhouse gas emissions of 74.6 MMT CO_2e (Massachusetts Executive Office of Energy and Environmental Affairs, 2014), maximum biochar sequestration is only 0.91% of 2014 Massachusetts greenhouse gas emissions. For perspective, we recalculate this figure with none of the constraints used in the Kelty (2008) report, i.e. assuming that all annual forest growth might be converted to biochar. Long-term sequestration increases by a factor of about 3, to just 2.73% of 2014 emissions, even in the very unlikely scenario of using all forest growth to produce biochar. Biochar may also provide additional greenhouse gas reduction benefits, for example reduction of N_2O emissions from agricultural soil (Kammann, Ratering, Eckhard, & Müller, 2012), but such reductions vary and are not included in this analysis.

Given its carbon sequestration potential, biochar is clearly not a complete solution to the problem of climate change in Massachusetts, or a substitute for reducing CO_2 emissions from fossil fuel combustion and other sources. Other studies at a global scale have found that biochar might sequester a much greater proportion of anthropogenic carbon emissions, albeit with less precise information about potential for production of biomass for biochar on a global scale (Cowie et al., 2015).

As we show in section 7 below, the combination biochar carbon sequestration and the co-production of carbon-neutral energy with biochar pyrolysis means that biochar and its energy byproducts are carbon preferable to either existing fossil fuel combustion or to biomass combustion without biochar pyrolysis.

5.0 Biochar Pathways: Methods of Pyrolysis

This section of the report discusses pyrolysis methods and different techniques available for producing biochar. Case studies on different biochar producing plants and their costs are also presented.

5.1 Overview of Pyrolysis Methods and Technology

Biochar is produced from biomass by pyrolysis, a general term for a process which does not provide enough oxygen for complete combustion. Possible technologies include gasification, slow pyrolysis, fast pyrolysis, hydro-thermal carbonization and microwave pyrolysis. In general, pyrolysis decomposes biochar into some combination of hydrocarbons in the form of volatile liquids (bio-oil, pyroligneous acid, tar, etc.); a syngas which may be composed of hydrogen (H_2), methane (CH_4), carbon monoxide (CO); and carbon-rich biochar (Bridgewater, 2004; Laird, Brown, Amonette, & Lehmann, 2009). Many pyrolysis liquids and gases can be used as sources of energy. But biomass-pyrolysis products vary greatly, depending on factors including biomass feedstock, available oxygen, pyrolysis temperature, and biomass residence time during the pyrolysis process.

Biologically, biomass consists of hemicellulose, cellulose, lignin and some other minor organics (Bridgwater, Meier, & Radlein, 1999). Each of these materials degrades at different temperature and pressures. While biomass pyrolysis methods and products vary greatly, they are often classified as fast or slow pyrolysis, as determined by pyrolysis temperature, feedstock residence time, and the rate at which the feedstock is heated. Slow pyrolysis typically takes place at temperatures up to 475 degrees C (though temperatures can be higher), while fast pyrolysis occurs at temperatures upwards of 800 degrees C. Slow pyrolysis has feedstock residence times from ten minutes to over an hour, while fast-pyrolysis methods use smaller feedstock particles and residence times of ten minutes or less. In general, slow pyrolysis creates more biochar than fast pyrolysis, along with syngas, pyroligneous acid (or wood vinegar), and some tars. Fast pyrolysis generally produces syn-gas, bio-oil, and a smaller proportion of biochar than slow pyrolysis. Slow or fast pyrolysis methods may be chosen based on the desired mix and characteristics of end products.

Differences in biochar yield from slow and fast pyrolysis correlate with net energy differences. Since biochar is composed primarily of combustible carbon, it represents potential energy. Producing more biochar means extracting less energy from biomass. Fast pyrolysis thus favors energy production from biomass, and less carbon sequestration in the form of biochar. Bio-oil is a primary liquid product of fast pyrolysis, which can be used as a substitute for fossil oil (with further refining), although bio-oil has less energy content per unit volume than fossil oil.

One product of slow pyrolysis is wood vinegar (or pyroligneous acid), a liquid composed of acetic acid, methanol (wood alcohol), acetone, tars, water, and many minor components (FAO, 1987). Though some components of wood vinegar are combustible, raw wood vinegar is not combustible, and therefore not a potential fuel. In principle, wood vinegar can be refined into its principle components (acetic acid, methanol, and acetone) all of which have commercial values. Indeed before fossil petroleum was widely available, wood vinegar was a source of many useful chemicals (FAO, 1987). However, the market for wood vinegar is not yet well defined in Massachusetts. Unprocessed wood vinegar from some tree species has been employed as a traditional medicine, a sterilizing agent, a fertilizer, and foliar spray, among other uses (Loo, Jain, & Darah, 2007), but the current market and market value for wood vinegar are unclear.

In addition to biochar quantity, biochar quality also varies with slow and fast pyrolysis conditions, and especially with pyrolysis temperature. The higher temperatures of fast pyrolysis favor a more crystalline carbon structure, which approaches graphite at sufficient pyrolysis temperatures. This high-temperature biochar is extremely stable in the soil (recalcitrant) persisting for centuries to millennia. On the other hand, the graphite-like biochars of fast pyrolysis lack the cation exchange capacity (CEC) and volatile organic compounds (VOCs) of biochars produced at lower temperatures, characteristics that likely promote plant growth.

The portion of biomass which becomes biochar varies with the pyrolysis method, and in section 6 we identify estimated biochar proportion for each of the case-study biochar producers. For carbon sequestration, the carbon proportion of biochar and recalcitrant portion of carbon are also important factors. Here we use estimates of biochar having 79% carbon content (mean of 271 biochar samples from woody biomass; UCD Soil Chemistry, 2017), 97% of which is recalcitrant (J. Wang et al., 2016), resulting in an estimate of 77% of biochar weight as recalcitrant carbon.

5.2 Case Studies: Representative Biochar Production Methods in Massachusetts

In this section we profile five methods of biochar production. We include these cases because they represent a range of technologies, a range of required labor and capital, and a range of biochar products and coproducts. Since the first four methods are currently practiced Massachusetts, their feasibility is established, at least under certain economic conditions. The final case described here (but not included in the economic analysis) is based on a 2002 University of New Hampshire study of a commercial-scale bio-oil plant, for which there are currently no operating examples in the New England region.

5.2.1 Homeowner Scale: The CharCone 24, manufactured by Spitjack, Easthampton, Massachusetts

Biochar is distinguished from charcoal primarily by its intended use rather than its composition (Lehmann & Joseph, 2015a). Since charcoal has been produced for millennia and is still a major cooking fuel in the world (IEA, 2012), traditional charcoal production offers clues about methods to produce biochar. But many traditional production technologies—for example simple pits and brick kilns—are inefficient (low yield of char per unit of biomass) and/or create excessive air pollution (by modern standards). A number of improved but still simple methods have been proposed and tested around the world.

Many such improved designs incorporate the globally ubiquitous 55-gallon metal drum, including the well-known Top-Lit Up Draft (TLUD) design (IBI, 2017). Compared to pits and kilns, drum-based designs offer more control of feedstock and air flows, resulting in greater char yields and potentially reducing pollution. Yet the simple design and low material cost also makes such technology widely accessible. Such designs use batch processing, where biochar can be discharged from the drum only after completion of pyrolysis, when the equipment has cooled.

A similar but more sophisticated production approach is represented by cone designs, which must be purpose built (rather than using a recycled drum). A Massachusetts example is the CharCone 24, a small cone kiln primarily designed for homeowners to produce biochar for soil improvement and carbon sequestration, but also useable for cooking and grilling. The basic design of the CharCone 24 goes back over a thousand years to Japan. The modern version was modified and popularized by Kelpie Wilson and refined by the Ithaka Institute, with the CharCone design now being produced by Spitjack (spitjack.com) of Easthampton, Massachusetts. The CharCone was designed primarily to handle homeowner woody yard waste as a feedstock, but it can use any type of dry biomass for making biochar.

The volume of the CharCone 24 is 22.3 gallons, with a 34” top diameter, 13” bottom diameter, and 15” depth. The ideal feedstock is less than 1” in diameter and less than 10” in length (requiring some cutting of typical brush). The CharCone is filled with feedstock and then lit. Once the initial feedstock is partially combusted, more feedstock is added on top. One batch consumes approximately 10 cubic feet or 100 pounds of woody feedstock (depending on feedstock density). The burning process takes 1.5 – 2.5 hours, depending on the size of the feedstock. When the CharCone is filled with charred material, it is quenched using 3-5 gallons of water or a hose. Water drains from the bottom of the cone.

Peter Huntington, a graduate student at UMass Amherst, tested the CharCone and collected the data used for the economic analysis below. Huntington’s tests resulted in a 22% yield of biochar (on a dry weight basis). Processing each batch required approximately 3.5 hours, including initial set up, wood processing, burning, final quenching and biochar retrieval. Of this time, approximately 1 hour was required for active work, with 2.5 hours used for occasional feeding and monitoring. These tested times are used in the economic comparison below, but times likely vary with the specific methods used by different operators, and with their experience.

Compared to burning brush on a rural property, the CharCone design greatly reduces smoke and produces biochar, a useful soil amendment which sequesters carbon for long periods of time. Similarly, producing biochar is carbon preferable to chipping brush, which results in biomass that quickly biodegrades and releases its carbon to the atmosphere (though CharCone combustion may result in more emissions of other air pollutants than chipping). Compared to other methods described below, the CharCone technology captures heat only for uses such as grilling, and does not capture other potential coproducts of pyrolysis (e.g. pyroligneous acid, bio-oil). It can be seen as an improvement to current homeowner brush management practices that is practical on a small but potentially broad scale. If widely adopted, CharCone use could result in a significant quantity of biochar production in the Commonwealth.

5.2.2 Farm-Scale Biochar Retort: New England Biochar, Eastham, Massachusetts

While a solution like CharCone may be appropriate for individual homeowners, the production scale is limited by the small size of the pyrolysis receptacle, and from an economic standpoint, this solution is only feasible with low-cost or no-cost labor. A Massachusetts example of the next larger production scale is New England Biochar in Eastham, Massachusetts, which "specializes in building biochar production systems on a small to community scale" (New England Biochar, 2017). The company produces and sells biochar, biochar fertilizer mixes, and wood vinegar at wholesale and retail levels. In addition, New England Biochar is a manufacturer of slow-pyrolysis retorts for biochar production and provides consulting services on biochar production and utilization.
New England Biochar's mission is "to make the best possible biochar; to harvest all the available energy from the process to offset fossil fuels; to make the process safe and smoke free; and, to make the process profitable on a farm or community scale" (New England Biochar, 2017). Compared to the other commercial-scale technologies profiled here, the New England Biochar technology is the most mature, with a number of working examples installed.

A typical retort produced by New England Biochar retort can batch process approximately 3 cubic yards of biomass (27 times more volume than a CharCone) into 1 cubic yard of biochar. In such a batch system, biomass is loaded and processed, allowed to cool, and then biochar is removed. One batch in a New England Biochar retort requires approximately 8 hours to load and run, and an additional 8 hours to cool before unloading. To optimize use of labor, two retorts can be employed, with one batch processed each day in each retort, and each batch cooling overnight.

After initial ignition, combustible pyrolysis gases are burned in the combustion chamber to maintain pyrolysis at an optimal temperature of approximately 450° C. Unlike the CharCone and more basic biochar drums and kilns, the New England Biochar retort is sealed except for an exit for pyrolysis gases. Combustion exhaust gases are recirculated through the combustion chamber to ensure complete combustion of gases and to minimize emission of pollutants. Biochar yield is approximately 30% on a dry-weight basis. Each batch also produces 40-50 gallons of wood vinegar and a small amount of tarry residue. New England Biochar retorts have successfully processed many different types of biomass. At the Eastham site, the primary feedstock is small roundwood (e.g. 2"- 4" diameter) obtained from local landscaping, tree pruning, tree removal, etc.

There are several possible extensions and modifications for the basic batch retort manufactured by New England Biochar. The company now produces a continuous-feed retort in addition to the batch system, increasing biomass processing capacity and allowing labor to be used more efficiently (labor likely being the largest cost in such an operation). The retorts also produce excess heat which can be removed for heating homes, greenhouses, etc. Total heat production is approximately 1.5 MMBtu of hot water per retort load (assuming feedstock at 20% moisture content). However, making consistent use of this heat requires coordinating biomass processing with heating demand (e.g. making biochar during winter). Recently, New England biochar has successfully run an electricity-producing Stirling-cycle engine from one of its retorts. Unlike heat as a byproduct, electricity can be utilized by feeding it into the electricity grid whenever it is produced.

Compared to obtaining biochar from a modified biomass boiler, biomass gasification system, or bio-oil plant (cases described in this section below), producing biochar is the primary objective in the New England Biochar system—biochar is not a byproduct, as in some of the other cases described. This allows greater control of production conditions, especially temperature, for obtaining biochar with characteristics suitable for its intended use. As discussed in section 3 above, preferred agricultural biochars are produced at lower pyrolysis temperatures than used in some biochar production methods.

Optimizing biochar for agricultural use is consistent with New England Biochar's business model, where much of its income is derived from the sale of biochar mixed with compost, worm castings, etc. Such product mixes provide consumers and farmers with a ready-to-use, organic soil amendment. The target market is home-scale and small commercial growers who value biochar for both its positive effect on garden yields and for its contribution to mitigating climate change.

5.2.3 Producing Biochar in Commercial Biomass Boilers

One potentially attractive method to obtain biochar is deriving it from biomass combustion equipment, that is, taking advantage of incomplete combustion of biomass in existing or new biomass boilers. This approach does not require dedicated facilities for producing biochar. However, the supply of existing suitable boilers is fixed, and not every existing boiler produces residue that constitutes quality biochar for agricultural use. In this section we describe some potential advantages and limitations of using existing or new biomass boilers as a source of biochar. For this topic we have not identified any published literature, and so rely solely on information from industry experts.

NextChar of Amherst, Massachusetts is a regional supplier of biochar for agricultural and environmental remediation, selling in increments ranging from 0.5 cubic feet to truckload quantities of 80 cubic yards. The NextChar team is well known in biochar circles for its extensive knowledge of biochar properties. The company strategy is to supply only high-quality biochars with the characteristics of “high porosity, little or no ash, no contaminants, little or no volatile-organic compounds and a neutral pH" (NextChar, 2017).

One strategy NextChar has used to source biochar is contracting with existing biomass electricity generation plants. For example, in New Hampshire there are six biomass electricity plants of less than 23 MW in size (Biomass Magazine, 2017), most of which were constructed in the 1980s. NextChar has contracted with one such plant for delivery of approximately 700 tons of biochar per year.

While using existing biomass plants to produce biochar has attractions, in practice there are a number of challenges. Different phases of a boiler combustion process can result in charcoal (incompletely burned biomass), for example, carbon can be contained in fly ash from boilers not equipped for fly-ash reinjection. Sourcing biochar from an existing plant first requires finding a plant with a significant portion of charcoal in its combustion residuals. The biochar must then be tested to determine its characteristics, and to determine for which purposes it is suitable. Biochar characteristics vary with the combustion temperature in a specific boiler, where in a boiler the residual is produced, and the biomass feedstock. Boiler residues must also be tested for potential contaminants.

A potential problem with obtaining biochar from commercial biomass boilers is excessive ash content. Every biomass boiler produces ash, though the proportions of ash to biochar vary. IBI standards require that ash content be declared for all biochar products. For the product known as high-carbon biomass ash, additional standards apply, for example the requirement that producers declare that only clean cellulosic biomass was used to produce the high-carbon ash.

Ash is not necessarily a problem as an agricultural soil amendment. Indeed it can provide useful minerals and raise pH to desired levels, a common requirement for Massachusetts soils (see section 3 above). NextChar markets a high-carbon ash product known as BlaK, which stands for biomass, lime and potassium (K). The product is approximately equal proportions of biochar and ash (a liming agent) by weight, and includes about 3% potassium and 1% phosphorous (McLaughlin, 2017). But by volume, BlaK is about 90% biochar (given the lower density of biochar than the other components). This product is intended for applications where all of the components are desirable soil additions. In this case existing high-carbon boiler ash, with suitable testing and quality assurances, can provide a useful and relatively low-cost agricultural soil amendment.

Though NextChar has not modified existing biomass boilers to increase the proportion of biochar, this is possible at least in principle, and at least for some boilers. Like New Hampshire, the west coast states of California, Oregon, and Washington have a number of legacy biomass boilers (Biomass Magazine, 2017). Biochar Supreme in Everson, Washington, is a retail and wholesale supplier of biochar for agriculture and environmental remediation, which has "blended science and creativity to produce optimal outcomes" (Biochar Supreme, 2017). The company has successfully modified existing boilers for up to 4% biochar yield by dry weight (Anderson, 2017).

However, boiler modification can include a number of complications. When a boiler's controls and/or design are altered to avoid biochar combustion (increasing residual carbon), the boiler must still operate properly, and original boiler air emissions standards must still be met. Increasing the biochar proportion can greatly increase the ash-char volume, potentially requiring new ash-char handling equipment or procedures. And unlike ash, biochar is combustible, and thus must be quenched to prevent combustion upon removal from a boiler. Finally, since each boiler-modification combination is unique, ensuring a high-quality biochar product requires a process of extensive testing and boiler adjustment. All of this adds cost to what may initially appear to be a simple proposition. Though costs vary by boiler, Biochar Supreme CEO Renel Anderson suggests that 10% of boiler capital cost is a reasonable first approximation for modification capital costs (Anderson, 2017). For the economic analysis in section 6, we present a hypothetical boiler modification scenario that is consistent with Biochar Supreme's experience.

In principle, it would possible to design commercial biomass boilers at the scale of existing boilers, but with the specific goal of co-producing biochar and heat. A purpose-built boiler could provide a higher proportion of biochar while still meeting emission requirements, minimizing labor costs, etc., and without being custom designed for each application. This direction may represent a less expensive way to sequester carbon with biochar, and could be widely adopted, given that commercial boilers are widely used (Garcia-Perez, 2017).

5.2.4 Combined Heat and Biochar Processor: NextChar, Amherst, Massachusetts

Boiler modification does not appear to be a scalable strategy for a growing biochar industry (McLaughlin, 2017). Even when modified for a biochar yield of up to 4% (Anderson, 2017), substantially more biomass is required for a given biochar output than when biochar is obtained from equipment designed specifically for this purpose, where the biochar proportion can reach 30% by dry weight. And as noted above, the number of existing biomass plants is small, with not every plant being suitable for modification to increase biochar production.

Given these issues, NextChar has developed its own patent-pending biochar processor, which provides combined heat and biochar (CHAB). A NextChar processor handles about 15 tons of biomass dry matter per day, or 25 tons at 40% moisture content (McLaughlin, 2017). The processor is currently at a pilot stage. NextChar expects that to optimize labor costs, a typical facility will use 4 processors, consuming about 20,000 tons dry biomass per year, and yielding about 5,000 tons of biochar annually (25% biochar yield on a dry-weight basis). In addition to biochar, such a facility would produce about 15 MMBtu of heat per hour of operation, with a number of possible thermal applications.

Equipment for a NextChar 4-processor facility would cost approximately $2.5 million, with perhaps another $1 million for site costs, buildings, etc., or a total $3.5 million investment. A staff of 10 is expected to be able to provide 24x7 operation. We estimate the biochar production cost of such a plant in section 6 below. As with New England biochar's retort, the NextChar processor is purpose-designed for biochar production, providing more control of biochar characteristics than when biochar is obtained as a byproduct of another process. And this approach is fully scalable, i.e. biomass feedstock availability and market demand are the only limits on the number of processors that could be deployed. Having a replicable, proprietary retort design also facilitates obtaining the high-quality biochar upon which NextChar has built its reputation.

5.2.5 Commercial Biomass Gasification for Electricity, Heat, and Biochar: Roberts Energy Renewables, Ashfield, Massachusetts

At the writing of this report, Roberts Energy Renewables is planning a $7.8 million installation of a 2 MW (electric) plant at the site of their lumber and forest products business in Ashfield, Massachusetts. Sawmills typically require large amounts of 3-phase (industrial) electricity for electric motors. This has not been available at the Roberts' site, which to date has relied on diesel generators to produce its own electricity. But electricity produced from diesel fuel is expensive, and not sustainable. The planned Biogen G1300 biomass gasifier will utilize sawmill waste and low-grade forest wood to simultaneously produce electricity for sawmill operation, excess electricity to sell back to the grid, heat for drying wood and other on-site thermal applications, and a residual biochar product for agricultural use. Obtaining energy from forest biomass is carbon neutral in the long run (as we discuss in section 7 below), and the biochar component of the project will provide net carbon sequestration.

The Biogen gasifier represents the most complex technology used in the four Massachusetts-based case studies. Biogen is based in the Dominican Republic, but manufactures biomass gasifiers for delivery around the world. At the Roberts location, waste wood will be the primary biomass feedstock. Wood chips are heated to 900° C in the absence of air, producing a synthesis gas composed primarily of the combustible gases CH_4, CO, and H_2. The gasifier also produces biochar, amounting to about 10% of wood input by dry weight, as well as a small amount of wood vinegar. The synthesis gas from the gasifier feeds three Caterpillar internal combustion engines, each of which powers a 667 kW electric generator, for electricity use on site and/or to be fed into the electric grid. Excess heat is collected from both the gasifier and internal combustion engines. In the Roberts operation, this waste heat will be used primarily for wood drying, but in other applications heat could also be used in any application with a steady demand for thermal energy. Applications such as greenhouse heating and district heating are also possible, but would result in not utilizing the waste heat for part of the year (i.e. in summer).

The Biogen system has overall efficiency rating of 83%, meaning this portion of the potential energy in the biomass feedstock is converted to useable electricity, heat, or potential energy in biochar. The Biogen technology thus represents a very efficient way to utilize the limited biomass resource available in Massachusetts. Because of this high efficiency, the Roberts facility will qualify to sell Renewable Energy Certificates (RECs), contributing to Massachusetts' renewable energy portfolio and providing an additional income stream for the owners.

The Roberts system is expected to consume about 21,000 U.S. tons (at 40%-45% moisture content) of low-grade wood per year, providing a needed regional market for low-grade wood. The availability of such markets encourages active forest management and forest thinning, increasing both forest growth rates and timber quality. A crew of 8 will keep the facility running around the clock, with at least 2 operators on site at all times, providing a small boost to local employment.

The nominal 2 MW Biogen system is projected to generate 16,128 MWh per year of electricity, for a 92% capacity factor, as well as 10 MMBtu of useable heat while in operation, and an estimated 1260 tons of biochar annually. Compared to some other biochar production methods described here, the Biogen technology provides a greater variety of useful products from the biomass resource, although this comes at the cost of lower biochar yields than the other technologies.

5.2.6 Commercial Bio-Oil Plant: DynaMotive Energy Systems

As a final example potentially relevant to Massachusetts, a 2002 study by the University of New Hampshire (Farag, LaClaire, & Barrett, 2002) evaluated the potential for a for a bio-oil plant in northern New Hampshire, using technology from DynaMotive Energy Systems of Canada. The plant evaluated would have used a fast pyrolysis technology to produce bio-oil as a primary product, with a biochar byproduct. Bio-oil, as the name suggests, is a liquid fuel. With additional refining, it can be used as a substitute for fuel oil, diesel fuel, etc. However, the energy content of bio-oil is substantially less than fossil oil, suggesting a lower market value per barrel than for fossil oil. The DynaMotive technology reviewed had an estimated bio-oil yield of 72% and char yield of 23% on a dry-weight basis, along with production of some noncondensable syngas.

The smallest plant evaluated, with a 100 Mg per year biomass input (at 45% moisture content), had an estimated capital cost of $6.6 million in 2002, perhaps similar to the Biogen plant reviewed above (depending on price changes since 2002). The DynaMotive technology is complex, and estimated operating costs were greater than for other technologies reviewed here.

We exclude the DynaMotive option from the economic analysis presented in the next section, in part because there are no operating DynaMotive examples in New England, but more importantly, because there is currently no obvious market for bio-oil. The New Hampshire study estimated a bio-oil production cost of $1.27 per gallon (2002 dollars), but given the low bio-oil energy content, the price per unit of energy was substantially more than for diesel fuel or fuel oil. Bio-oil production would require some kind of subsidy to be financially viable. The Biogen technology planned by Roberts Energy

Renewables is eligible to sell RECs for the electricity produced, partially reimbursing the owners for the social benefit of producing renewable energy, but there is currently no comparable reimbursement mechanism for the production of bio-oil. While technically feasible, bio-oil production appears unlikely in the current economic and regulatory environment.

6.0 Economics of Biochar for Carbon Sequestration

Producing biochar from forest biomass and utilizing biochar as an agricultural soil amendment have the potential for many economic impacts, including direct impacts in the forestry and agriculture sectors, indirect impacts on related industries like those supplying biochar equipment, and environmental impacts like carbon sequestration. In the current study we consider only the narrow policy question of the cost of sequestering atmospheric carbon using biochar.

6.1 Biochar Sequestration Cost, Estimation Method and Assumptions

We assume that mitigating climate change will require a combination of carbon emissions reductions and increases in carbon sequestration. Given this, the economic cost-effectiveness question is how net carbon emissions can reach sustainable levels at the minimum cost. Here we consider the cost of one option, increasing carbon sequestration using biochar. To estimate this carbon sequestration cost, we first calculate the cost of biochar production (capital and operating costs), and then subtract the values of biochar agricultural benefits and the values of biochar coproducts. The result is a net cost of biochar carbon sequestration (excluding any subsidies, e.g. from REC sales). Formally:

$$Biochar\ sequestration\ cost = \frac{(K\alpha + C)}{\Delta CO_2} - B_a - B_c \tag{1}$$

where:

K is the capital cost for a biochar system;
C is operating cost for a biochar system, including labor, biomass feedstock, etc;
ΔCO_2 is the change in atmospheric CO_2, which equals the amount of CO_2 sequestered;
B_a is the biochar benefit in agricultural use;
B_c is the benefit of biochar coproducts: pyroligneous acid, thermal energy, electricity, etc;
and α is a capital recovery factor:

$$\alpha = \frac{r(1+r)^T}{(1+r)^T - 1}$$

where:

r is an annual discount rate; and
T is the number of years the capital investment is expected to last.

Here we consider biochar to be carbon negative to the extent that biochar contains recalcitrant (or stable) carbon, and consider carbon emissions from pyrolysis to be carbon neutral, since in the long run these emissions will be reabsorbed by growing forests (assuming sustainable forest management). However, in section 7 we consider the time dynamics of biomass and biochar carbon in more detail.

The benefit of mitigating climate change is an external benefit for anyone who sequesters carbon (the benefits accrue mostly to others), so some policy intervention will likely be needed to incentivize carbon sequestration. For example based on equation 1, if a subsidy equal to the net biochar sequestration cost (plus normal overhead and profit) were made available, we would expect that market forces would then operate to sequester carbon with biochar—biochar producers could cover the cost of making biochar and make a normal profit after selling the biochar and its coproducts. Similarly, buyers would purchase biochar and its coproducts because prices would equal value to purchasers, for example in increasing agricultural production. And if the agricultural and coproduct values should equal biochar production cost (greater values than estimated here), no subsidy would be needed—sequestration would happen as result of normal market activity.

As noted in section 1, the net biochar sequestration cost is also a possible measure of the social cost of carbon, i.e. how much it costs to reverse carbon emissions that have already occurred. Society would not necessarily want to spend more to prevent carbon emissions than it would cost to sequester the same emissions. However, in the case of Massachusetts biochar this interpretation must be applied with caution, since as shown in section 5, the total quantity of emissions that can be sequestered with biochar in Massachusetts is very small in relation to current carbon emissions.

6.2 Biochar Sequestration Costs for Representative Technologies: Results and Discussion

Table 6-1 below shows biochar sequestration cost (based on equation 1) for the five representative technologies reviewed in section 5.2. Required capital investments, operating parameters, and any coproducts of each technology are as described in section 5.2 above. Since wood vinegar currently has no well-defined market in Massachusetts, we assign it a value of zero, though this understates its future potential (see discussion in section 5.1). Agricultural values are as estimated in section 2. Combined biochar distribution and application costs are based on a study of biomass wood ash application to agricultural land in Georgia (Warren, 2014).

As stressed throughout this report, biochar is not a homogeneous product, with different biochars having different characteristics and uses. Yet lack of data precludes making biochar-specific estimates for agricultural value and for persistence in agricultural soils. In Table 6-1 we thus use the same estimates for these values, though we recognize that in practice, values likely vary.

Table 6-1. Cost Carbon Sequestration with Biochar: Massachusetts Case Studies

	Char-cone	New England Biochar retort	Modified biomass electric plant	NextChar CHAB processor	Biogen G1300 gasifier
Plant size (input Mg/day, 40% MC)	0.06	9	367	101	63
hours per day	3.5	24	24	24	24
days per year	75	330	330	330	336
Biomass Mg/year @ 40% MC	4.1	2,831	121,208	33,333	21,000
Biomass Mg/year, dry weight	2.5	1,699	66,664	20,000	12,600
Plant capital cost	$549	$558,000	$3,152,908	$3,500,000	$7,800,000
plant life, years	20	20	20	20	20
average return on capital	10%	10%	10%	10%	10%
Annualized capital cost	$64	$65,542	$370,339	$411,109	$916,185
Biomass fuel costs					
biomass input @ 40% MC	4.1	2,831	7,362	33,333	21,000
biomass price/Mg, 40% MC	-	$(28)	$25	$25	$25
Total biomass fuel cost per year	-	$(79,279)	$184,055	$833,333	$525,000
Plant annual operating costs					
labor cost	-	$150,000	-	482,380	$482,380
maintenance, % of capital cost	0.0%	5.0%	5.0%	5.0%	5.5%
annual maintenance cost	-	$27,900	$157,645	$175,000	$430,000
utilities, supplies, and other costs	$80	$31,100	-	-	-
Total plant operating cost	$80	$209,000	$157,645	$657,380	$912,380
Total annual cost	$144	$195,263	$712,040	$1,901,822	$2,353,565
Electricity production, MWh	-	-	not included	-	16,128
Electricity value, $/MWh	-	-	not included	-	$85
Total electricity value per year	-	-	-	-	$1,370,880
Heat production per hour, MMBtu	-	1.50	-	18.00	10.00
Heat utilization rate		50%		50%	75%
Net utilized heat, MMBtu/hour		0.75		9.00	7.50
Heat value, $/MMBtu	-	$9.01	-	$9.01	$9.01
Total heat value per year	-	53,668	-	642,082	544,797
Net annual cost	$144	$141,595	$712,040	$1,259,740	$437,888
Biochar yield, percent dry weight	22%	30%	3%	25%	10%
Annual biochar production, tons	0.54	510	2,133	5,000	1,260
Biochar production cost per ton	$268	$278	$334	$252	$348
Biochar distribution cost per ton	-	$14	$14	$14	$14
Biochar ag value per ton	$57	$57	$57	$57	$57
Net cost biochar per ton	$211	$235	$291	$209	$304
Biochar carbon content	79%	79%	79%	79%	79%
Recalcitrant carbon portion	97%	97%	97%	97%	97%
Carbon sequestered per Mg biochar	77%	77%	77%	77%	77%
Cost of sequestration per Mg C	$303	$337	$418	$300	$437
Cost of sequestration/Mg CO_2	$83	$92	$114	$82	$119

Based on Table 6-1, costs of sequestration appear to be similar for the biochar technologies considered, though this cost similarity masks significant differences in production approaches, suitable applications for each technology, and characteristics of the biochar produced. Following are important notes and caveats about the cost estimates for each technology.

6.2.1 CharCone

This technology is aimed at homeowners rather than at a commercial production market. While in section 5.21 we describe labor requirements based on a test of the CharCone, for the cost analysis we assume a labor cost of zero, i.e. that a homeowner would operate a CharCone without expecting compensation. Similarly, we assume that a homeowner would only make biochar with biomass available for free, perhaps from a homeowner's own property or from neighbors. Based on the results in Table 6-1, assigning any cost to labor or biomass feedstock would clearly make CharCone biochar more expensive than other technologies. Given Massachusetts wages, a commercial venture (producing biochar for sale) would optimally invest in some larger-scale, less labor-intensive technology, as described in the other case studies. However, CharCone level technology may be economically feasible in lower-income countries where wages are less than in Massachusetts. Based on the testing by Peter Huntington, a single operator could successfully operate multiple CharCones, perhaps three or four simultaneously, thus utilizing labor more efficiently.

6.2.2 New England Biochar Retort

Unlike the CharCone, the New England Biochar Retort is a commercial-scale technology, though the smallest scale of the four commercial technologies that we review. It is relatively labor-intensive to operate, with labor cost being 72% of total costs, a larger proportion than for the other technologies we review.

However, the labor-intensive nature of the process also allows it to accommodate less processed biomass feedstocks. An important factor in the overall economics of this technology is the assumption that a fee can be charged for disposing of waste biomass from landscaping operations, tree maintenance, etc. The $-28 biomass cost reflects the fee actually charged for wood disposal at New England Biochar's Eastham location. In addition to small commercial ventures, one can imagine this technology used by town or county-level governments to process biomass waste at local transfer stations.

As discussed above, the thermal output from the New England Biochar Retort is significant. Here we assume a 50% utilization rate, meaning that half of the heat produced in a year might replace another fuel, and we assume the thermal energy replaced to be from natural gas at current prices. Making use of the available thermal energy would require installing the retort in a location where the thermal energy could be used.

6.2.3 Modified Biomass Boiler

As noted in section 5.23, each boiler and its modification for greater biochar production is unique. While we believe the scenario presented uses plausible values, there is inherently more uncertainty about the cost of this option than of other options.

For this study we assume no labor cost, i.e. we assume the boiler is running anyway and there are no additional costs to produce biochar. In reality there may be a small additional labor cost due to the increase in boiler ash/char volume.

The number of existing boilers that could be modified is also finite and rather small. In principle, new biochar-producing boilers could be built, for example, commercial or institutional-scale heating boilers; even residential pellet stoves might be designed to produce a biochar residual. But for this study we found no such examples to profile.

Finally, it should be noted that the biochar yield rate is lower for existing boiler conversions than for any other technology we studied. If maximizing biochar production from the limited quantity of forest biomass available in the Commonwealth is a policy goal, existing boiler modifications are not necessarily a preferred solution.

6.2.4 NextChar CHAB Processor

The NextChar processor produces biochar at a larger scale than the first three technologies reviewed. It also has a larger capital cost, with a corresponding reduction in the proportion of total cost allocated to labor. Given that the processor is still in a pilot stage, capital cost and operating parameters are still have some uncertainty.

For this scale of plant, we assume that it will be necessary to purchase biomass in the form of wood chips. These typically have a moisture content of 40%-45%. Prices vary with location and chip specification (size, species, etc.). For this study we use a price of $25 per U.S. ton, a recent price posted in New Hampshire (NHTOA, spring 2017).

With the larger scale operation and larger biomass consumption comes a larger thermal energy output from the processor. As in the New England Biochar scenario, we assume the NextChar processor is collocated with a facility requiring thermal energy, and that 50% of the thermal output is used for an application that would otherwise use natural gas. The larger scale of the NextChar processor makes utilizing the thermal energy a relatively important aspect of the overall processor economics.

6.2.5 Biogen – Roberts Energy Renewables

Like the NextChar processor, the Biogen project being developed by Roberts Energy Renewables, Inc. for Roberts Brothers Lumber Co., is relatively large scale and capital intensive for biochar production, with labor accounting for a small portion of operating costs. It is the only technology we review that produces electricity. At 2 MW, the plant is very small compared to typical biomass electricity generating plants (of perhaps 50 MW) and tiny compared to typical fossil-fuel electricity generating plants (of perhaps 500 MW). For biomass energy, the small plant scale is advantageous both for sourcing and transporting the biomass energy supply, and for utilizing the waste heat that is an inevitable byproduct of biomass combustion or pyrolysis.

As noted above, the Biogen technology is the most complex that we review, and has the greatest number of coproducts. And since the biochar yield is also relatively low (compared to other technologies), the final cost of biochar carbon sequestration depends to a much greater extent on the value of the coproducts, especially the value of electricity. Plausible values of electricity could make the Biogen technology either the least or most expensive carbon sequestration method reviewed in this study.

For the Roberts case study, we assume all electricity produced will be sold back to the grid at a price of $85/MWh. Of the 10 MMBtu thermal output, about 86% will be used to dry wood chips for sale off site and 14% will be used for drying lumber, drying cordwood, and during winter, heating company facilities. Since the Roberts thermal demand is mostly not seasonal, we assume that the 75% of thermal energy used outside of the Biogen system would otherwise have been provided by natural gas.

6.3 Existing Policy Instrument: RECs

If there is a net cost to sequester carbon with biochar, a suitable policy instrument (such as a carbon credit) will be needed to incentivize sequestration. While no such policies exist in Massachusetts today, the existing Renewable Portfolio Standard (RPS) and Alternative Energy Portfolio Standard (APS) programs provide for the sale of Renewable Energy Certificates (RECs) for electricity from biomass and Alternative Energy Credits (AEC) for biomass thermal energy sales. In both cases projects must meet specific criteria to qualify for the sales. Since our objective in this study is to estimate the true cost of carbon sequestration using biochar, we omit REC and AEC sales from the economic analysis, though they may be financially important for some projects.

The Roberts Energy Renewables project is expecting to sell RECs for perhaps $40/MWh electric and $22/MWh thermal, which are important to the success of the project. Of course these prices change regularly based on both market conditions and policy development. Since the Biogen technology project produces large amounts of both electrical and thermal energy coproducts, it is perhaps better positioned to benefit from existing energy subsidies than the other technologies. While no carbon sequestration credit yet exists, existing programs can effectively subsidize carbon sequestration, at least in some situations.

6.4 Other Simplifying Assumptions for the Economic Analysis

As described in section 2 above, biochar’s environmental impacts are complex, and not completely understood. There is potential for many other positive impacts from biochar. These include: 1) reducing emissions of nitrous oxide (N_2O, a greenhouse gas) in fields where both biochar and nitrogen fertilizers are applied; 2) stabilizing and reducing the decay rate of native soil organic matter, thereby reducing CO_2 emissions from this decay; 3) reducing emission from fertilizer production (an energy-intensive process), if biochar application allows for reductions in fertilizer use; and 4) increasing plant growth rates and associated carbon sequestration (Cowie et al., 2015). All of these benefits have been observed with biochar use, but are clearly context dependent, and not easy to fully monetize. Similarly, for simplicity we omit the cost of any local air pollutants that may be emitted in the process of biochar production, which may represent important costs in some contexts.

7.0 Biochar and Dynamics of Biomass Carbon

Some of the interest in and motivation for biochar production can be traced to the existence of the Terra Preta soils of the Amazon Region, created at least in part by biochar additions over centuries to millennia, and surviving for equally long periods of time (Glaser, Haumaier, Guggenberger, & Zech, 2001). Biochar is clearly a technology for the long run, much longer than typically considered in economic analyses. In this section we consider two aspects of biochar carbon dynamics: how long biochars likely persist in soils, and how biochar-energy coproduction systems compare to simple biomass combustion systems in terms of atmospheric carbon impacts over time.

7.1 Persistence of Biochar in Soil

As described throughout this report, biochar consists of organic matter heated to a point where the chemical structure of its carbon changes. While soil biota break down organic carbon, some forms of carbon are more accessible than others. As described by Lehmann et al. (2015b), soil biota may target the most easily decayed forms of carbon first, implying that the rate of decay depends in part on what other materials are available in a given soil. A number of factors thus influence carbon-decay rates in soils, including the structure of the carbon (which depends on pyrolysis temperature and other conditions), the soil biota present, the soil moisture level, the presence or absence of other organic matter, minerals, etc.

Biochar carbon is often described as recalcitrant (stable), with soil residence times of centuries to millennia, or labile (unstable), with soil residence times of months to years. In reality this is an oversimplification, there being a continuum of carbon residence times based on the factors listed above. Another issue is empirically projecting carbon decay over the very long run (more than a century) based on data collected over at most a few years. However, the labile-recalcitrant distinction is generally useful for the purpose of this study. While there is a great difference between sequestering carbon for a year (labile) as compared to a century (recalcitrant), there is not necessarily a meaningful economic difference between carbon stability for 100 years as compared to 1000 years.

One way to consider the economics of carbon decay is to calculate the present value of biochar replacement, i.e. how much it would cost to make additional biochar to sequester the carbon again, and how much that is worth today based on different discount rates for future costs. As shown in Table 7-1, even with low, sustainability-oriented discount rates of 1%, 2%, or 3%, the present value of replacing biochar in 100, 500, or 1000 years approaches zero. Over a long enough period of time, the social cost of simply replacing biochar as needed is very small, i.e. very little annual effort is needed to do this. Thus while even recalcitrant carbon is not actually permanent, from an economic perspective it is nearly so.

Table 7-1. Cost of Future Biochar Replacement

Biochar replacement cost:			$400.00/ton	
Present value of replacing one tone of biochar				
	Years in future			
Discount rate	1	100	500	1000
1.0%	$396.04	$147.88	$2.76	$0.02
2.0%	$392.16	$55.21	$0.02	$0.00
3.0%	$388.35	$20.81	$0.00	$0.00

7.2 Economics of Biomass and Biochar Carbon Flows

Biochar carbon economics are fundamentally tied to biomass carbon economics, since the same biomass could either be directly burned as an energy source, or be converted in pyrolysis to a combination of biochar, energy, and coproducts. For many years biomass energy was assumed to be carbon neutral: new tree growth reabsorbs any carbon released by burning wood, assuming that forestland remains intact and is sustainably managed. But there is a time delay between releasing carbon dioxide in biomass combustion and reabsorbing that carbon in new tree growth, a delay that may be decades or centuries, depending on the circumstances. During this delay the carbon released from biomass combustion causes greenhouse gas damage just like any other atmospheric carbon. Many studies have now established that characterizing biomass energy as carbon neutral is an oversimplification of complex carbon dynamics (Cherubini, Peters, Berntsen, Stromman, & Hertwich, 2011; Holtsmark, 2012).

Biomass energy utilization has been controversial in Massachusetts, especially biomass used in relatively large-scale (e.g. 50 MW) electricity-generating facilities. To assist in developing new rules for biomass energy, the Commonwealth commissioned the “Biomass Sustainability and Carbon Policy Study” by the Manomet Center for Conservation Sciences (Walker et al., 2010; Walker, Cardellichio, Gunn, Saah, & Hagan, 2013; hereafter referred to as the "Manomet Report"), which was itself controversial.

In most applications, biomass energy use is less energy efficient than a fossil fuel used in the same application, i.e. somewhat more carbon is released from biomass combustion than for a fossil fuel burned to accomplish the same task, due to the composition of biomass and the equipment available for utilizing it. In the language of the Manomet Report, a “carbon debt” is incurred with burning biomass. Over time, forest regrowth absorbs this atmospheric carbon, gradually reducing the “debt.” The Manomet report calculated simple payback periods, or the number of years of forest growth required to reduce a carbon debt to zero. Results varied with the energy application and reference fossil fuel, but paybacks were generally measured in decades.

Timmons et al. (2016) published results of a study that recreated and extended the results of the Manomet Report. A key observation of this study is that forests have a finite ability to absorb atmospheric carbon. Young forests grow quickly, consuming large amounts of CO_2, but as forests age, growth slows and carbon absorption eventually ceases (or nearly so). The ability of forests to absorb fossil-fuel carbon is thus limited. By contrast, the ability of a forest to absorb carbon emissions in a biomass energy cycle is unlimited— each forest harvest creates room for new trees to absorb the carbon released by the harvest and combustion. Biomass harvest, combustion, and regrowth can continue in perpetuity, as long as forests are managed sustainably.

An initial carbon release followed by decades of carbon absorption is a parallel of a financial investment, where an initial capital investment is incurred in order to obtain a flow of annual returns. Internal rate of return (IRR) is a financial metric used to assess the strength of an investment. IRR is reported as a percentage rate, with larger IRR being preferred to smaller. Timmons (2016) calculated IRR for the biomass energy scenarios in the Manomet Report, and showed that from a sustainability perspective, biomass energy should be preferred to fossil energy for any IRR greater than zero (which was true in every scenario studied). But IRR was much greater for some biomass scenarios than for others, suggesting that some biomass applications should be preferred.

In this report we extend the results of Timmons (2016) by calculating IRR for biochar scenarios. In the biochar scenarios, biomass undergoes pyrolysis, useful energy is obtained, some biomass carbon is immediately sequestered as biochar in agricultural soils (as studied in this report), and the portion of carbon emitted to the atmosphere is gradually reabsorbed by growing forests. Figure 7-1 shows the model (in STELLA software) used for this study, where stocks are represented by rectangles, flows by double lines with valves, and parameters and outputs by circles. Single lines represent dependencies.

As shown in Table 7-2, in general we do not find great differences in short-run carbon dynamics of biochar pyrolysis as compared to simple biomass combustion. IRR are all greater than zero, indicating that from a sustainability perspective, all biochar-energy coproduction technologies studied should be preferred to their fossil-fuel alternatives.

Since biochar technology directly sequesters carbon while simple biomass combustion does not, intuitively one would expect greater returns from a biochar system than from a simple biomass combustion system. The main reason we find similar results is that biochar production equipment is not necessarily as efficient in generating and capturing energy as simple biomass combustion equipment, since biochar production must accommodate a number of different criteria and objectives (as described above).

Figure 7-1. STELLA model used for carbon IRR calculations

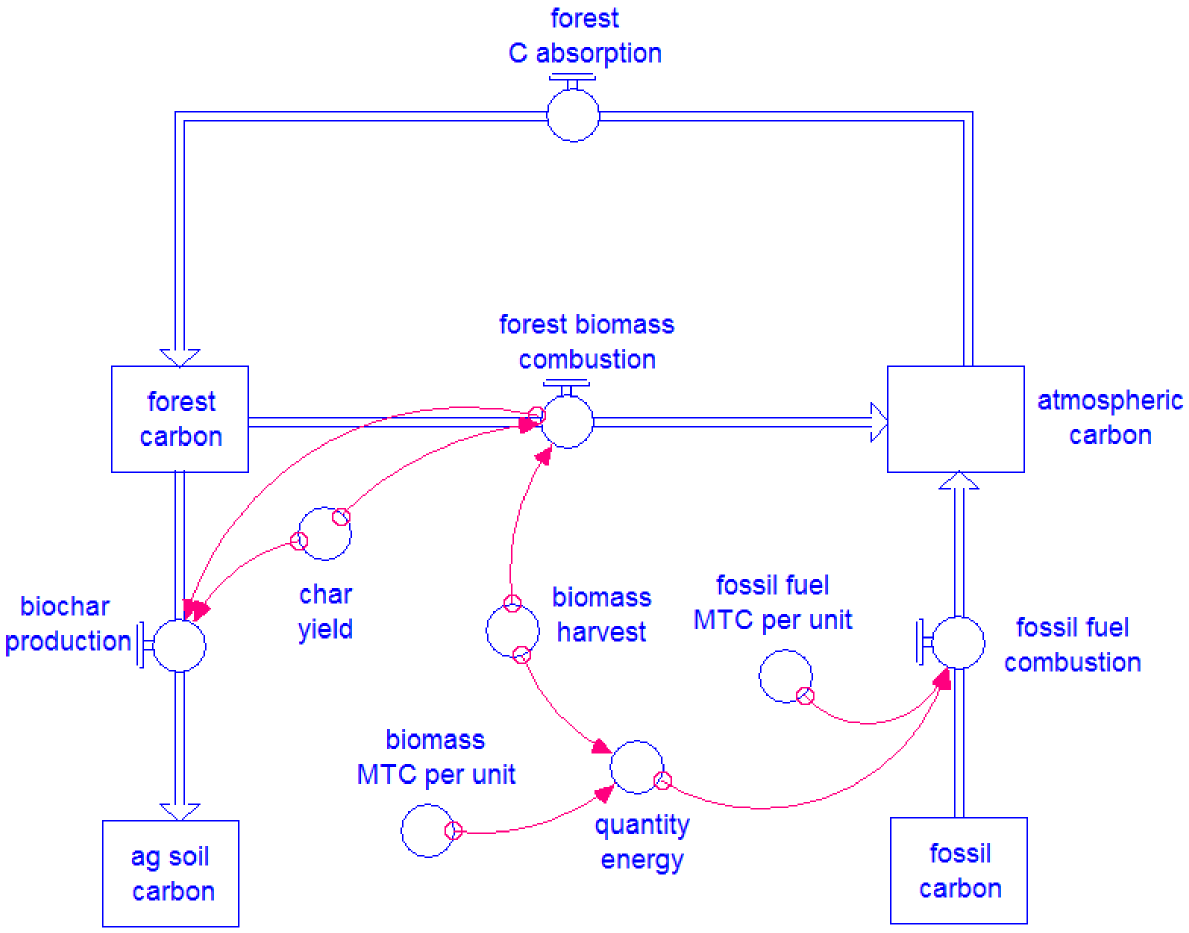


Table 7-2. IRR for Original Manomet Scenarios and Biochar Scenarios

Original Manomet Scenario	Internal Rate of Return (IRR)
biomass vs. oil thermal	8.3%
biomass vs. natural gas thermal	1.6%
biomass vs. coal electric	2.1%
biomass vs. natural gas electric	0.1%
Biochar Scenario	
NextChar vs. oil thermal	6.9%
NE Biochar vs. oil thermal	6.5%
NextChar vs. natural gas thermal	2.2%
NE Biochar vs. natural gas thermal	2.2%
Biogen vs. natural gas electric	1.5%

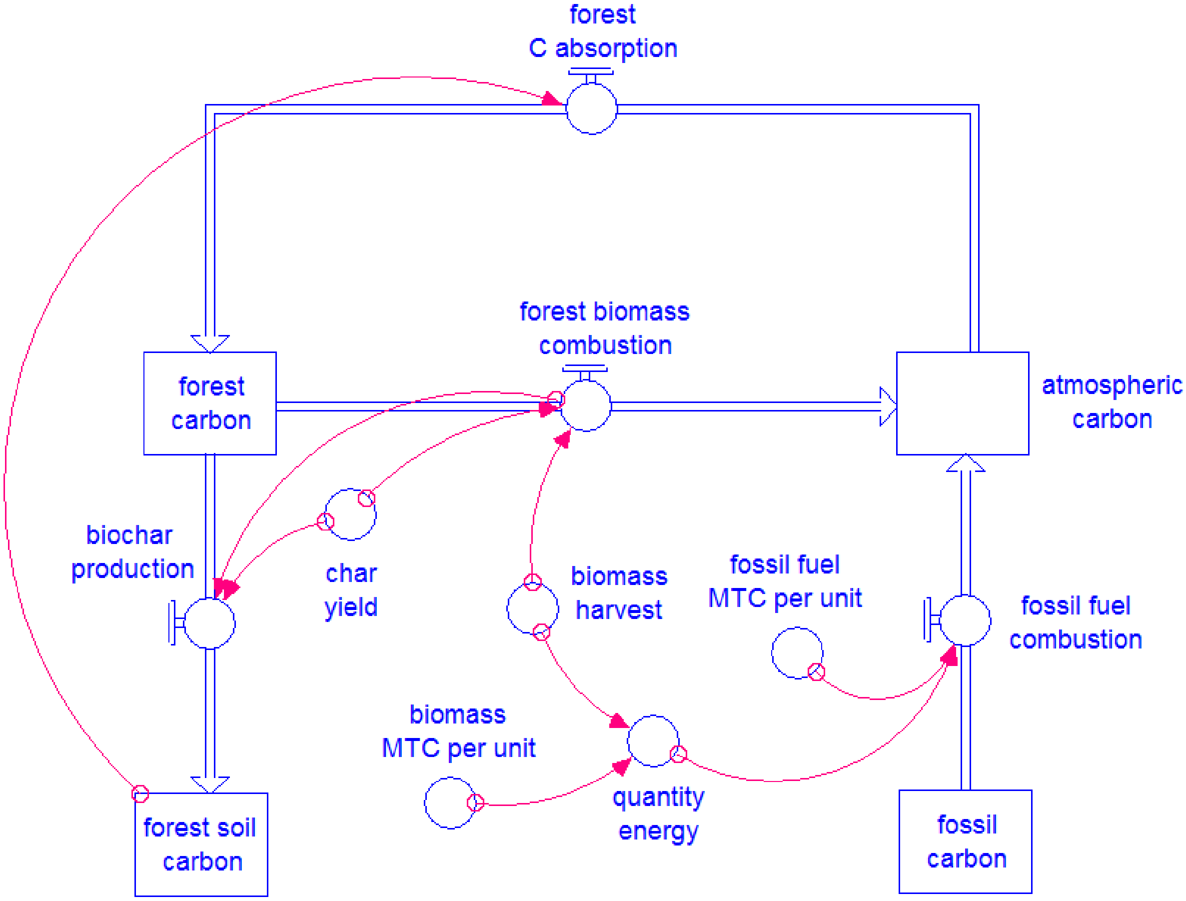
We thus find greater initial carbon debts for the biochar scenarios than for simple biomass combustion. Also, we count only the recalcitrant (or stable) portion of the biochar carbon as being effectively sequestered. The short-lived labile portion of biochar carbon will soon be converted by soil processes to atmospheric CO_2. This labile portion of the biochar is carbon that is emitted without producing any useful energy (as it would do if burned), further increasing the carbon debt.

One exception to this general result is the IRR for the Biogen gasification system vs. natural gas electricity, as compared to the IRR for large-scale biomass generation (e.g. 50 MW) vs. natural gas electricity, as presented in the original Manomet Report. While at 1.5% the Biogen-natural gas IRR is still rather low, it is 15 times greater than the IRR of just 0.1% for biomass-natural gas scenario. Capturing and utilizing the waste heat from the gasifier and engine are the main reasons for this improvement. These results thus support use of biomass energy in high-efficiency applications where waste heat can be captured and utilized, which in general will mean smaller rather than larger-scale biomass-biochar utilization.

While the IRR results from biochar and energy coproduction are modest, this perhaps misses the main point. As noted above, forests have a finite ability to absorb carbon, and thus have limited potential for net carbon sequestration from past and present fossil-fuel emissions. As can be seen in Figure 7-1, carbon sequestration in soils represents an additional carbon sink, one which greatly expands the total carbon sink capacity—a benefit not captured by IRR. While biomass energy technology can be seen a successor to fossil-fuel technologies that increase atmospheric carbon, biochar technology can be seen as a restorative approach that also partially reverses past fossil-fuel carbon releases. And of course biochar has other purposes, including increasing soil productivity. If carbon IRR for biochar and energy coproduction are modestly lower than for simple biomass combustion, this is perhaps the price paid for biochar's other benefits.

Another possible benefit of a biochar system, not reflected in the model of Figure 7-1, is the possibility of applying biochar to forest soils rather than agricultural soils, and perhaps increasing the rate of forest growth. This would create a beneficial feedback loop, as indicated in Figure 7-2 by the new arrow from "forest soil carbon" to "forest C absorption". If biochar applied to forest soils increases the rate of forest growth, the total carbon sequestration rate (from trees absorbing carbon) would increase over time. While we believe this effect is likely, there is very little data with which to assess the magnitude of such an effect, and we thus omit estimates of increased forest carbon sequestration in this report.

Figure 7-2. STELLA model modified to reflect possible increases in forest growth



8.0 Discussion and conclusions

This study finds that expanding biochar use would be generally beneficial for Massachusetts, in terms of both sequestering atmospheric carbon and improving the Commonwealth's agricultural land resources. We estimate that the net cost of sequestering carbon using agricultural biochar in Massachusetts is approximately \$102/metric ton of CO_2 (average of 4 commercial methods from Table 6-1). However, this estimate is sensitive to a number of assumptions about biomass feedstock costs, capital and operating costs for pyrolysis equipment, biochar and coproduct benefits, etc. A cost of \$102/metric ton CO_2 is greater than many literature estimates for the social cost of carbon. For example, Tol (2011) reports a central value of \$48/metric ton CO_2, based on 311 studies in the literature, and \$22/metric ton CO_2 based on only peer-reviewed studies (N = 220). However, these studies attempt to derive a social cost of carbon by estimating the value of future climate change damages, an exercise fraught with uncertainties about actual climate change effects. Damage-based estimates must also make difficult judgements about how much to discount future damages, whether to weigh damages to rich and poor nations equally, etc. Using a cost-effectiveness approach, we assume that systematic increases of greenhouse gas in the atmosphere must eventually cease. Our estimate of the social cost of carbon simply reflects the cost of reversing a ton of CO_2 emissions using biochar in Massachusetts.

The potential scale of Massachusetts biochar industry is modest, based on the quantity of forest biomass that could be sustainably harvested (Kelty et al., 2008) for biochar production. For example, if the entire sustainable biomass supply were used in 2 MW gasification systems (as in case study 5.2.5), the Massachusetts biomass supply could support 71 facilities totaling 142 MW of electricity production at peak capacity, directly employing approximately 700 people in the gasification operations. While these represent significant contributions to Massachusetts renewable energy production and carbon sequestration, for perspective it should be noted that this scenario would replace 0.03% of Massachusetts 2015 electricity production, would replace 3.2% of distillate fuel oil, and would sequester 0.2% of the Commonwealth's 2015 greenhouse gas emissions (less than estimated in section 4.2, since the gasification technology has a 10% biochar yield). The scale of Massachusetts fossil-fuel use dwarfs potential remediation by biomass/biochar. A number of other climate-change mitigation solutions are clearly required. In the long run, biochar's contribution to Massachusetts agriculture may be more important than its energy contribution, given possible food requirements in a climate-changed, more-populated world.

In general, we find that availability of land on which to apply biochar is not a constraint on carbon sequestration, though application at rates greater than required for crop yields effectively increases the cost of sequestration. For maximum carbon sequestration in the long run, biochar application on forest, non-commercial farms, grass turf, and similar lands could be considered.

A biochar industry would likely represent one portion of Massachusetts biomass energy industry, given that much of the same biomass feedstock could be used either for direct combustion or biochar manufacture. Additional sources of organic matter for biochar include food waste, landscaping debris, wastewater treatment solids, etc. And while we have only considered biochar agricultural uses here, Massachusetts biochar production would have a number of other applications (filtration, environmental remediation, etc.) and would support related industries.

Biochar production must strike a difficult balance between production cost, agricultural value of biochar, carbon sequestration value, and biochar coproduct values. To some extent these represent trade-offs, i.e. to gain greater value with respect to one quality, other qualities are diminished. More research about such trade-offs is needed. As stressed throughout this report, biochar is not a single, homogenous commodity, but rather a family of related products that have differing characteristics. Yet much of the existing research on biochar has not sufficiently isolated variables of interest, including biochar feedstock and pyrolysis conditions, biochar characteristics, and characteristics of soils to which biochar has been applied. It is thus difficult to conclude which kinds of biochar are most beneficial in which situations, and to estimate the corresponding biochar values.

In Massachusetts, future research should focus on biochar from woody feedstock (which appears to have the greatest potential for production) and improvements to agricultural soils of lower quality, which presumably have the most to gain from biochar additions. Future research could usefully identify effects of different biochars (based on IBI characteristics listed in section 2.0) in these situations, and for different crops that are of interest for Massachusetts agricultural production. Potential use of biochar for cranberry production is another significant question, given the value of the Massachusetts cranberry crop. Future research could also assess potential biochar effects on forest productivity.

In addition, future research could explore different aspects of developing a biochar industry. For example, how can markets be developed for potentially valuable biochar coproducts including wood vinegar, which have uncertain market values today? To what extent do Massachusetts farmers believe that biochar provides tangible value for crop production? Are capital costs a barrier to farmers utilizing biochar, given that substantial investments may be made initially, in exchange for decades or even centuries of increased crop yields? Public education on potential biochar benefits will likely be needed to develop a biochar industry, and research could assess how to most effectively implement biochar education.

Like addressing the problem of climate change itself, creating a Massachusetts biochar industry likely requires some kind of policy intervention. Biochar climate-change benefit is a pure public good, which implies underinvestment by the private sector. And even private benefits such as increased yields accrue over so many harvests that their present value is likely understated when private discount rates are applied (rather than sustainability-oriented social discount rates). Biochar holds the potential for significant social benefits in Massachusetts, but a social approach is likely required to realize these benefits.

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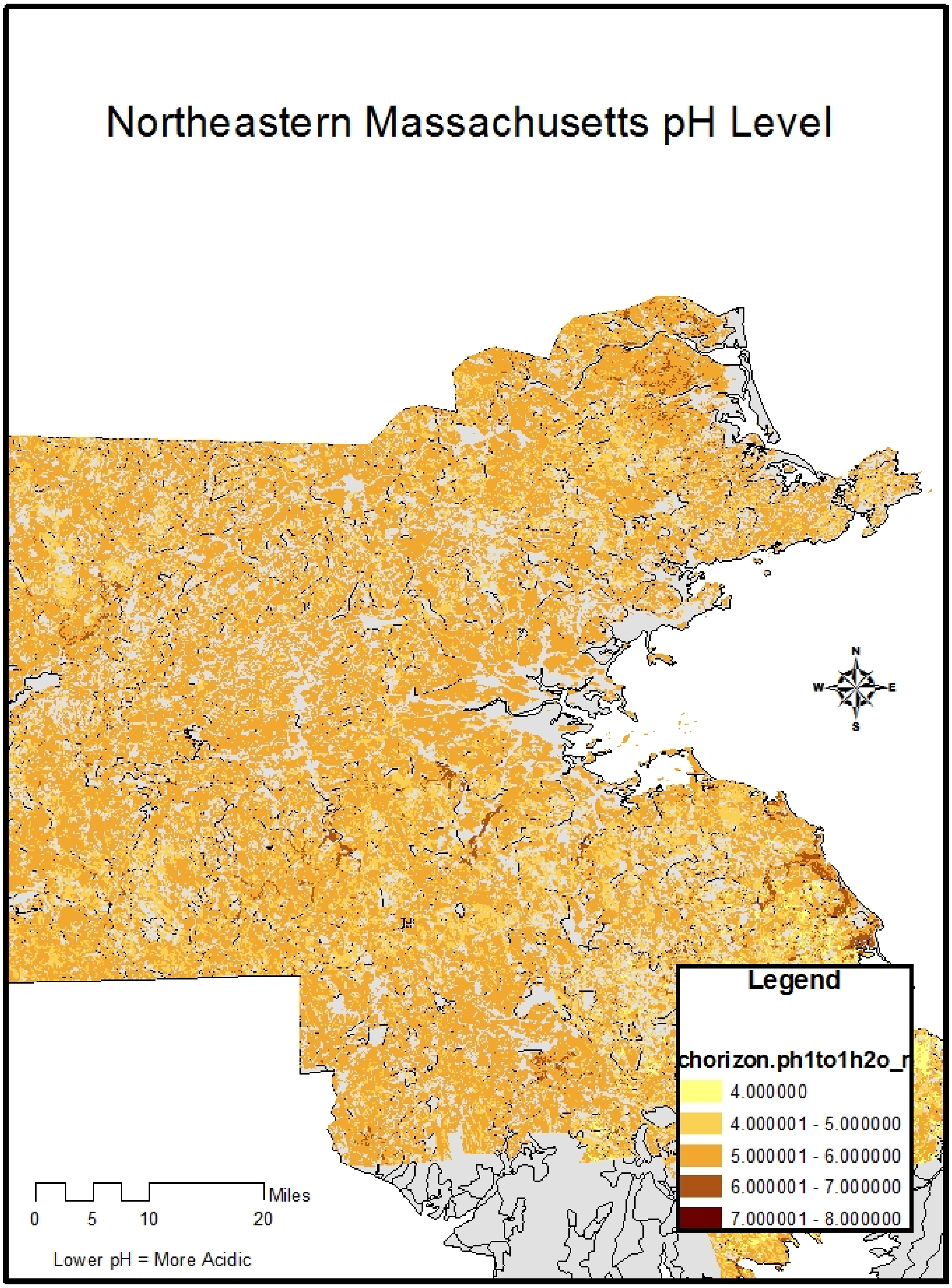
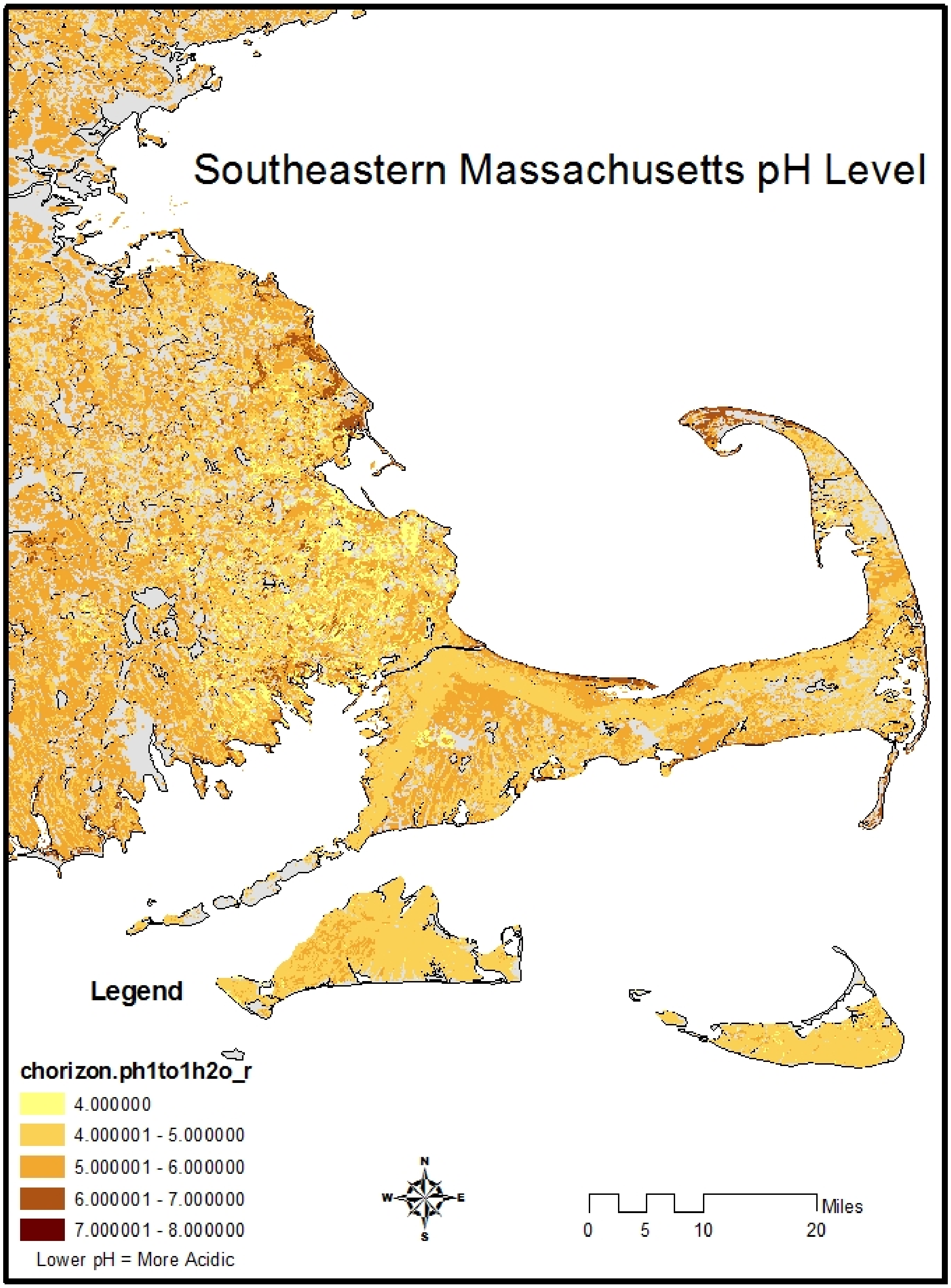
Appendix 1: Massachusetts Regional pH Maps

A1-1 Northeast



Soil data from USDA Natural Resource Conservation Service, Soil Survey Geographic Database (SSURGO): https://www.nrcs.usda.gov/wps/portal/nrcs/surveylist/soils/survey/state/?stateId=MA

A1-2 Southeast



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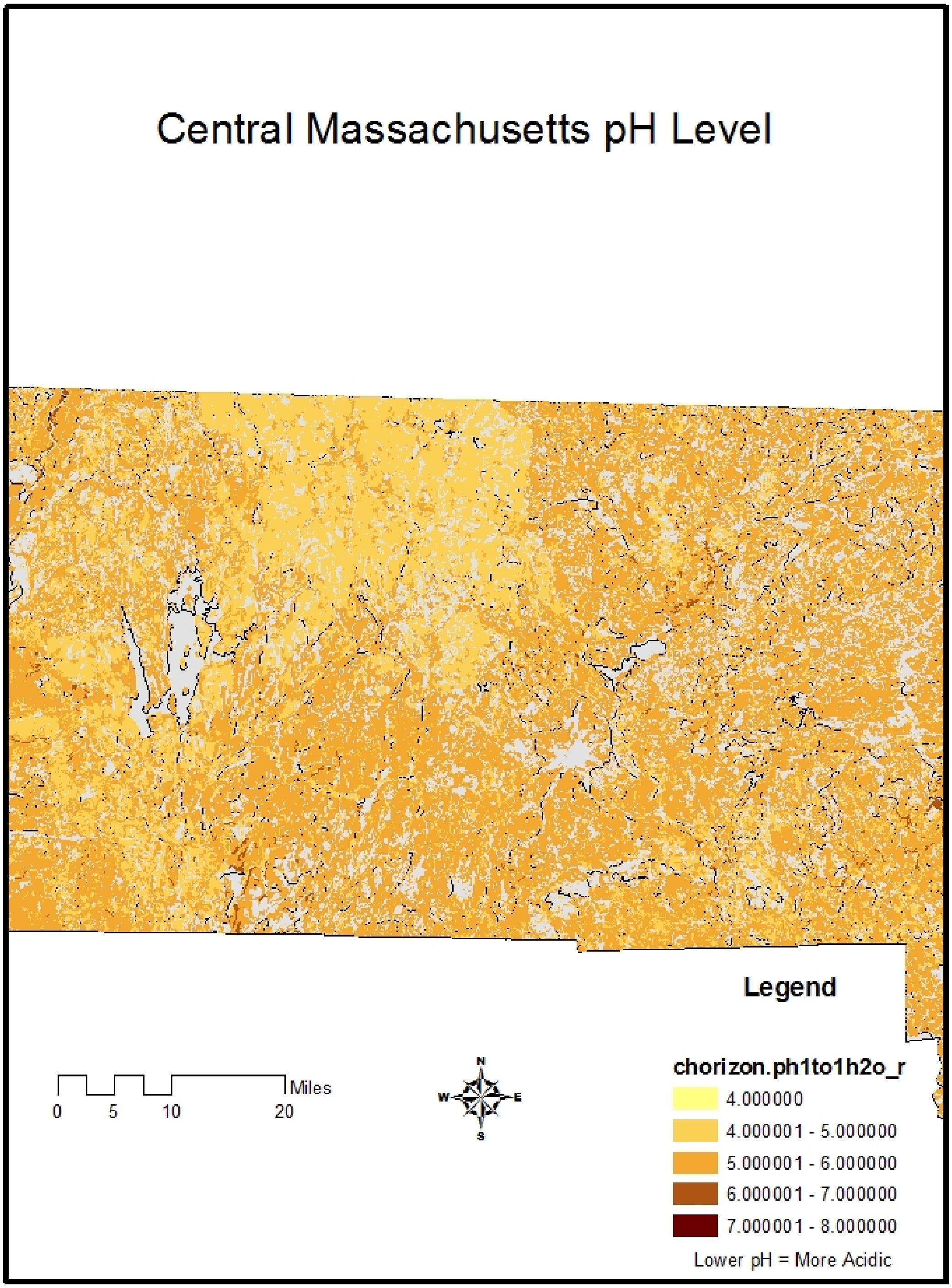
A1-3 Central



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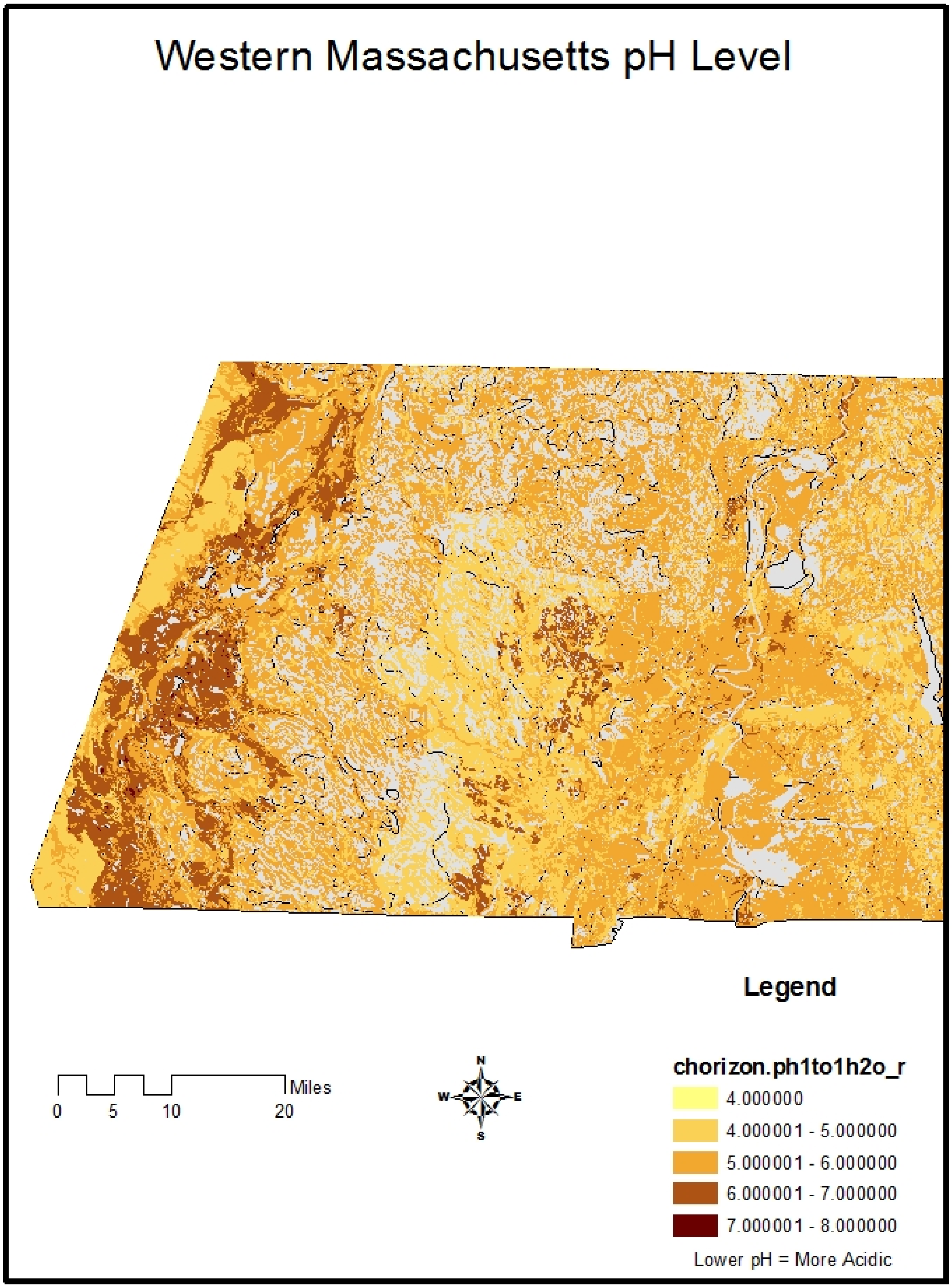
A1-4 West



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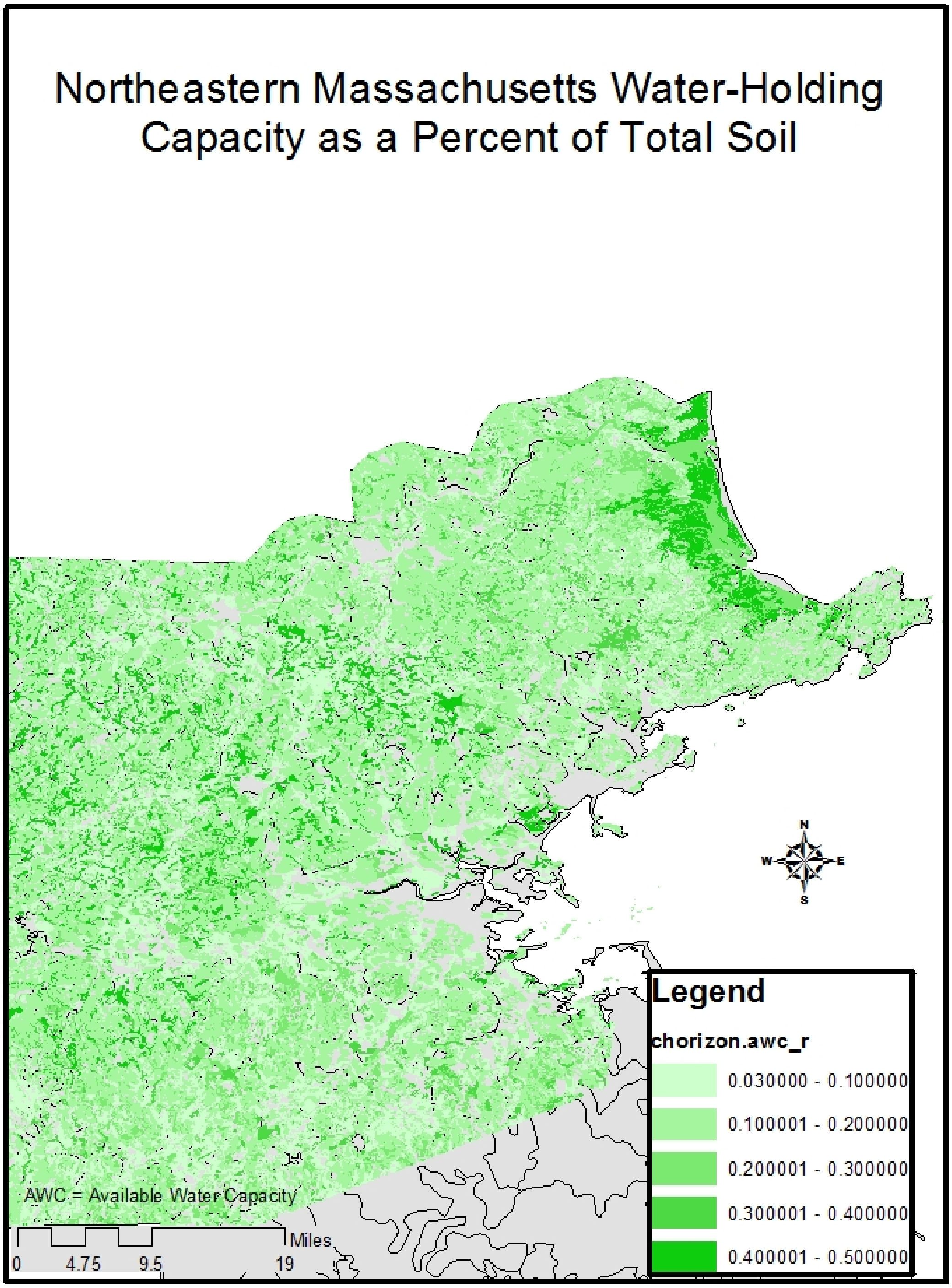
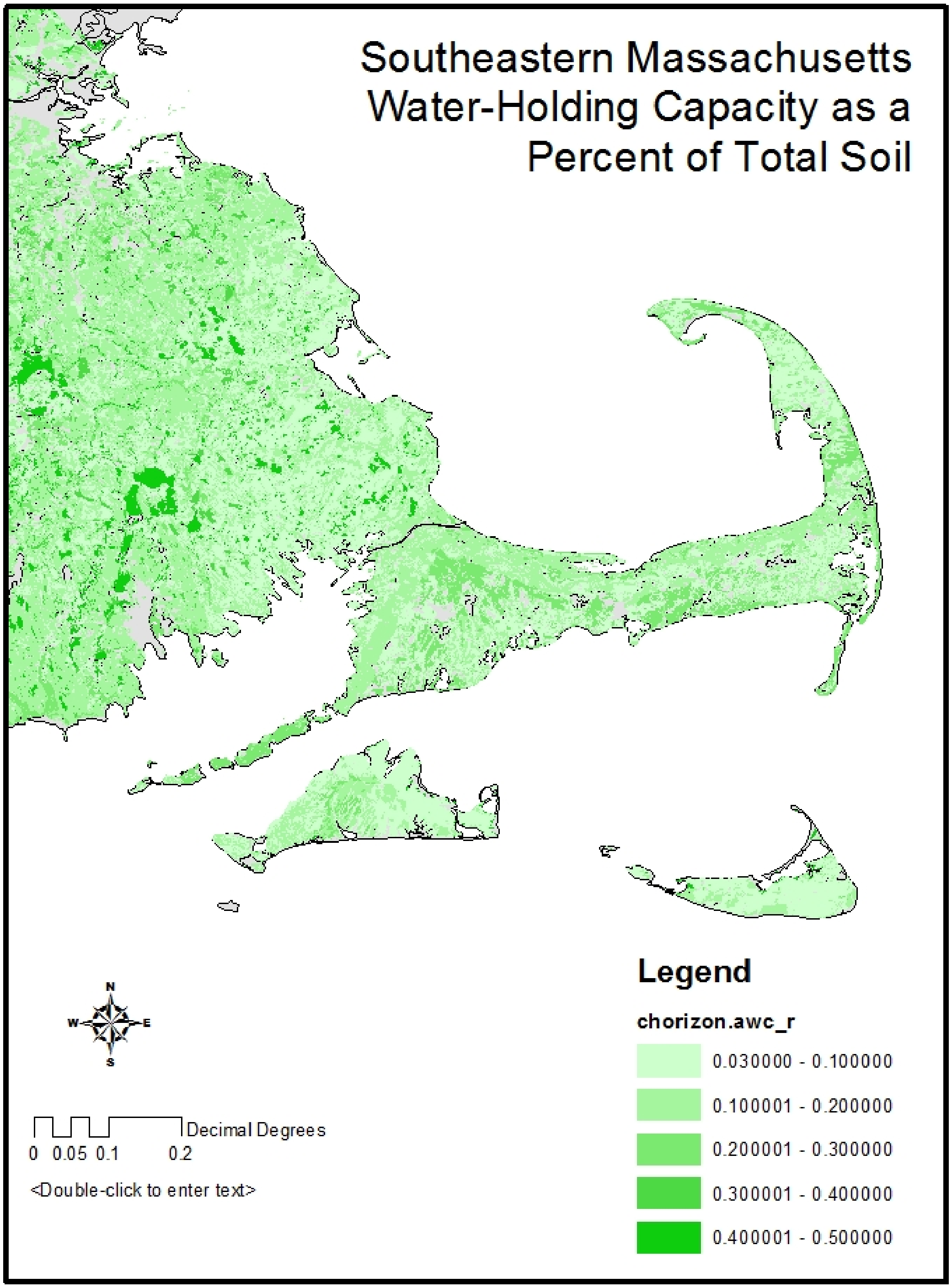
Appendix 2: Massachusetts Regional Water Holding Capacity Maps

A2-1 Northeast



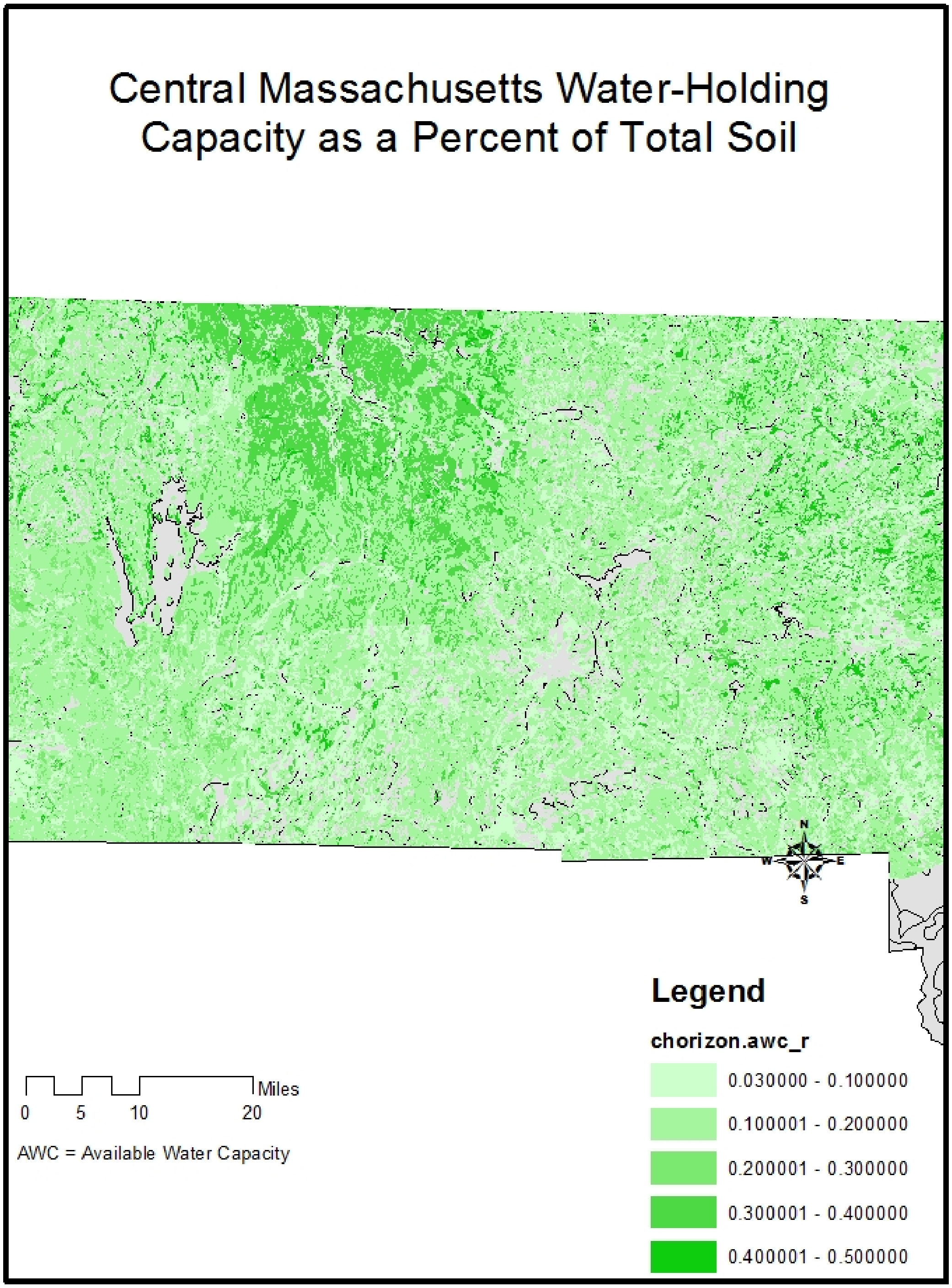
Soil data from USDA Natural Resource Conservation Service, Soil Survey Geographic Database (SSURGO): https://www.nrcs.usda.gov/wps/portal/nrcs/surveylist/soils/survey/state/?stateId=MA

A2-2 Southeast



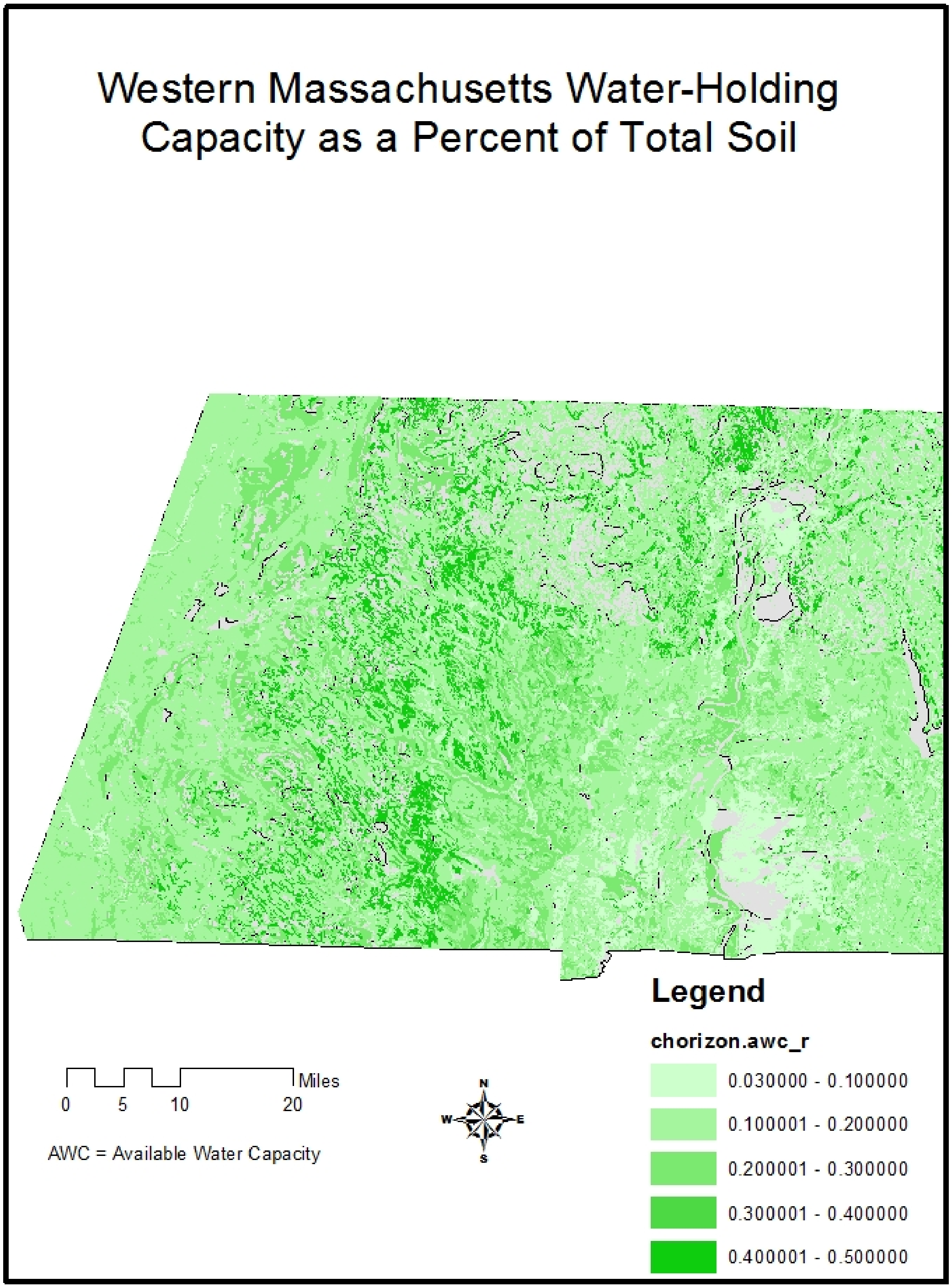
Soil data from USDA Natural Resource Conservation Service, Soil Survey Geographic Database (SSURGO): https://www.nrcs.usda.gov/wps/portal/nrcs/surveylist/soils/survey/state/?stateId=MA

A2-3 Central



Soil data from USDA Natural Resource Conservation Service, Soil Survey Geographic Database (SSURGO): https://www.nrcs.usda.gov/wps/portal/nrcs/surveylist/soils/survey/state/?stateId=MA

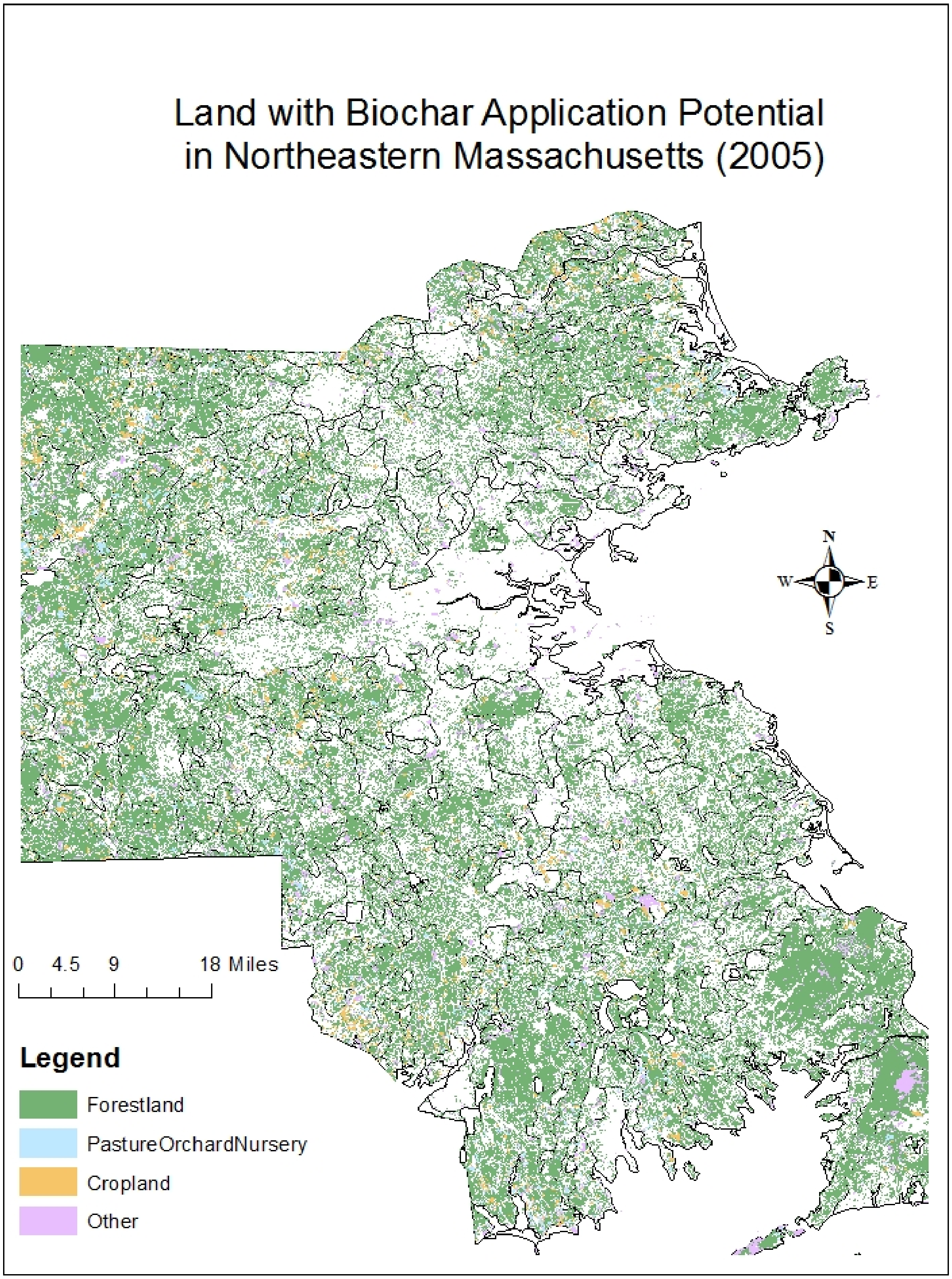
A2-4 West



Soil data from USDA Natural Resource Conservation Service, Soil Survey Geographic Database (SSURGO): https://www.nrcs.usda.gov/wps/portal/nrcs/surveylist/soils/survey/state/?stateId=MA

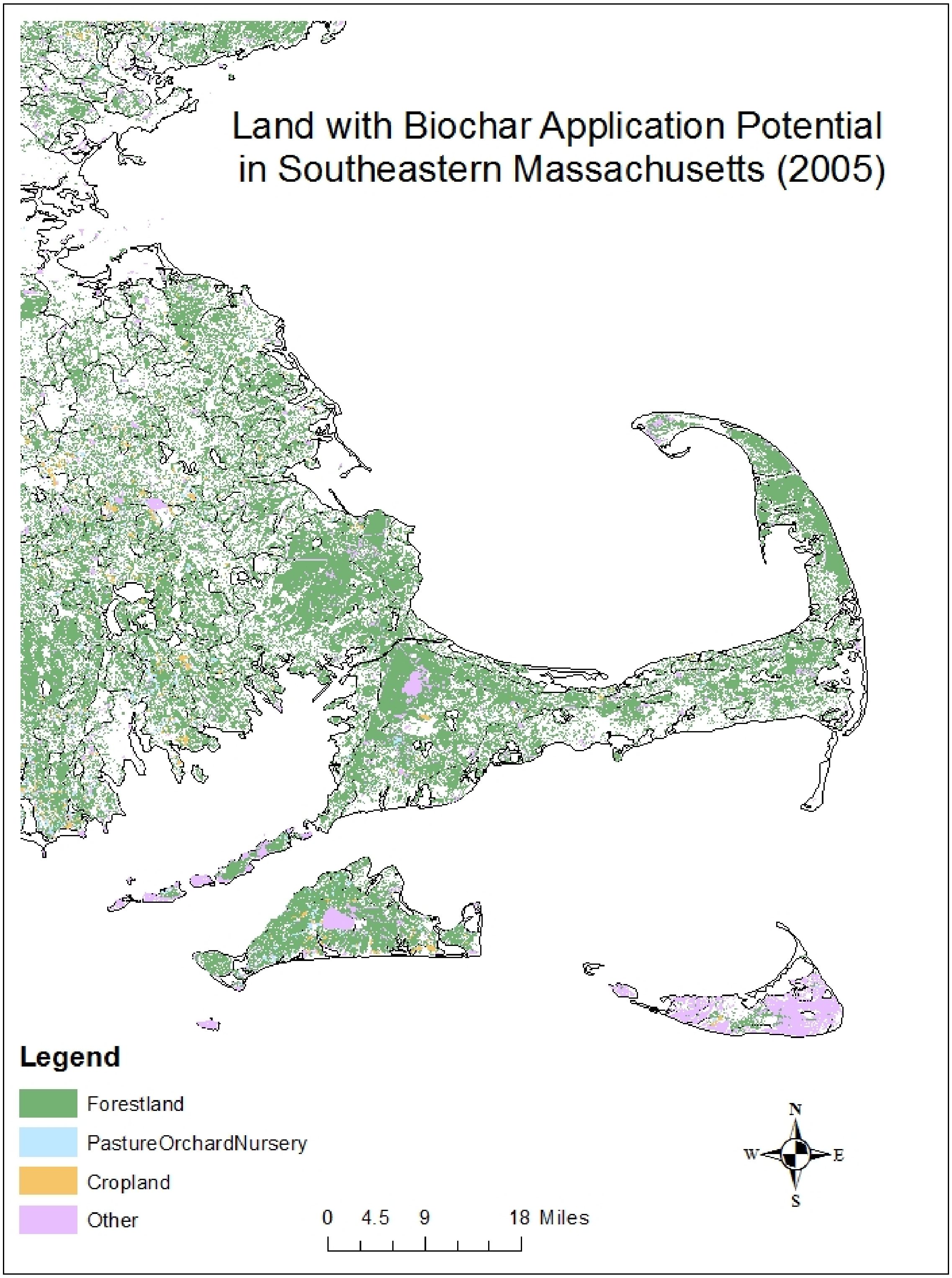
Appendix 3: Massachusetts Regional Land-Use Maps

A3-1 East



Land use data from MassGIS: http://www.mass.gov/anf/research-and-tech/it-serv-and-support/application-serv/office-of-geographic-information-massgis/datalayers/lus2005.html

A3-2 Southeast

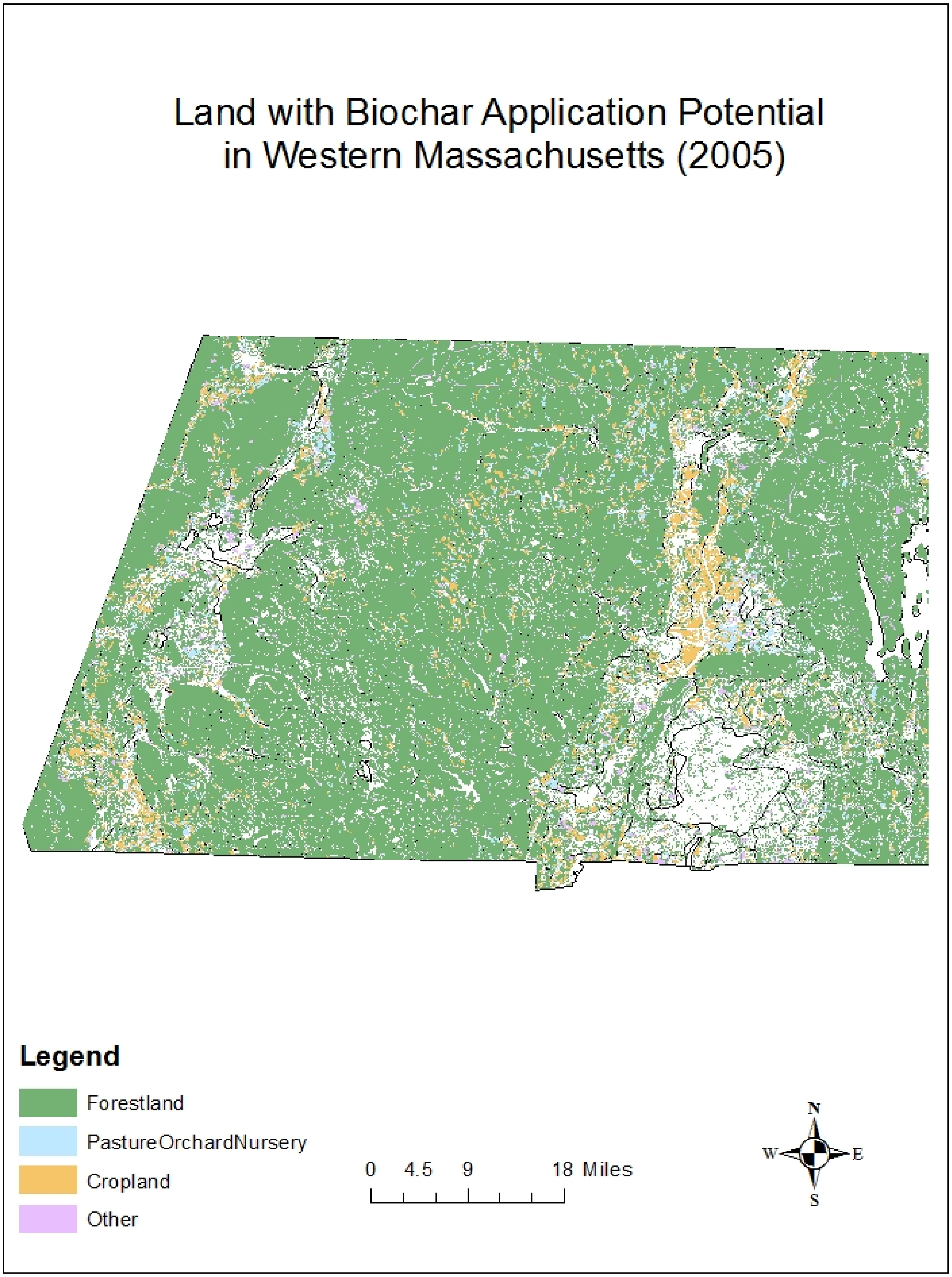


Land use data from MassGIS: http://www.mass.gov/anf/research-and-tech/it-serv-and-support/application-serv/office-of-geographic-information-massgis/datalayers/lus2005.html

A3-3 Central

Land use data from MassGIS: http://www.mass.gov/anf/research-and-tech/it-serv-and-support/application-serv/office-of-geographic-information-massgis/datalayers/lus2005.html

A3-3 West



Land use data from MassGIS: http://www.mass.gov/anf/research-and-tech/it-serv-and-support/application-serv/office-of-geographic-information-massgis/datalayers/lus2005.html