19

Economics of Biochar Production, Utilization and Greenhouse Gas Offsets

Bruce A. McCarl, Cordner Peacocke, Ray Chrisman, Chih-Chun Kung and Ronald D. Sands

Introduction

In order for pyrolysis and agriculturally applied biochar to be an important development, they must jointly be an economically attractive alternative. This economic attractiveness could arise from a combination of:

- valuable energy commodity yields (as also discussed in Chapters 8 and 9);
- value arising from biochar as a soil additive (see Chapters 5 and 12);
- valuable greenhouse gas (GHG) offsets generated by offsetting fossil fuels, reducing emissions from use of agricultural inputs and sequestering carbon (C) (see Chapter 18); and
- value arising from other chemical products.

In addition, revenues from these items must offset the economic and GHG costs of raising, harvesting, hauling and storing the biomass feedstock, along with those of employing pyrolysis and then transporting and applying the biochar.

This chapter reports on an analysis approach that assesses the economic and GHG consequences of biochar–pyrolysis production, using a crop residue case as a specific example. Namely, we use a case study involving collection of maize residue and transportation to a large fast or slow pyrolysis facility (in contrast to Chapter 20, which examines small-scale pyrolysis opportunities), yielding both energy products and biochar with the biochar applied to cropland (other biochar systems are discussed in Chapter 9). Specifically, we examine the:

- cost of feedstock harvest, hauling, storage and use, along with implications for nutrient replacement and tillage alteration;
- value of energy production and the costs of associated processes;
- value of biochar application and subsequent implications for crop production;
- GHG-related accounts involving:
    - offsets for displaced fossil fuels;

- emissions saved and increased from fossil fuels and manufactured agricultural inputs employed in the farm-to-pyrolysis facility-to-farm process; and
- sequestration enhancements and losses involved with residue recovery and biochar application.

In examining these factors we realized that many items are uncertain and develop only a preliminary case study on net economic benefits and a simultaneous GHG life-cycle assessment. We also explore how the case study net benefits are affected by variations in assumptions involving alternative feedstocks, pyrolysis facility/operation costs, energy prices, C prices and other factors.

Pyrolysis and biochar

Biochar is produced by pyrolysis (Bridgwater and Peacocke, 2002; Demirbas and Arin, 2002) and, to a limited extent can, also be a by-product of gasification (Bridgwater, 2005). Pyrolysis is the chemical decomposition of organic materials by heating in the absence of oxygen (O) (see Chapters 1, 7 and 8) where:

- Fast pyrolysis involves biomass being rapidly (on the order of 5 to 10 seconds) heated to between 400°C and 550°C.
- Slow pyrolysis involves slower heating to less than 400°C (although other definitions have higher temperatures; see Chapter 8). The biomass is typically in the reactor for at least 30 minutes and possibly several hours.

During pyrolysis biomass is converted into three products:

1. a liquid product that is commonly called bio-oil, pyrolysis oil or bio-crude;
2. a solid char that can be used in a range of applications, including use as a soil additive (then called 'biochar') or as a source of energy in the conversion process;
3. a non-condensable gas product containing carbon monoxide (CO), carbon dioxide (CO_2), hydrogen (H_2), methane (CH_4) and higher hydrocarbons, 'syngas' or 'pyrolysis gas'.

Slow pyrolysis yields relatively more biochar, but less bio-oil. Wright et al (2008) indicate that fast pyrolysis yields about 15 per cent biochar, 70 per cent bio-oil and 13 per cent syngas. Ringer et al (2006) indicate that under slow pyrolysis, about 35 per cent of the feedstock C ends up as biochar, 30 per cent as bio-oil and 35 per cent as syngas (for additional information, see Chapter 8).

In both cases, the bio-oil can then be cleaned and further processed to produce higher-quality fuels (Czernik and Bridgwater, 2004), gasified to produce electricity, or it can be refined to produce chemical feedstocks such as resins and slow-release fertilizers, as well as have selective food chemicals recovered from it (Baum and Weitner, 2006). Each of these products is a potential source of value.

While biochar was initially viewed as a source of energy and can be burned to supply process energy, it can be used in water purification, gas cleaning, metallurgical industries and for charcoal in home cooking. In addition, it has lately been regarded as a potentially valuable soil amendment where it stores C in stable form along with storing nutrients and water (see Chapters 1 to 6, 9, 11, 12 and 18).

Finally, both the energy products and the biochar as a soil additive have GHG implications, displacing fossil fuel use and associated emissions, along with sequestering C (see

Chapter 18). In considering these GHG impacts, one must consider the full life cycle of GHGs released in the farm-to-factory-to-biochar application system.

Examination of a biomass to pyrolysis feedstock prospect

This section examines the economic and GHG value that would arise from producing biochar and other products under fast and slow pyrolysis using agricultural biomass. We present a somewhat general discussion of feedstock possibilities, along with a concrete application using data representative of the case of maize residues as a feedstock. In calculating the value of such a prospect, we consider benefits and costs, first, and then examine implications from changes in the GHG balance.

Costs and benefits

The economic costs and benefits of fast and slow pyrolysis, as well as the associated products, considered are:

- feedstock production and collection;
- value lost by feedstock removal in terms of altered nutrients and tillage on fields from which crop residue was harvested;
- feedstock hauling;
- feedstock storage and pre-processing;
- feedstock processing;
- pyrolysis operation;
- energy sales;
- biochar hauling and application; and
- biochar-induced cropping system gains.

Each is discussed separately below.

Feedstock production and collection

Biomass requires some form of assembly, harvesting, collection and compaction, all of which involve costs (Caputo et al, 2005). In the case of:

- *Urban municipal wastes:* this could involve separation, assembly at a transport point, possibly compaction and then truck loading, and could involve a tipping fee to municipal agencies (NSWMA, 2005). One should also consider the value of saved landfill space (Read et al, 2008), as well as the possible costs of removing or dealing with any materials such as nails or contaminants in the pyrolysis phase. However, there may be cases where these items can be obtained at no cost with the facility collecting a tipping fee in lieu of a disposal fee.
- *Energy crops such as switchgrass or hybrid poplar:* this would involve the costs of the inputs to raise and harvest the commodity, such as seed, rootstock, fertilizer, fossil fuels, equipment, labour and land value, along with movement to a transport point, compaction and loading.
- *Milling residues or processing by-products such as bagasse:* this could involve the cost of buying them away from their current use (or savings in cost if they are now a disposal item), as well as costs of moving to a transport site, compacting and loading along with the amount one might need to pay the processor for access.
- *Logging or cropping residues:* this would involve the inputs to harvest and transport to a hauling site, along with compaction and loading (Polagye et al, 2007), as well as the future productivity losses or nutrient replacement costs from removal (unless the produced biochar is returned to the site from where the biomass originated or other appropriate soil amendment is used).

More specifically, costs for harvesting and moving maize crop residues to the field edge are assumed to equal US\$10.91 t^{-1} based on a rice straw feedstock supply study by Fife and Miller (1999). We adjust this up to US\$13 after some discussion with Environmental Protection Agency (EPA) personnel and to account for higher energy costs, and we add US\$10 for a payment to the farmer.

When considering the use of a feedstock, it is necessary to consider the costs and benefits of that feedstock were it not diverted to pyrolysis. In the case of maize stover, this involves analysis of the net value if it remains in the field. In this case, the items arising are lost nutrients and sequestration from its diversion as well as increased tillage costs due to its presence (note that we are assuming a sufficient amount is left in the field to avoid increased erosion).

Agronomists have argued that when crop residues are removed, this removes nutrients that must be replaced by commercial fertilizers in subsequent production operations. In terms of amount, we employ estimates of nutrient loss after removal of maize residue developed in an Argonne National Laboratory (2006) report. This amounts to 2.7kg needed for replacement of nitrogen (N) per tonne of residue removed, along with 1.6kg of phosphorus (P) and 8.3kg of potassium (K). Based on current costs of these items, we compute the replacement cost for these as US\$10.08 t^{-1} of residue removed. This would vary if other feedstocks were used.

Additionally, for a crop such as maize, tillage is partially motivated by a need to handle the large volume of crop residue. We assume that when the crop residue is removed, tillage intensity can be reduced and can credit the difference in cost from conventional to no-till farming at US\$20.60 per hectare amounting to US\$5.59 t^{-1} removed. The farm gate price then includes the harvest cost, the nutrient replacement, farmer payment and the savings from reduced tillage, and amounts to US\$27.59 t^{-1}.

Furthermore, we assume the crop residue yield is 3.75t ha^{-1}, which leaves the remaining quantity of residue for erosion control needs and is motivated by the adjustments in the billion tonne study (Perlack et al, 2005). Consequently, each hectare produces 3.75t of feedstock at a farm gate price of US\$27.59 t^{-1}.

The use of other feedstocks would raise different issues and calculation procedures. Specifically, when using:

- *Logging residues:* one would employ essentially the same procedures, examining the extra costs of harvest and hauling to the field edge, but might have to include the cost of on-site chipping and compaction, a differential loss factor in storage and hauling, and a savings in costs for handling residue such as the need for collection and burning, among others.
- *Dedicated energy crops:* one would need to consider the opportunity cost of the land in other usages, such as conventional crop production along with rotation length and differential yields over time.
- *Municipal wastes:* one might encounter cases where firms may pay the pyrolysis plant a tipping fee to take waste materials. Sorting, separation and subsequent disposal of inerts may reduce the income opportunity significantly.

Feedstock hauling and storage

A significant cost element when using some feedstocks is hauling costs. This may well be straightforward when looking at municipal wastes or processing by-products as it merely requires computation of distance and number of truckloads to obtain a total cost. However, when examining energy crops as well as logging residues, the calculation becomes more complex. In particular, one must take into account the size of the feedstock need and the service area required to supply that feedstock. Here we present an approach to this.

First, we consider the size of the operation. A pyrolysis operation using 70,000t yr^{-1} of residue at 3.75t ha^{-1} with 5 per cent loss in hauling and storage requires a land area of 19,600ha for production under a diverse landscape where the proportion of maize cropping area to total land area is close to 20 per cent (as observed in key Iowa maize-producing counties). This implies a substantial hauling effort and associated cost.

We used McCarl et al's (2000) adaptation of French's (1960) procedure to approximate hauling cost, which assumes that the pyrolysis plant is in the centre of a square surrounded by a grid layout of roads. In turn, the hauling cost (H) and average hauling distance ($\bar{D}$) is given by the following formulae:

$$H = (b_0 + 2b_1\bar{D})S / Load$$

and

$$\bar{D} = \sqrt{\frac{S}{640Y}} \qquad [1]$$

where:
$\bar{D}$ is the average distance the feedstock is hauled in miles;
S is the amount of feedstock input for a biorefinery to fuel the plant, which we assume is 1Mt plus an adjustment for an assumed 5 per cent loss in conveyance and storage;
Load is the truck load size, which we assume to be 20t;
Y is the crop yield (3.75t ha^{-1}, or 1.5t $acre^{-1}$) multiplied by an assumed crop (maize) density of 20 per cent based on physical size versus maize density in mid-western US states that have a high intensity of maize production;
640 is a conversion factor for the number of acres per square mile;
b_0 is a fixed loading charge per truckload and is assumed to be US$90 per truckload for a 20t truck; and
b_1 is the charge for hauling including labour (per mile) and maintenance costs, which is assumed to equal US$2.20.

This calculation already includes 5 per cent yield loss, a service area of 19,600ha of cropland and an average hauling distance of 14.8km with a cost of US$6.86 t^{-1}.

The hauling cost is sensitive to the case at hand, which would vary across feedstocks and time as petroleum and other input costs change. Note that hauling costs can be cut in half, with much higher yields, as might exist with dedicated energy crops, while they fall about 10 per cent with increased feedstock density. The cost of hauling also has a great impact. Larger volumes increase hauling with, for example, a plant ten times the size experiencing hauling costs that are three times higher. Hauling cost in our case study amounts to about 20 per cent of the feedstock cost and would be reduced by being located close to a municipal waste source (although sorting, pre-treatment and drying costs may be required).

The assumptions used here are reasonable for agricultural commodities, but may not be so in the case of forest logging residues or other product hauling. The US Department of Agriculture (USDA) Forest Service has an alternative calculation procedure that is embedded in the Forest Residues Transportation Model (FoRTS) (USDA, 2008).

Finally, since crop residues such as those from maize are seasonal, we also assume the need for secondary storage and handling to be US$25 t^{-1} based on conversations with EPA personnel (pers comm, 2008). All of this together makes the feedstock cost US$59.44 t^{-1}. Since this and most of the assumptions above would vary with feedstock, a sensitivity analysis is performed across a spectrum of feedstock costs.

Costs of plant operations

Processing biomass into energy costs money. This cost is composed of a fixed and a variable cost component. The fixed cost would be an amortized one-year value of the equipment costs considering purchase price, loan terms, salvage value, etc. The variable cost would involve the costs per unit of production including labour, energy, materials handling etc. Both are highly uncertain given that this is largely a prospective technology that has not been applied at a commercial scale.

In constructing the cost estimate, we assumed the maize stover was delivered in a wet form on a whole basis. The overall system consists of three modules:

- *Module I:* biomass preparation (reception, drying, comminution, storage, feeding);
- *Module II:* fast pyrolysis to a bio-oil product (based on an integrated fluid-bed process using the biochar and syngas for process heat and fluidization, plus recovering the excess biochar for sale);
- *Module III:* electricity generation in a 2 × 7MWe dual fuel diesel engine fuelled by bio-oil and diesel.

For all three modules, costs associated with the system include an annual fixed cost of capital (assuming all of the capital is borrowed), as well as the annual operating costs of the plant. The operating costs include feedstock, labour, utilities, maintenance and overhead. The procedures under which these costs were derived were obtained from Peacocke et al (2006) and Aston University (2002).

A base plant size of 10t hr^{-1} dry feed input was used. The assumed fast pyrolysis process yields and feed properties are given in Table 19.1. The product yields are used in a plant design model to assess the mass and energy balance needed to ensure that the process is optimized for energy efficiency and product yields. The mass and energy balance outputs are employed to size the equipment, which is then costed. The equipment costs are based on actual or published costs in the US at the end of 2007. The lower

Table 19.1 *Fast pyrolysis of maize stover: Summary of modelling assumptions relative to fast pyrolysis at 10t hr^{-1} (dry feedstock basis)*

Feedstock	
Moisture (weight %, dry feed basis)	6.8
Ash (weight %, dry feed basis)	5.9
Reactor temperature (°C)	450
Yields (weight %, dry feedstock basis)	
Biochar	14.8
Organics (pyrolysis liquid)	59.8
Water (of pyrolysis)[1]	11.1
Pyrolysis gases	14.2
Gas yields (weight %, dry feedstock basis)	
CH_4	0.3
CO	3.8
CO_2	10.1

Note: 1 Excludes moisture present in the maize stover, which is recovered in the final liquid product.

Source: chapter authors

Table 19.2 *Summary of primary process inputs and outputs*

	Rate	*Units*
Process inputs		
Dried maize stover	10.0	t hr^{-1}
Water in feed	0.7	t hr^{-1}
Natural gas consumption (preheat burners)	31	kg hr^{-1}
Cooling water consumption	89	t hr^{-1}
Diesel for dual fuel engines	83.6	kg hr^{-1}
Process outputs		
Pyrolysis liquid out (includes water in feedstock)	7.81	t hr^{-1}
Excess char	444.6	kg hr^{-1}
Condensate to drain from process	103	kg hr^{-1}
Stack gases		
CO_2	3161	kg hr^{-1}
N_2	7321	kg hr^{-1}
H_2O	593	kg hr^{-1}
O_2	671	kg hr^{-1}
NO_x	1.7	kg hr^{-1}
SO_2	0.7	kg hr^{-1}
Power		
Gross electrical output	12.9	MW_e
Net electrical output	12.5	MW_e

Source: chapter authors

heating values of the char and recovered pyrolysis liquids are taken as 11.4MJ kg^{-1} and 16.1MJ kg^{-1}, respectively.

The pyrolysis data arise from experimental data on Iowa maize stover (J. Piskorz, RTI Ltd, Canada, personal communication, 2008). The pyrolysis biochar composition was identical to that in Zabaniotou and Ioannidou (2008), corrected for temperature and ash content. The biochar generated from maize stover is nearly 40 per cent by weight ash, which means that it may not be an ideal fuel for use in the biochar combustor and may have more value as a soil amendment. The process inputs and outputs are given in Table 19.2. All of the pyrolysis gases are used for process heat, fluidizing and are oxidized in the biochar combustor prior to discharge. All the produced pyrolysis liquids are, in turn, used for electrical power generation in dual-fuelled diesel engines, which is an area still under development. Note that it is also possible to make use of a modified gas turbine, avoiding the need for the diesel as a pilot fuel (alternatively, biodiesel could be used).

The associated estimated total capital costs are given in Table 19.3.

These capital costs are then amortized over the life of the project for use system cost estimation. Plant life is assumed to be 20

Table 19.3 *Total capital investment cost estimates for the three plant modules in US$ million (2007 basis)*

Plant component	*Capital cost (US$ million)*
Pre-treatment plant cost	3.6
Pyrolysis plant cost	10.6
Power generation capital costs	9.6
Total capital costs	23.7

Source: chapter authors

Table 19.4 *Annual costs of raw pyrolysis liquids production in US\$1000 yr^{-1} and variation with delivered feedstock cost*

	Cost delivered (US\$1000 t^{-1} (dry feedstock))			
	33	44	55	66
Pre-treatment capital cost (annualized)	367	367	367	367
Biomass pre-treatment operating cost	334	334	334	334
Cost pyrolysis capital	1080	1080	1080	1080
Feedstock cost	2310	3080	3851	4621
Utilities – water	3867	3867	3867	3867
Labour	900	900	900	900
Maintenance	423	423	423	423
Overhead	423	423	423	423
Annual liquids production cost	5624	6394	7164	7934

Source: chapter authors

years for 80 per cent availability with an interest rate of 12 per cent. Feedstock preparation costs are assumed to be US\$11.35 t^{-1} to dry, comminute, size and store the maize stover prior to pyrolysis. The liquids production costs for different maize stover costs are given in Table 19.4.

This involves the annual use of 70,080t of feedstock yielding 55,000t of bio-oil (including the water from pyrolysis and that in the feedstock), costing between US\$102 and US\$144 t^{-1} of bio-oil.

Costs for electricity generation consist of fixed and variable costs. The cost components are given in Table 19.5, where the first six rows account for the electricity cost only. In order to obtain total cost, we add the costs from the bio-oil and arrive at an annual total cost. We also divide by the electricity output to obtain a cost per kilowatt hour. Costs between 9.7 and 12.2 US cents kWh^{-1} are above current (2008) US prices for energy; but credits for reductions in greenhouse gas emissions have not yet been applied.

The same cost structure was used for the scenario of a slow pyrolysis plant where we used exactly the same fixed pyrolysis cost for 1t of biomass. For the slow pyrolysis scenario, fixed and operating costs for biomass pre-treatment were reduced by 50 per cent; but the other operating costs were assumed to remain the same per tonne of feedstock. These costs would vary under use of alternative feedstocks depending upon feedstock properties such as water content.

The fixed and operating costs for the modules are transformed into a per tonne feedstock basis by dividing by 70,080 for use in the calculations below.

Selling energy

As mentioned above, the pyrolysis plant yields bio-oil, syngas and electricity. For this case study, the relative yields are assumed to be 70 per cent bio-oil (including the feedstock water) and 13 per cent syngas for fast pyrolysis, and 30 per cent bio-oil and 35 per cent syngas for slow pyrolysis (see Chapter 8).

In the following, an approach is developed to value these items. For simplicity and based on available data, we assumed for both the fast and the slow pyrolysis scenario that the bio-oil and syngas were used in plant operation and electricity generation. In turn, it was assumed that the fast pyrolysis plant produced 1.25MWh t^{-1} of feedstock, while slow pyrolysis produced 25 per cent of the

Table 19.5 *Costs of electricity production in US\$1000 yr^{-1} and their variation with delivered feedstock cost: net electrical output is 12.52MW_e (427.3 US therms)*

	Cost delivered (US\$1000 t^{-1} (dry feedstock))			
	33	*44*	*55*	*66*
Capital amortization	978	978	978	978
Labour cost	124	124	124	124
Utilities	1507	1507	1507	1507
Overheads	188	188	188	188
Maintenance	235	235	235	235
Total electricity	3339	3339	3339	3339
Bio-oil cost (from Table 19.4)	5624	6394	7164	7934
Total cost of electricity and bio-oil	9742	10,512	11,282	12,052
Electricity production cost (US cents kWh^{-1})	9.7	10.5	11.4	12.2

Source: chapter authors

electricity of fast pyrolysis or 0.31MWh t^{-1}. In terms of cost, we compute that fast pyrolysis-related generation encounters an operating cost of US\$26.64 t^{-1} feedstock with a fixed cost of US\$20.18 t^{-1}. For slow pyrolysis, we assumed that the costs per unit of electricity were the same, and since the slow pyrolysis electricity output was only 25 per cent of the electricity generated by fast pyrolysis that the costs of electricity produced by slow pyrolysis were 25 per cent of that produced by fast pyrolysis.

This information is summarized in Table 19.6. At a sale price of US\$80 MWh^{-1}, we obtain the sales levels shown in Table 19.6 and observe that both fast and slow pyrolysis lose money based only on energy sales. This may explain why the practice is not in widespread use. However, in order to look at final profitability, one needs to also consider biochar and GHGs as a source of income along with other chemicals. The biochar and GHG aspects are evaluated in subsequent sections.

In general, we could have tried to value the bio-oil using a proxy-products approach as an equivalent to a conventional product. Even though the use of market prices is preferable for the commodities, the infant nature of the pyrolysis oils markets precludes this approach. For example, one could assume that the value of the bio-oil is proportional to the energy content and, thus, might be approximately 25 per cent of the heating oil price.

Net saleable biochar

In this analysis we assume that some of the biochar is used to supply energy for the fast pyrolysis plant, while all of it is sold in the slow pyrolysis plant. In particular, in the fast pyrolysis plant we assume the net yield is 0.0445t t^{-1} feedstock, while for slow pyrolysis we assume 0.35t t^{-1} feedstock.

Biochar as a soil amendment

Lehmann et al (2003) found that the application of biochar to soil led to a reduction of N leaching by 60 per cent and increases of crop productivity by 38 to 45 per cent, which we assume to translate into a 20 per cent saving in fertilizer and 10 per cent savings in irrigation and seeds. Others have found yield increases of up to 140 per cent on poor soils under recommended fertilization (Lehmann and Rondon, 2006).

Table 19.6 *Returns and costs (US\$ t^{-1} feedstock) as well as biochar yields (t t^{-1} feedstock) for fast and slow pyrolysis as value items are applied*

	Fast	*Slow*
Feedstock cost	–\$59.44	–\$59.44
Pyrolysis cost (modules I and II)	–\$46.82	–\$42.05
Generating cost (module III)	–\$43.26	–\$10.81
Electricity value	\$100.00	\$25.00
Net margin (electricity only)	–\$49.52	–\$87.30
Biochar yield	0.045	0.350
Biochar value	\$2.00	\$15.75
Biochar haul cost	\$0.39	\$3.07
Net margin (electricity + biochar)	–\$47.91	–\$74.63
GHG value	\$3.29	\$4.55
Net margin all	–\$44.62	–\$70.08

Source: chapter authors

Since we are using US Corn Belt data, we neglect the irrigation savings (since irrigation is not prevalent there) but assume that biochar applications lead to a 5 per cent yield increase of maize at an application rate of 5t ha^{-1}. For an average baseline maize grain yield of 4.07t ha^{-1} selling for US\$137.50 t^{-1}, the yield increase is US\$60 ha^{-1} yr^{-1}. Nutrients, lime and seed are also replaced. The value of that replacement based on application rates under Iowa crop budgets (Duffy and Smith, 2008) amounts to a saving of US\$73.4 ha^{-1} when biochar is applied. The net value across yield increases and input savings realized for crop production then calculates to US\$143.4 ha^{-1}.

The gains from biochar have been shown to persist somewhat permanently after the application as the biochar remains in the soil without rapid degradation. We thus treat this as an annuity capitalized forever at 5 per cent and multiply by 20 to obtain the net present value. However, we assume this gain only occurs the first time that the biochar is applied and that the biochar can be applied ten more times without further gain. Consequently, the net gain calculates to twice (equivalent to 20/10) the annual gain with a net present value of US\$286.80 ha^{-1}. We also assume based on examination of manure application costs that the application of biochar to soil would cost US\$20 t^{-1} for a net value of US\$236.80 ha^{-1}. This calculates to a biochar value of US\$47.36 t^{-1} at the field with an assumed application rate of 5t ha^{-1} or US\$32.94 t^{-1} at the plant after hauling costs are deducted. This value is below the approximate combustion value of the biochar as of this writing (Central Appalachian coal in August 2008 was worth about US\$139.30 for a short tonne, which contains 12,500MmBtu t^{-1}, while we assume biochar has approximately 4900MmBtu t^{-1} or 39.2 per cent of that of the coal, making its combustion value approximately US\$54.73 t^{-1}); but the price of coal has escalated radically in recent times (coal having been about US\$45 in December 2007, yielding a biochar combustion value of US\$17.70 t^{-1}).

The next step is to determine the proportion of land to which biochar can be applied, which varies in different assessments between a few tonnes to several tens of tonnes without universally applicable recommendation (Lehmann and Rondon, 2006). We set the biochar application rate at 5t ha^{-1}. The pyrolysis plants use crop residues from 19,600ha and after a biochar shrinkage of 5 per cent due to less than perfect recovery, conveyance, application, fire and other losses, the pyrolysis plants yield enough biochar annually to treat 3 per cent of the land under fast pyrolysis and 23.75 per cent under slow pyrolysis. (A major issue that this chapter will not try to resolve is that we assume this gain is repeated year after year with no change in hauling cost. In actuality, the biochar may be applied to different fields – even those of other crops or on fields without residue harvest – that are successively further away and may also be applied up to some maximum holding point for the soil. It is also possible that the second application enhances the gains.) Therefore, the value of applying biochar to the land where the residue is harvested calculates to US$7.15 ha^{-1} under fast pyrolysis and US$56.24 ha^{-1} under slow pyrolysis. This amounts to US$2.00 t^{-1} feedstock for fast pyrolysis and US$15.75 t^{-1} for slow.

Hauling biochar to the field

When biochar is applied as a soil supplement, it must be hauled back to the field. In this case, we assume an identical hauling distance to that obtained when calculating the cost for moving the feedstock and similar cost structure, but moving only the amount of the biochar. We also assume a different fleet of trucks is involved employing different handling procedures to control the combustibility of the biochar. Thus, we do not factor in backhauling. Rather, we charge US$1.38 km^{-1} for a round trip and also increase the fixed cost per truckload by 50 per cent. This yields a hauling cost estimate of US$8.78 t^{-1} of biochar when using fast or slow pyrolysis. This biochar hauling cost amounts to US$0.39 t^{-1} of the raw maize residue feedstock under fast pyrolysis and US$3.07 t^{-1} of feedstock when using slow pyrolysis (note this may not be appropriate as the fast pyrolysis biochar bulk density is likely much lower than that of the slow pyrolysis biochar).

In turn, and as summarized in Table 19.6, after adding in the value of the biochar offset by its hauling cost we find that there is a net US$47.91 loss for fast pyrolysis and a loss of US$74.63 for slow pyrolysis.

GHG offset

The net GHG effect is another possible component of value. The pyrolysis with biochar prospect is emitting GHGs based on fossil fuel use during residue harvest, as well as the C consequences of residue removal, nutrient replacement, feedstock hauling, feedstock transformation, biochar hauling and biochar application. It is GHG reducing in that it employs electricity generation from a renewable source, recycling C rather than emitting the C stored in fossil fuels, along with biochar-induced reductions in nutrient use and increases in sequestration.

Residue removal and sequestration loss. In terms of the original fields from where the residue is removed, we assume that the residue removed contains 45 per cent C, of which 2 per cent is taken from the sequestered soil stock by its removal. Thus, we have 0.09t C sequestration reduction per tonne of crop residue removed. Converting these values to CO_2, this results in a loss of 0.033t CO_2 t^{-1} removed. We also assume, based on Kim et al (2008), that this is an impermanent form of C and is only worth 50 per cent of more permanent forms.

Nutrient replacement. Crop residue removal may also cause an increased need for nutrients such as N, P and K, as discussed earlier. This causes additional GHG emissions in the manufacture and use of fertilizers. In order to estimate these impacts, we used the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) assumptions for the GHG releases involved in manufacturing these inputs (Wang, 1999; Argonne National Lab, 2006; Wang et al, 2007), plus the amounts for nitrous oxide (N_2O) emissions calculated after IPCC (2006). This results in increased emissions of 0.019t CO_2 equivalent (CO_2e) when 1t of residue is removed to replace the nutrients therein. We also used the GREET assumption of 0.011t CO_2e t^{-1} of maize residue for fossil fuel emissions during harvest collection and movement to the farm gate.

Feedstock and biochar transport. Hauling emissions also need to be factored in and we did this assuming that a diesel-powered truck was used travelling 2.133km L^{-1} diesel. Overall, hauling calculated to a total travel distance of 480,000km along with 1440km for biochar under fast pyrolysis and 7.960km under slow pyrolysis. This amounted to 0.0021t and 0.0024t CO_2e t^{-1} feedstock removed for fast and slow pyrolysis, respectively.

Plant operation. Fossil fuel is also used in operating the pyrolysis plant. We assume that the operation requires 217t of natural gas and 586t of diesel, with about two-thirds of the 15 per cent yield of biochar burned for fuelling the plant and the slow pyrolysis syngas used for fuel. Using GREET emission factors, we arrive at an estimate that plant fossil use generates an emission level of 0.33t CO_2e t^{-1} feedstock. We reduce the diesel use to 25 per cent for the slow plant since it is used in the generation phase and only 25 per cent of the power is generated under slow pyrolysis.

Fossil fuel offset. Biofuels are recycling C. Namely, as crops grow they absorb CO_2 from the atmosphere and accumulate the C in the body of the plant. At the time of combustion, this C is released. Consequently, the emissions from using the bio-oil and syngas in generating biochar and electricity are recycled C that is not a net addition (as would be the case if fossil fuels were used releasing C long stored in the ground). As a consequence, we credit for the C that would have been used to generate the electricity yielded by the plant (see Chapter 18). We assume that the electricity replaces electricity that would have been generated in a coal-fired plant. Under the GREET assumptions and the electricity levels given above, this yields an offset rate of 0.765t CO_2 t^{-1} feedstock under fast pyrolysis and 0.191t CO_2 t^{-1} under slow.

Reduced inputs. Application of biochar also reduces input needs at the farm level as a consequence of improved nutrient use (see Chapters 5 and 15), saving the emissions from making and applying nutrients, as well as the N_2O emissions arising from nitrification and denitrification that derive from fertilized fields (see Chapter 13). We compute the saved emissions from this process as 0.004t CO_2e t^{-1} feedstock for fast and 0.028t CO_2e t^{-1} for slow pyrolysis.

Sequestration enhancement. Biochar resides in the soil for a long period of time (see Chapter 11) and consists of approximately 75 per cent C. As such, biochar sequesters the C held in the soil in a manner that overcomes many of the permanence and volatility issues that commonly arise in criticisms of biological sequestration possibilities (see discussion in West and Post, 2002; Post et al, 2004; Smith et al, 2007; Kim et al, 2008). Thus, we credit the total C content of the biochar as a sequestration offset and this amounts to a credit of 0.122t CO_2e t^{-1} feedstock for fast and 0.963t CO_2e t^{-1} for slow pyrolysis.

Net balance. The balance of all C credits is reflected in Table 19.7 and equals a net offset of 0.823t CO_2e t^{-1} of feedstock for fast pyrolysis and 1.113t CO_2e t^{-1} for slow pyrolysis. This amounts to 108 per cent of the coal equivalent emissions for the electricity generated under fast pyrolysis and 595 per cent for

Table 19.7 *Estimated GHG offsets (in $CO_2e\ t^{-1}$ of feedstock) for fast and slow pyrolysis*

Category	*Discount*	*Fast pyrolysis*	*Slow pyrolysis*
Collect feedstock on farm		0.011	0.011
Haul feedstock and biochar		0.002	0.003
Replace lost nutrients on farm		0.007	0.007
Save fuel in tillage		–0.018	–0.018
Operate pyrolysis		0.033	0.033
Reduce nutrients used on farms		–0.004	–0.028
Credit for displacement of coal electricity		–0.765	–0.191
Sequestration lost due to residue removal	0.5	0.033	0.033
Sequestration gain from biochar		–0.122	–0.963
Net GHG effect		–0.823	–1.113

Source: chapter authors

slow pyrolysis. Therefore, the offset efficiency is greater than the power offset due to the sequestration and nutrient offset elements.

C leakage. Also of significance, the feedstock needed for pyrolysis is not dependent upon food crops. Such competition has been the subject of growing recent concern in the context of ethanol and biodiesel production, particularly in terms of leakage in the form of international replacement of lost marketed production and C debts (Fargione et al, 2008; Searchinger et al, 2008). Rather, under pyrolysis, less competition may well exist as by-product residues can be used. In small-scale applications, the heat produced from the pyrolysis unit could also provide energy for on-farm use, such as heat and electricity for lighting, fans, refrigerators, milking machines, etc. No estimates are provided here for this effect.

GHG value. Finally, let us turn our attention to the value of the GHG offset. We can use contemporary prices of about US\$4 t^{-1} CO_2e on the Chicago Climate Exchange or about US\$35 on the European Exchange as indicators of potential future value. We use US\$4 in our summary calculations below and consider higher values in the sensitivity analysis section.

Totality of value

Table 19.8 summarizes the calculations in the above sections, yielding a total estimate of value. This indicates for the numerous assumptions made in this chapter that the fast and slow pyrolysis power plants are both unprofitable under current conditions, with the slow plant being less so, largely due to its higher value energy sales, with the biochar value also making a difference to some extent. An investigation of sensitivity to a number of the above assumptions is pursued in the next section.

Table 19.8 *Economic assumption and results summary with economic results reported per tonne of feedstock*

	Fast pyrolysis	*Slow pyrolysis*
Main assumptions		
Size of plant (L yr^{-1})	70,080	70,080
Yield bio-oil (%)	70	30
Yield syngas (%)	15	35
Yield biochar (%)	15	35
Land used (ha)	19,600	19,600
Average feedstock hauling distance (km)	14.8	14.8
Results (US$ t^{-1} feedstock)		
Cost of feedstock	−$59.44	−$59.44
Value of energy created	$100.00	$25.00
Value of biochar	$2.00	$15.75
Biochar hauling cost	−$0.39	−$3.07
Fixed cost of facility	−$34.13	−$21.28
Operating cost of facility	−$55.95	−$31.58
GHG market effect	$3.29	$4.55
Net value	−$44.62	−$70.08

Source: chapter authors

Sensitivity analysis

The above assumption-laden procedure requires a sensitivity analysis to help draw inferences about how critical various factors are. Several investigations were performed, leading to the following results given that all other elements are held constant:

- Fast pyrolysis is profitable as long as the electricity price rises above US$115 MWh^{-1} while slow pyrolysis requires a price above US$304 MWh^{-1}. Higher energy prices clearly favour fast pyrolysis.
- Fast pyrolysis becomes profitable when the GHG price is above US$58 t^{-1} CO_2e, which is substantially above the level of the European price (30 Euros t^{-1} in late August 2008 or US$41 t^{-1} CO_2e), meaning that European implementations are closer to being profitable than those in the US if the biochar and GHG incomes can be captured. The CO_2e price would need to rise above US$71 t^{-1}, or more than 25 per cent above the European price, before slow pyrolysis is profitable.
- There are a wide range of experimental findings on the yield implications of biochar application. We assumed that biochar application increased crop yield by 5 per cent on fields to which it was applied and only led to gains once. Under a more substantial increase of 43 per cent, slow pyrolysis becomes profitable. Fast pyrolysis gains at a much slower rate, requiring a 193 per cent yield increase to become more profitable.
- If biochar prices are high, then the value particularly of slow pyrolysis increases. In other words, when the biochar value exceeds US$246 t^{-1}, slow pyrolysis

becomes profitable (Chapter 9 reports values in the neighbourhood of US\$450 t^{-1}; but this is in a new market and the large quantities arising under large-scale production typically lower such values substantially). Fast pyrolysis requires a value in excess of US\$1047 t^{-1}.

- The capital costs of construction are rather uncertain as are, to a lesser extent, the operating costs. Lowering the total plant fixed plus operating cost by 49 per cent or more makes fast pyrolysis profitable. While slow pyrolysis becomes more profitable, the feedstock alone exceeds the value of products under base assumptions and no pure operating cost change can make it profitable.
- It is possible that feedstocks will be available that can be obtained for tipping fees or under other arrangements. If we reduce the feedstock costs, both pyrolysis options become more profitable. For fast pyrolysis, feedstock costs would need to decrease to US\$14 or less to be profitable. In the case of slow pyrolysis, this alone cannot make the prospect profitable. Rather, a US\$11 t^{-1} fee (a subsidy for operations) would be needed to be profitable.

Omitted factors

The biochar/pyrolysis possibility is one of several ways in which biomass could be used to achieve net reductions in GHG emissions. If cellulosic conversion to ethanol becomes practical and profitable, then this process would compete for biomass feedstocks. There is also the possibility of using crop residues to generate electricity directly. In addition, both biochar production and residue-based generation could be coupled with the CO_2 capture and geologic sequestration. Even though none of these pathways have been implemented at a large scale, the biochar pathway uses technologies that are likely to be available in a relatively short timeframe and, thus, may be an important current action. Cellulosic conversion to ethanol and geologic carbon dioxide capture and storage (CCS) are currently not available.

If the value of crop residue becomes high enough, other sources of biomass, such as switchgrass, fast-growing poplars, logging residues and milling residues, will become available. Future studies should include alternative feedstocks, as well as the possibility of multiple feedstocks. Additionally, while many factors were considered above, several other factors, such as changes in erosion, water use, water quality and altered air pollution emissions under biofuels versus fossil fuels, were not covered and warrant closer attention in future studies.

A final omitted item meriting discussion involves the nature and dynamic of the crop–biochar production relationship. Very simplifying assumptions were made above on yield increases/nutrient decreases in association with biochar application. It was also assumed that once the biochar was applied, it would permanently enhance yields and lower input requirements. Furthermore, after the first application, it was assumed that no more gains could be achieved. These are undoubtedly not entirely accurate assumptions, and future work might include diminishing returns to applications and dynamics of applications and responses.

Conclusions

Pyrolysis and associated biochar are valuable in terms of nutrient reductions, yield increases, bioenergy products and GHG offsets. These are partly offset by the costs of production, hauling and processing, along with some increases in GHG emissions. An approach was developed for analysing the profitability of such a case and implemented for maize residue.

On balance in our maize residue case study (which is assumption laden, relying on highly uncertain data), we found fast and slow pyrolysis to be currently unprofitable. We find these results particularly sensitive to crop yield enhancement, plant fixed/operating costs, and GHG and energy prices. We do find the value of biochar applied to soil is close to its value as an energy source. However, under current European levels of GHG offset prices, biochar use as a soil amendment in agriculture already exceeds its combustion value.

References

Argonne National Laboratory (2006) *Fuel Cycle Assessment of Selected Bioethanol Production Pathways in the United States*, Report, Argonne National Laboratory, Chicago, IL

Aston University (2002) *Development of Advanced Fast Pyrolysis Processes for Power and Heat*, JORS-CT97-0197, Final report submitted to the European Commission, Brussels

Baum, E. and Weitner, S. (2006) *BIOCHAR Application on Soils and Cellulosic Ethanol Production*, Clean Air Task Force State Climate Network, Boston, MA

Bridgwater, A. V. and Peacocke, G. V. C. (2002) 'Fast pyrolysis processes for biomass', *Renewable and Sustainable Energy Reviews*, vol 4, pp1–73

Bridgwater, T. (2005) 'Fast pyrolysis based biorefineries', Paper presented at the Annual Meeting of the American Chemical Society, Washington, DC, 31 August 2005, http://membership.acs.org/P/PETR/2005-Biorefineries/Presentation-10.pdf

Caputo, A. C., Palumbo, M., Pelagagge, P. M. and Scacchia, F. (2005) 'Economics of biomass energy utilization in combustion and gasification plants: Effects of logistic variables', *Biomass and Bioenergy*, vol 28, pp35–51

Czernik, S. and Bridgwater, A. V. (2004) 'Overview of applications of biomass fast pyrolysis oil', *Energy and Fuels,* vol 18, pp590–598

Demirbas, A. and Arin, G. (2002) 'An overview of biomass pyrolysis', *Energy Sources*, vol 24, pp471–482

Duffy, M. and Smith, D. (2008) *Estimated Costs of Crop Production in Iowa – 2008*, Report, Iowa State University, IA, www.extension.iastate.edu/AGDM/crops/html/a1-20.html

Fargione, J., Hill, J., Tilman, D., Polasky, S. and Hawthorne, P. (2008) 'Land clearing and the biofuel carbon debt', *Science*, vol 319, pp1235–1238

Fife, L. and Miller, W. (1999) *Rice Straw Feedstock Joint Venture, Rice Straw Feedstock Supply Study for Colusa County, California*, Western Regional Biomass Energy Program, Lincoln, NE

French, B. C. (1960) 'Some considerations in estimating assembly cost functions for agricultural processing operations', *Journal of Farm Economics*, vol 62, pp767–778

IPCC (Intergovernmental Panel on Climate Change) (2006) *Guidelines for National Greenhouse Gas Inventories*, IPCC, Cambridge University Press, Cambridge, UK, www.ipcc–nggip.iges.or.jp/public/2006gl/index.htm

Kim, M.-K., McCarl, B. A. and Murray, B. C. (2008) 'Permanence discounting for land-based carbon sequestration', *Ecological Economics*, vol 64, pp763–769

Lehmann, J. and Rondon, M. (2006) 'Biochar soil management on highly-weathered soils in the humid tropics', in N. Uphoff (ed) *Biological Approaches to Sustainable Soil Systems*, CRC Press, Boca Raton, US, pp517–530

Lehmann, J., da Silva Jr., J. P., Steiner, C., Nehls, T., Zech, W. and Glaser, B. (2003) 'Nutrient availability and leaching in an archaeological Anthrosol and a Ferralsol of the Central Amazon basin: Fertilizer, manure and charcoal amendments', *Plant and Soil*, vol 249, pp343–357

McCarl, B. A., Adams, D. M., Alig, R. J. and Chmelik, J. T. (2000) 'Analysis of biomass fueled electrical power plants: Implications in the agricultural and forestry sectors', *Annals of Operations Research*, vol 94, pp37–55

NSWMA (2005) *NSWMA's 2005 Tip Fee Survey*, NSWMA Research Bulletin 05–3, http://wastec.isproductions.net/webmodules/webarticles/articlefiles/478–Tipping%20Fee%20Bulletin%202005.pdf, accessed 31 August 2008

Peacocke, G. V. C., Bridgwater, A. V. and Brammer, J. G. (2006) 'Techno-economic assessment of power production from the Wellman Process Engineering Ltd and BTG fast pyrolysis processes', in A. V. Bridgwater and D. G. B. Boocock (eds) *Science in Thermal and Chemical Biomass Conversion*, CPL Press, vol 2, pp1785–1802

Perlack, R. D., Wright, L. L., Turhollow, A., Graham, R. L., Stokes, B. and Erbach, D. C. (2005) *Biomass as Feedstock for a Bioenergy and Bioproducts Industry: The Technical Feasibility of a Billion-Tonne Annual Supply*, US Department of Energy and US Department of Agriculture, Forest Service, Washington, DC, US

Polagye, B. L., Hodgson, K. T. and Malte, P. C. (2007) 'An economic analysis of bio-energy options using thinnings from overstocked forests', *Biomass and Bioenergy*, vol 31, pp105–125

Post, W. M., Izaurralde, R. C., Jastrow, J., McCarl, B. A., Amonette, J. E., Bailey, V. L., Jardine, P. M., West, T. O. and Zhou, J. (2004) 'Enhancement of carbon sequestration in US soils', *Bioscience*, vol 54, pp895–908

Read, A. D., Phillips, P. and Robinson, G. (2008) 'Landfill as a future waste management option in England: The view of landfill operators', *Geographical Journal*, vol 164, pp55–66

Ringer, M., Putsche, V. and Scahill, J. (2006) *Large-Scale Pyrolysis Oil Production: A Technology Assessment and Economic Analysis*, National Renewable Energy Laboratory, NREL/TP-510-37779, www.nrel.gov/docs/fy07osti/37779.pdf

Searchinger, T., Heimlich, R., Houghton, R. A., Dong, F., Elobeid, A., Fabiosa, J., Tokgoz, S., Hayes, D. and Yu T.-H. (2008) 'Use of US croplands for biofuels increases greenhouse gases through emissions from land-use change', *Science*, vol 319, pp1238–1240

Smith, G. A., McCarl, B. A., Li, C. S., Reynolds, J. H., Hammerschlag, R., Sass, R. L., Parton, W. J., Ogle, S. M., Paustian, K., Holtkamp, J. A. and Barbour, W. (2007) in Z. Willey and W. L. Chameides (eds) *Harnessing Farms and Forests in the Low-Carbon Economy: How to Create, Measure, and Verify Greenhouse Gas Offsets*, Duke University Press, Durham, NC

USDA (US Department of Agriculture) (2008) *Forest Residue Trucking Simulator (Version 5)*, US Forest Service, www.srs.fs.usda.gov/forestops/biomass.htm, accessed 20 May 2008

Wang, M. (1999) *GREET 1.5 – Transportation Fuel-Cycle Model, Volume 1: Methodology, Development, Use, and Results*, ANL/ESD-39, vol 1, Center for Transportation Research, Argonne National Laboratory, Argonne, IL

Wang, M, Wu, M. and Hong, H. (2007) 'Life-cycle energy and greenhouse gas emission impacts of different maize ethanol plant types', *Environmental Research Letters*, vol 2, article number 024001

West, T. O. and Post, W. M. (2002) 'Soil organic carbon sequestration rates by tillage and crop rotation', *Soil Science Society of America Journal*, vol 66, pp1930–1946

Wright, M. M., Brown, R. C. and Boateng, A. A. (2008) 'Distributed processing of biomass to bio-oil for subsequent production of Fischer-Tropsch liquids', *Biofuels, Bioprocessing, and Biorefining*, vol 2, pp229–238

Zabaniotou, A. and Ioannidou, O. (2008) 'Evaluation of utilization of maize stalks for energy and carbon material production by using rapid pyrolysis at high temperature', *Fuel*, vol 87, pp834–843