CLIMATE-POSITIVE FARMING REVIEWS

A review of pyrolysis and biochar as climate-positive biomass technologies for the Scottish Uplands

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Executive summary

This report reviews the potential of pyrolysis and biochar as climate-positive technologies in Scottish upland farming. **Pyrolysis** is the process of heating biomass in a low-oxygen environment. Once started, the process produces more energy than it uses and can thus be a source of useful heat. The final residue is a carbon-rich solid material with a cellular structure, similar to charcoal, called biochar. **Biochar** has physical and chemical properties that make it an interesting soil amendment and agricultural input. In addition, biochar resists decay in the soil and thereby constitutes a form of long-term carbon storage. In the upland farming context, a technology which promises to convert biomass into heat while providing a useful agronomic input and increasing soil carbon warrants further investigation. Key findings of this review are that:

Biochar is most **climate-positive**…

1. …When the surplus heat from the pyrolysis process is captured to replace heat from fossil-fuelled boilers.
2. …When the biochar can act as a long-term store of carbon in the soil. This is most pronounced for woody biochars applied to cooler, drier and more acidic soils.

Biochar's **agricultural benefits** include…

3. …Replacing liming agents on acidic soils and replacing fertilisers or improving fertiliser use efficiency on nutrient-poor soils. These benefits are most pronounced for herbaceous biochars, which contain more ash.
4. …Improving the efficiency of fermentation processes such as composting, ruminant digestion and manure management.
5. …Significantly improving crop yields, in specific circumstances that are as yet under-researched. There is some indication that biochar that has been aged outdoors, or pre-treated in other ways, may be more beneficial for crop yields.

However, there are **technical challenges**…

6. …Pyrolysis is most efficient with chipped or shredded feedstock, which must also be as dry as possible. This has handling and storage implications.
7. … The smallest commercially available pyrolysis units are likely to be over-sized for farms in the Scottish climate and do not run well on partial loads.

If the technical challenges can be overcome, the best case in the Scottish Uplands would appear to be biochar from forestry wastes, pyrolyzed to optimise for high carbon stability and high heat production and applied to cool, acidic soils in order to boost tree or grass growth after having been co-composted with livestock manures.

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Introduction

Conventional approaches to biomass energy treat it as a carbon-neutral technology, assuming that carbon sequestration through photosynthesis offsets the emissions from combustion (see for example, Dept for Business Energy & Industrial Strategy, 2020). This takes a linear, fundamentally unsustainable, view of biomass production. A more sustainable approach to biomass energy would explicitly consider what is returned to the soil to support future photosynthesis. Table 1 gives some examples.

Table 1: Overview of biomass energy technologies

Technology	Biomass input	Energy outputs	Return to soil	Contributions to soil food web			State of science
				Nutrients	Metabolic Energy	Structure	
Combustion	Firewood or other dry biomass	High heat	Ash	Yes, but v. low pH	No	No	Established
Biodiesel	Oilseed rape	Liquid fuel	Oilseed cake	Yes	Yes	Some	Established
Anaerobic digestion	Manure, green biomass	Biogas fuel	Digestate	Yes	Some	Some	Established
Pyrolysis	Woodchips or other small dry biomass	High heat	Biochar	Yes	No	Yes	Emerging
Compost heat	Manures wood shavings, other biomass	Low heat over a long period	Compost	Yes	Yes	Some	Under-researched

While these all warrant further research, this report focuses on pyrolysis and biochar. Wood pyrolysis is the process of heating woody biomass in a reduced oxygen environment. This releases combustible gases and liquid condensates in varying proportions. The gases can be burned to generate additional heat to maintain the pyrolysis reaction. Once started, the process produces more energy than it uses and can thus be a source of useful heat. It is also possible to pyrolyse many other kinds of organic matter. The final residue is a carbon-rich solid material with a cellular structure, similar to charcoal, called biochar.

Biochar has applications in agriculture, usually as a soil amendment, though it can also be used as an additive in animal feed or composting processes. Biochar's physical and chemical properties – a high porosity and surface area as well as many positively-charged surfaces –

mean that it can improve water and nutrient retention in soil. In addition, biochar resists decay in the soil and thereby constitutes a form of long-term carbon storage.

In the upland farming context, a technology which can convert woody materials into heat and a useful agronomic input while also increasing soil carbon storage warrants further investigation. This report outlines the current state of theory and practice at the time of writing, especially in Scotland.

Climate Impact

Pyrolysis and biochar are increasingly being promoted as negative emissions technologies (NETs) with global potential to contribute to climate change mitigation (Smith, 2016; Sykes et al., 2020; Werner et al., 2018; Woolf et al., 2010) and will likely be included in future IPCC reports. Assessing the climate impact of pyrolysis-biochar is complex because there are several co-dependent processes at work, each of which is highly context-specific. As an overview, there are three basic climate impact pathways:

1. **Pyrolysis is a source of heat** that can replace other sources of heat, with the climate impact depending on the specific pyrolysis process and the source of heat being replaced.
2. **The resulting biochar is a long-lived store of carbon**, with its longevity influenced by the original biomass, the specific pyrolysis process and by the type of soil it is applied to.
3. **The biochar has an impact on carbon cycling** in the ecosystem, by affecting rates of photosynthesis and soil respiration.

These three impact pathways are discussed below.

Climate Implications of the Pyrolysis Process

Pyrolysis processes and outputs are largely determined by the temperature of the process (McLaughlin, 2020). Biomass is a mixture of carbon-containing organic compounds (mainly lignin and cellulose) with a lot of moisture. As heat is applied to biomass in a low-oxygen environment and the temperature increases up to about 200°C, first the moisture is driven off. As one continues to apply heat to reach 350-400°C, the biomass becomes completely black and the constituent organic compounds begin to break down, releasing combustible gases and liquids (“syngas” and “bio-liquids”). In most pyrolysis units, these combustible gases are swept out and burned in a separate chamber to keep supplying heat to the process, making it self-sustaining. The carbon that remains in the material consolidates into graphene layers, creating the highly porous texture of biochar. If the temperature rises even further, at around 600°C these graphene layers start collapsing into ordered sheets and the porosity reduces again.

The output of a pyrolysis process is therefore defined largely by its temperature. A 300°C pyrolysis process produces charcoal: it still contains a lot of combustible compounds, which makes it a good fuel. Biochar is typically produced at pyrolysis temperatures of 500-600°C, which will drive off as many volatile compounds as possible but will not start to create graphene sheets, thus resulting in a porous, high-carbon structure.

From the above description it follows that:

- **Biochar yield** decreases as the pyrolysis temperature increases because the biomass breaks down more and has released part of its mass as syngas and bio-liquids.
- As the syngas and bio-liquids are driven off and combusted, higher temperature pyrolysis processes also eventually produce more **useful heat**.
- **Biochar longevity in the soil** increases when processed at greater temperatures because the carbon that remains is in chemical forms that resist decay, mainly graphene sheets.
- The **adsorptive capacity** of the biochar is optimised at a pyrolysis process temperature of 500-600°C, because the tars have been driven off, but the graphene sheets have not started to collapse.

Additional considerations include the residence time of the biomass in the pyrolysis chamber, as well as the circulation rate (or "sweep") of gases through the chamber. Each of these variables then affects the climate impact of the pyrolysis-biochar process. Optimising for one variable necessarily entails trade-offs in another.

It is clear for example, that optimising for heat production alone would mean combusting the biomass, rather than pyrolyzing it. This would react all the carbon in the wood with oxygen, release the maximum amount of energy, but leave only ash and no biochar. Pyrolysis thus necessarily entails an "energy penalty" (Azzi et al., 2019, 2020) versus conventional biomass energy, which must be outweighed by other benefits in the use of the biochar in order to yield a net positive climate impact.

The energy source that is being displaced by pyrolysis is also very important in assessing the climate benefit (Thornley et al., 2015). For example, when compared against a heat pump supplied by solar or wind electricity, heat from pyrolysis would have less climate-benefit than when compared against heat from a kerosene or oil-fired boiler.

This highlights how the assumptions made regarding the baseline scenario, i.e. what would happen to the biomass if it was not pyrolyzed and how the heat would be produced if not from pyrolysis, have a great influence on the final climate impact of biochar. The lifecycle assessment approach (Azzi et al., 2019, 2020; Roberts et al., 2010; Thornley et al., 2015) allows these baseline assumptions to be made explicit. While these generally find that in many applications pyrolysis-biochar is net climate-positive, they also show that the impact is always context-specific, with technological and biological considerations.

Key Finding 1: Biochar is most climate-positive when the surplus heat from the pyrolysis process is captured to replace heat from fossil-fuelled boilers.

Finally, all technologies have an amount of "embodied energy" – i.e. the energy required to manufacture and install the equipment. This energy has an associated carbon footprint, which must be offset by carbon savings during operation in order to result in net emissions reductions. Disregarding the "embodied carbon" associated with a technology can result in over-optimistic assessments of its climate change mitigation potential. None of the research reviewed here analyses the embodied energy or carbon of pyrolysis-biochar systems.

Biochar as a Long-term Soil Carbon Store

Biochar's main climate benefit is its potential to act as a long-term store of carbon in the soil. There is at least an order of magnitude difference in decomposition rates between charred and uncharred biomass (Lehmann et al., 2009). Radiocarbon dating has found that charred biomass from forest fires can persist for more than 10,000 years in soils (Lehmann et al., 2009). However, while this gives an indication of biochar's potential longevity as a soil carbon store, it does not indicate how much of the original carbon has already been returned to the atmosphere. There is a great deal of research ongoing to answer this question, but for the purposes of this report and for climate change mitigation more generally, it is sufficient to recognise that biochar can store carbon on the decadal, centennial and millennial timescales relevant for combating climate change.

In addition, it is worth noting that biochar residence times in soil can be increased by a range of production factors (longer pyrolysis time and temperatures above 400°C) and soil factors (acidic, drier, cooler and less oxygenated soils) (Lehmann et al., 2009; Stensson, 2018; Tisserant & Cherubini, 2019). In addition, biochar produced from woody materials is generally more recalcitrant while biochar produced from herbaceous materials produces less recalcitrant biochar but more nutrient-rich ash (Stensson, 2018).

Key Finding 2: Biochar is most climate-positive when the biochar can act as a long-term store of carbon in the soil. This is most pronounced for woody biochars applied to cooler, drier and more acidic soils.

Impact of Biochar on Ecosystem Carbon Cycles

As noted above, the third potential climate impact of biochar is its effect on carbon cycling in an ecosystem. Figure 1 illustrates the potential impact on a healthy, unharvested ecosystem (blue items) of harvesting biomass for pyrolysis and applying the resulting biochar to the soil (orange items).

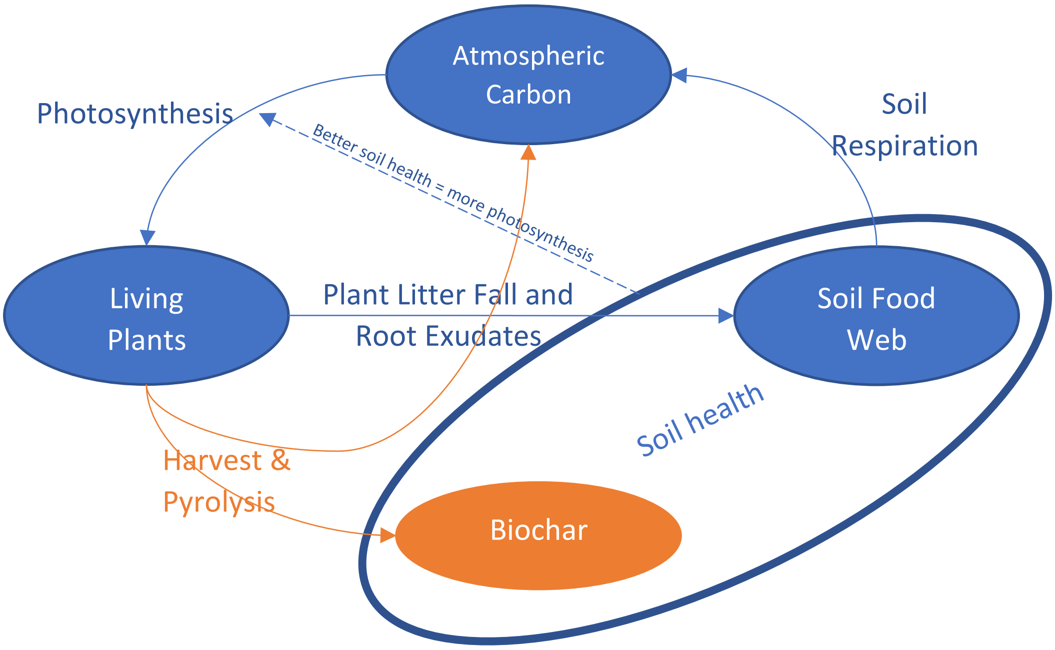

Figure 1: Simplified carbon flows in an ecosystem

The conceptual model shows how biochar application has an impact on soil health, which in turn affects rates of soil respiration and rates of photosynthesis. The first part of that relationship, the effect of biochar on soil health, is well understood. Biochar tends to have positive effects on soil structure, water holding capacity, pH, nutrient retention and bioavailability, toxicity and bioavailability of hazardous substances, soil thermodynamics and conditions for soil biota (Stensson, 2018). However, linking these biochar-induced increases in soil health to definite increases in photosynthesis and thus carbon draw-down is more difficult. The impacts of biochar application on crop yields are discussed further in the next section on Agricultural Use of Biochar, but it should be noted that increased crop yields are not directly equivalent to increased carbon draw-down through photosynthesis. Likewise, research on biochar’s effects on soil respiration and greenhouse gas fluxes is also inconclusive, leading two reviewers - Smith (2016) and Stensson (2018) - to discount them in their analyses. While biochar may have climate-positive effects on (agro-)ecosystem carbon cycles, it currently seems prudent to make the case for it as a climate-positive technology based on heat production and long-term soil carbon storage alone, as others have done (e.g. Azzi et al., 2020).

Agricultural use of Biochar

Biochar has been applied to agricultural soils for thousands of years, most famously by indigenous Amazonians, who built up the “Amazonian Dark Earths” - fertile soils that outlived the cultures that created them (Woods et al., 2009). There is also a growing body of literature on more recent agricultural applications for biochar. This report reviews the three main agronomic effects of biochar in turn.

Liming and Fertilising Effects

In a comprehensive meta-analysis, biochar application was found to increase crop yields in tropical soils by an average of 25% but to have no significant effect on crop yields in temperate soils (Jeffery et al., 2017). This is thought to be because biochar’s positive effects in tropical areas arise from its soil liming and fertilising (from the ash fraction) properties. In most temperate agricultural contexts, acid soil pH and nutrient availability are generally not limiting factors due to the underlying nature of most temperate soils as well as the regular application of soil amendments in many agricultural land holdings.

Key Finding 3: Biochar’s agricultural benefits include replacing liming agents on acidic soils and replacing fertilisers or improving fertiliser use efficiency on nutrient-poor soils. These benefits are most pronounced for herbaceous biochars, which contain more ash.

Biochar’s Effect on Fermentation Processes

Biochar has other uses in agricultural systems beyond its potential as a soil amendment. A recent study (Teodoro et al., 2020) shows that adding biochar can speed up a composting process, reducing odours, increasing the stability of the final product, neutralising its pH and increasing its moisture retention compared to normal compost. Similarly, a review by Kammann et al. (2017) concludes that biochar has potential applications in manure management, in composting and as a ruminant feed additive, but that more research is needed to establish the mechanisms by which benefits arise and what type of biochars are most useful. Research on using biochar as a ruminant feed additive (mixed with molasses) is still emerging but early results demonstrated benefits for livestock, for the soil and for the farm accounts (Joseph et al., 2015).

Key Finding 4: Biochar’s agricultural benefits include improving the efficiency of fermentation processes such as composting, ruminant digestion and manure management.

Biochar’s Effect on Crop Yields

Meta-analyses such as the one conducted by Jeffery et al. (2017) tend to hide the variability between individual trials, especially in an emerging field where the complex interactions between biochar application and crop responses are not fully understood. For example, Hammond et al (2013) report a doubling in spring barley yield in a 2011 field trial in Midlothian, Scotland. They hypothesise that this could be due to the fact that the biochar was aged outdoors for several years prior to being applied, a supposition echoed by other authors reviewed by Stensson (2018). This suggests that more research into biochar pretreatment, before it is applied to the soil, could lead to more consistent agricultural benefits.

It should be noted that very few studies on biochar application to temperate soils (of the 20 reviewed by Stensson, 2018 for example) find any significant negative effects on crop yields. The threshold for negative effects to predominate seems to be an application rate of about 30t/ha, probably due to excessive liming effects (Hammond et al., 2013). However, it would be important to assess cumulative effects from regular application and build-up in the soil.

Key Finding 5: Biochar's agricultural benefits include significantly improving crop yields, in specific circumstances that are as yet under-researched. There is some indication that biochar that has been aged outdoors, or pre-treated in other ways, may be more beneficial for crop yields.

Technological Considerations

Pyrolysis is a more complex process than simple combustion; and pyrolysis units have not benefited from the same amount of research and development effort as wood stoves and biomass boilers. Pyrolysis units have mainly been developed by individual experimenters and pioneers, although there are a few commercial manufacturers, as illustrated by Table 2.

Table 2: Overview of different available pyrolysis units

	No heat capture	Heat capture
Small-scale	Biochar kilns, such as those sold by CarbonGold in the UK. Many DIY designs are available online.	Biochar stoves. Several main families of designs: Anila stoves, Top-Lit Up-Draft (TLUD) stoves
Large-scale	Large-scale units designed to produce high-quality biochar. These can also be optimised for bio-liquids or "wood vinegar" production. E.g. BioGreen	Larger-scale units that can capture the heat from the process. The Pyreg 500 is designed for biochar production but has the capability for heat capture. Only the Biomacon range is designed primarily for heat production.

At the time of writing (Oct 2020), the Biomacon range of pyrolysis units are the most relevant for farm-scale application. This German company, founded in 2003, produces units designed for agricultural applications with a heat output ranging from 40 to 400 kW[1]. Importantly, the units can be heat-demand-led, rather than releasing heat as a by-product of the biochar production process. These have been installed on farms throughout Central and Northern Europe, including two Swedish farms: Lindeborgs Farm and Retreat and Hjalmsater Farm and Wedding Venue. The units require biomass pellets, dried woodchips or dried and shredded crop residues of <70mm size and <30% moisture content. Chipping and

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[1] For comparison, typical domestic gas boilers in the UK range from 20 to 45 kW. However they are only providing this heat output in short bursts, whereas pyrolysis units provide it continuously over a longer period. This is discussed below.

shredding biomass is not a high energy cost but has handling costs. Drying the biomass requires a well-ventilated storage area and takes time. Adding an artificial heat source to hasten the drying would significantly reduce the net energy benefit of the pyrolysis process. For ease of handling with farm machinery, Biomacon plants are loaded via a hopper and they automatically deposit the resulting biochar into tonne-bags hung on a rail.

Key Finding 6: Pyrolysis is most efficient with chipped or shredded feedstock, which must also be as dry as possible. This has handling and storage implications.

Sizing the units is a key challenge, as this needs to balance the available biomass input with the farm's demand for both heat and biochar. While it may be possible to bring these three variables (biomass availability, heat demand, biochar demand) into balance on an individual farm, it is more likely that farms would need to export heat or biochar or import biomass to make most economical use of their pyrolysis plant. Data on pyrolysis plant performance in use is difficult to come by and, at the time of writing, documented farm-scale case studies are rare in Europe and non-existent in the UK.

A recently published modelling case study based on a Swedish farm (Azzi et al., 2020) found that the farm's heat demand (125-180 MWh per annum) constrained the optimal use of the pyrolysis unit (a Biomacon 50kW). Pyrolysis units run optimally when they are producing their maximum heat output for an uninterrupted period of several days. However, in order not to waste the heat, this should only be done over a period of several days of cold weather. Throttling down the unit is possible but running it below 50% loading (i.e. 25kW of continuous heat output in this case) risks damaging it. When Azzi et al. modelled a smaller pyrolysis unit (30kW), this had a significant positive impact on their results, allowing a larger proportion of the farm's heat demand to be supplied by pyrolysis. Given that Scotland's climate is generally milder than Sweden's (Glensaugh research station has an annual heat demand of ca. 65MWh), issues with over-sized pyrolysis units could present a significant technical barrier.

Key Finding 7: The smallest commercially available pyrolysis units are likely to be over-sized for farms in the Scottish climate and do not run well on partial loads.

Conclusions and Relevance to the Scottish Uplands

This report has found that pyrolysis and biochar can, in specific circumstances, be climate-positive technologies with agricultural benefits. Table 3 compares the report's key findings with circumstances in the Scottish Uplands.

Table 3: Applying this report’s key findings to the Scottish upland farming context

Biochar is most **climate-positive…**	…When the surplus heat from the pyrolysis process is captured to replace heat from fossil-fuelled boilers.	Most Scottish farms rely wholly or partially on heat from diesel, oil, propane or kerosene boilers, so this benefit is likely to be realised, bearing in mind the technical limitations described below.
	…When the biochar can act as a long-term store of carbon in the soil. This is most pronounced for woody biochars applied to cooler, drier and more acidic soils.	Further research would be needed to confirm biochar stability in Scottish Upland soils, but these tend to be cooler and more acidic, if not necessarily dry. On farms with forestry plantings, thinnings and trimmings could provide a woody feedstock.
Biochar’s **agricultural benefits** include…	…Replacing liming agents on acidic soils; and replacing fertilisers or improving fertiliser use efficiency on nutrient-poor soils. These benefits are most pronounced for herbaceous biochars, which contain more ash.	Scottish Upland soils are generally nutrient poor and acidic, so biochar may yield agricultural benefits. Herbaceous materials for biochar production are more difficult to source on-farm.
	…Improving the efficiency of fermentation processes such as composting, ruminant digestion and manure management.	Most Scottish Upland farms include ruminant livestock, so these benefits are likely to be realised; further research in these areas is likely to be fruitful.
	…Significantly improving crop yields, in specific circumstances that are as yet under-researched. There is some indication that biochar that has been aged outdoors, or pre-treated in other ways, may be more beneficial for crop yields.	Scottish Upland farms do not generally grow arable crops, however it is likely that biochar would also have beneficial effects on grass and tree growth. More research is needed.
However, there are **technical challenges…**	…Pyrolysis is most efficient with chipped or shredded biomass, which must also be as dry as possible. This has handling and storage implications.	The costs of handling and processing the biomass must be outweighed by agricultural benefits for this technology to be viable on Scottish Upland farms without relying on payments for carbon offsets.
	… The smallest commercially available pyrolysis units are likely to be over-sized for farms in the Scottish climate and do not run well on partial loads.	Further technological development to produce smaller pyrolysis units is required if pyrolysis is to be widely adopted on Scottish Upland farms. However, farms that can make use of extra heat through diversification into other businesses needing heat (i.e. scale-up) could make use of currently available units.

Overall, despite a lack of specific research, this review suggests that that pyrolysis and biochar could fit quite well into the Scottish Upland context, especially on farms with a mix of livestock and forestry. **If the technical challenges can be overcome, the best case would appear to be biochar from forestry wastes, pyrolyzed to optimise for high carbon stability and high heat production and applied to cool, acidic soils in order to boost tree or grass growth after having been co-composted with livestock manures.** If something like this could be achieved, the climate benefits would likely be significant, though as discussed above, this is so context-specific that only a full lifecycle analysis would provide a definite answer for a specific farm system.

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