White Paper

Slow pyrolysis and soil fertility

Walter Kraus*

AquaPrawnics is a US agriculture company focused on integrated resource management. One of the main business areas is the production of an organic fertilizer based on biochar derived from a pyrolysis process. Hence, soil fertility is one of our core business segments. This White Paper addresses one of the largest challenges of our time, the negative effects of conventional agriculture on the environment, such as climate change, CO_2 emissions and chemical pollution of soil and waters. And the paper shows economically viable methods of how these problems can be mitigated or even reversed.

Organic matter and soil fertility

Organic matter is the component of the soil that consists of plant and animal residues at various stages of decomposition. Soil represents one of the largest carbon sinks on the planet and plays a major role in the global carbon cycle. Therefore, the dynamics and the capacity of organic matter in soils provide the ecosystem the service of carbon sequestration. The role organic matter plays in climate change issues have received considerable attention in recent years. At the UN conference on climate change in Paris, 2015, the initiative 4p1000 (https://www.4p1000.org) was started by the French government. The aim was to increase fertility in the organic matter of the soil by 0.4%. According to French research, the entire CO_2 issue would be solved if organic matter worldwide is increased by 0.4%, because organic matter is able to bind CO_2 in the soil (called carbon sequestration).

The concentration of organic matter in soils generally ranges from 1% to 6% of the total topsoil mass for most upland soils. Soils whose upper horizons consist of less than 1% organic matter are mostly limited to desert areas, while the organic matter content of soils in low-lying, wet areas (swamps, for example) can be as high as 90%. Soils containing 12-18% organic matter are generally classified as organic soils. Organic matter in the top part of the soil is the root cause of all life. Without the organic matter in the soil, life on our planet would simply not exist.

To understand what organic matter contains is quite revealing: In a single cubic yard of organic soil, one million nematodes (roundworms), one hundred million algae, one hundred billion mushrooms (they deliver nitrogen), thirty trillion bacteria convert every crumb of organic material into inorganic plant fertilizer, and not to forget, the cubic yard of healthy organic soil contains also 100 earthworms, which dig corridors for water and air up to eight meters deep[1].

Mushrooms also use the fertilized labyrinths produced by earthworms. In the corridors created by earthworms, mushrooms build networks of filamentous threads, which in turn connect the underground to a stable tissue. In it, the individual species rely on symbioses. In mycorrhiza, for example, mushrooms at the roots benefit from the organic plant material and, for every carbohydrate supply, they return the favor with nitrogen and phosphates, among other things. At times, they also disgust pests and diseases. In a large report on the microbial world of the soil, the Academy of American Microbiologists raves: "There are countless lively conversations under our feet." In a square with an edge length of 100 yards, roughly 15 tons of multicellular animals keep the food cycle going (mammals and birds not included).

---

* Walter Kraus is co-founder, President and chair of the Board of Directors of AquaPrawnics

The digestive power of this microcosm creates the nutrients that make plants grow year after year, without the use of mineral fertilizers.

Stressed soil

Unfortunately, conventional agriculture feeds on its own foundation. The soil in rich countries suffer from too much synthetic chemistry and liquid manure and too little organic matter. The abundance of mineral fertilizers diminishes the organic matter in the soil. After some decades of conventional agriculture, soils are worn out and organic matter is reduced heavily. In some fields regularly exposed to mineral fertilizer, the organic matter falls below 1 or 2% and are left with a soil quality comparable to desert areas. As a result, soils with reduced organic matter need more conventional fertilizers in order to produce crops. It is a vicious circle, because the increased amount of mineral fertilizer needed increases the problem of reduced organic matter. These worn down soils are not able to hold water and dry out quickly, with the consequence that these dry soils are much easier blown away by heavy wind or washed out by rain. Soil degradation is a serious problem. Since 1945, more than 3 Billion acres of soil were lost due to soil degradation. That is the size of China and India together.[2]

While it sometimes takes thousands of years for a fertile soil to develop, soil can be irrevocably destroyed through mineral fertilization within a few decades. On top of that, conventional agriculture is responsible for 15% of greenhouse gas emissions worldwide. However, organic agriculture is capable to reverse this grim scenario and substantially contribute to eliminate anthropogenic CO_2 emissions.

Pyrolysis of biomass

One preferred and highly effective method of choice to achieve a fundamental change with climate issues, is pyrolysis of biomass. Pyrolysis is a thermo-chemical conversion of organic feedstock in the absence of free oxygen and also, as far as possible, in absence of oxygen-donors such as steam or CO_2. For fast pyrolysis (further explained on page 9), the yield of condensable hydrocarbons (pyrolysis oil) is maximized. For slow pyrolysis (see also page 9), the oil yield is decreased whereas the pyrolysis char yield is higher. The technology is proven with various types of feedstock. Chart 1 shows the main carbon flows associated with pyrolysis of biomass.

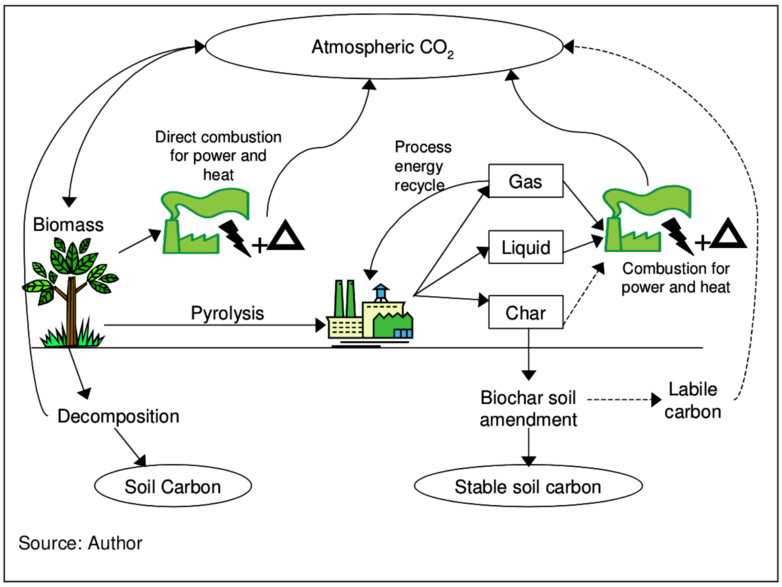
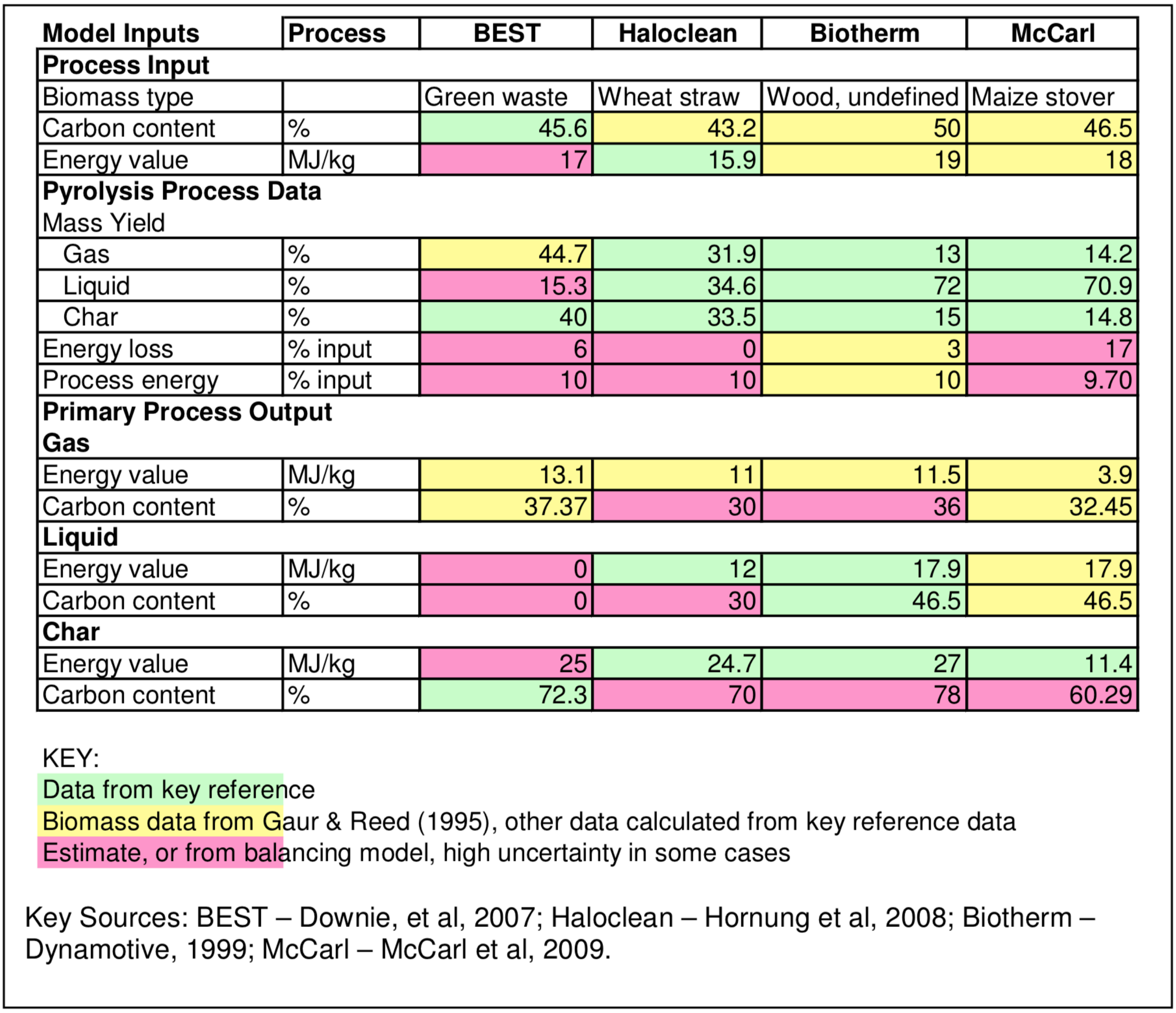


Chart 1: CO2 distribution in the pyrolysis process, Source: Brownsort Dissertation[3]

If biomass is pyrolyzed, the carbon and the energy value are split between three product streams: char, liquid and gas. The total mass of the products will be equal to the mass of the starting material, if properly accounted, and the total carbon content of the products will also equal that of the biomass. However, some energy is inevitably lost as heat from the process; meaning the total energy value in the feedstock is less than the starting material. Some energy is also required to run the pyrolysis process: to dry the feed, to heat to temperature, to drive equipment. In theory, all this can be supplied by recycle from the products, once the process has been started, with the effect that the product quantities available for use downstream of the pyrolysis process are reduced.

In a dissertation presented at the university of Edinburgh, Scotland, four different pyrolysis methods have been compared (see chart 2). Biotherm and McCarl was fast pyrolysis, BEST was slow pyrolysis and Haloclean was run at intermediate temperatures.



Model Inputs	**Process**	**BEST**	**Haloclean**	**Biotherm**	**McCarl**
Process Input					
Biomass type		Green waste	Wheat straw	Wood, undefined	Maize stover
Carbon content	%	45.6	43.2	50	46.5
Energy value	MJ/kg	17	15.9	19	18
Pyrolysis Process Data					
Mass Yield					
Gas	%	44.7	31.9	13	14.2
Liquid	%	15.3	34.6	72	70.9
Char	%	40	33.5	15	14.8
Energy loss	% input	6	0	3	17
Process energy	% input	10	10	10	9.70
Primary Process Output					
Gas					
Energy value	MJ/kg	13.1	11	11.5	3.9
Carbon content	%	37.37	30	36	32.45
Liquid					
Energy value	MJ/kg	0	12	17.9	17.9
Carbon content	%	0	30	46.5	46.5
Char					
Energy value	MJ/kg	25	24.7	27	11.4
Carbon content	%	72.3	70	78	60.29

KEY:
Data from key reference
Biomass data from Gaur & Reed (1995), other data calculated from key reference data
Estimate, or from balancing model, high uncertainty in some cases

Key Sources: BEST – Downie, et al, 2007; Haloclean – Hornung et al, 2008; Biotherm – Dynamotive, 1999; McCarl – McCarl et al, 2009.

Chart 2: Model inputs with pyrolysis: Source: Brownsort Dissertation[3]

From an environmental point of view and related to CO_2 sequestration, the benefits of slow pyrolysis show to be highest in the study, compared to the other methods of pyrolysis (see chart 2, mass yield of char).

Understanding the pyrolysis process is an important requirement to optimize this method. Temperature is the major denominator of the quality of the pyrolysis process. Chart 3 shows a comparative analysis of various pyrolysis scenarios, processed with different temperatures. High temperature pyrolysis (fast pyrolysis) is indicated by “Scenario Reference 6” and low temperatures (slow pyrolysis) indicated by “Scenario Reference 1”, where the product yields are compared for the different output products (gas, liquid and char).

The analysis shows that the gas yield is relatively the same with different process temperatures. However, char and liquid yields are fundamentally different with slow pyrolysis compared to fast pyrolysis. The lower the process temperature, the higher the char yield and the lower the liquid yield and vice versa, the higher the process temperature, the lower the char yield and the lower the liquid yield.

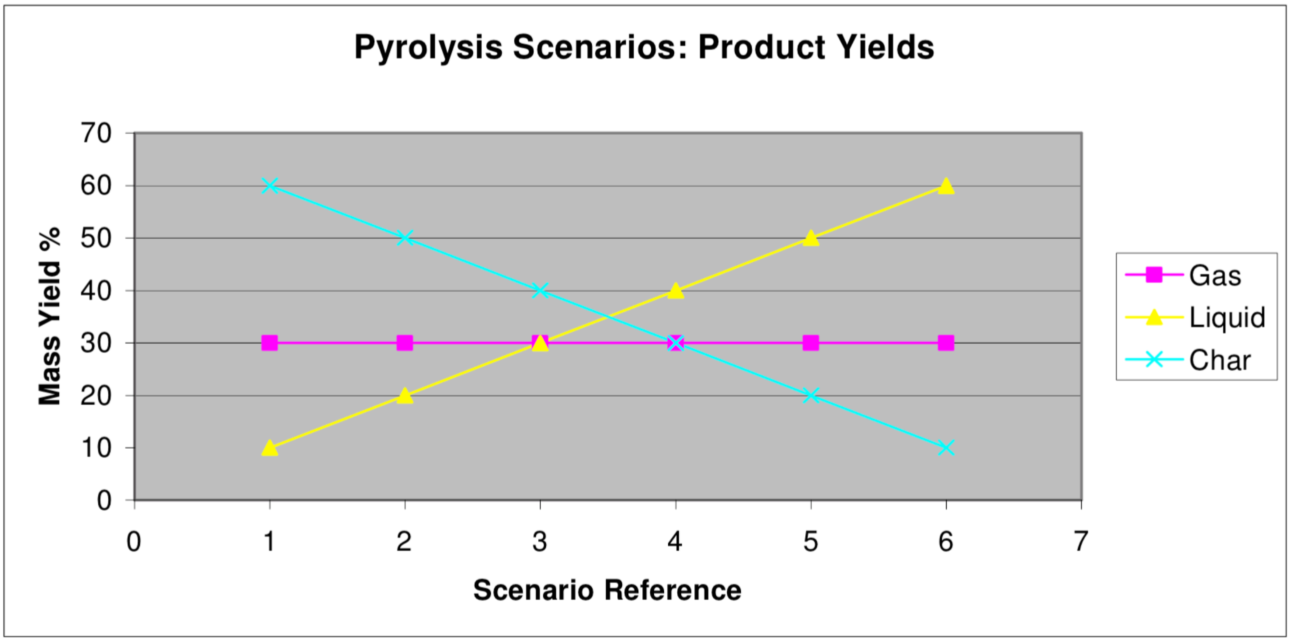


Chart 3: Product yields of pyrolysis: Source: Brownsort Dissertation[3]

The AquaPrawnics pyrolysis system is based on slow pyrolysis. There are indications that slow pyrolysis cuts CO_2 emissions roughly by half (see chart 3, red bars), compared with combustion of biomass (see chart 3, blue bars). The relatively high char mass yield (see chart 1: 40% char yield) indicates that this char is sequestered in the soil, if that char is used as soil amendment in agriculture. Once carbon sequestration is properly supported by politics via tradable carbon certificates, this sequestration will turn into a considerable revenue stream for slow pyrolysis operations.

The gas product is typically a mixture of carbon dioxide (9-55% by volume), carbon monoxide (16-51%), hydrogen (2-43%), methane (4-11%) and small amounts of higher hydrocarbons. The gases are usually present with nitrogen introduced to inert the pyrolysis equipment, this can be treated as a diluent and ignored for material balancing but will affect the heating value of the syngas. The carbon dioxide and nitrogen provide no energy value in combustion, the other gases are flammable and provide energy value in proportion to their individual properties. Use of this energy in the gas can be considered as renewable and largely carbon neutral. No special consideration of the carbon dioxide in the pyrolysis gas is required as it is not additional to what would result from biomass decomposition.

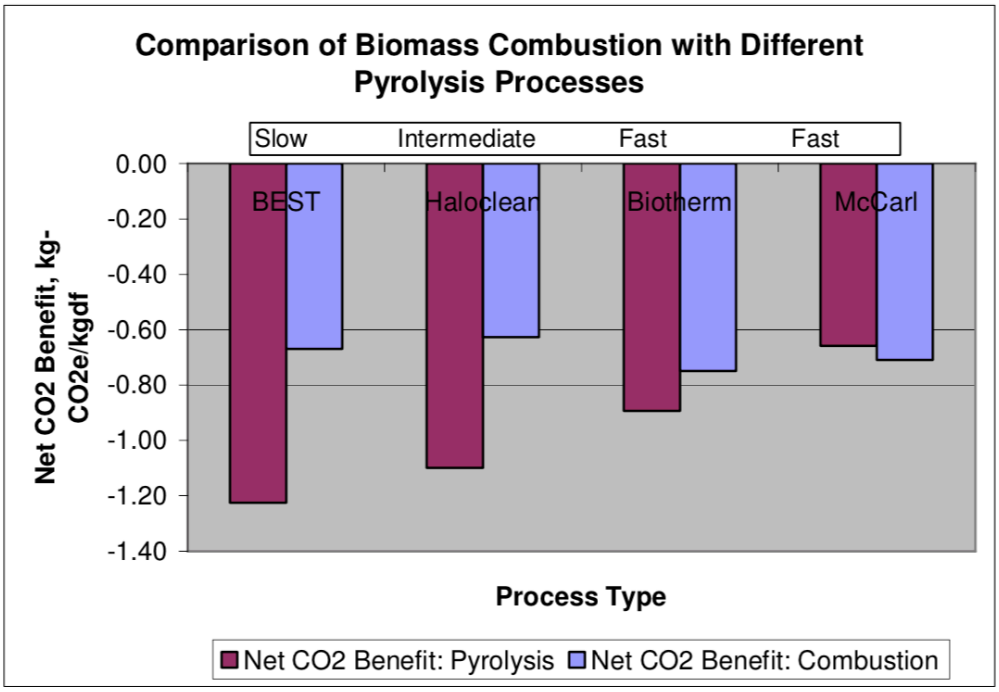
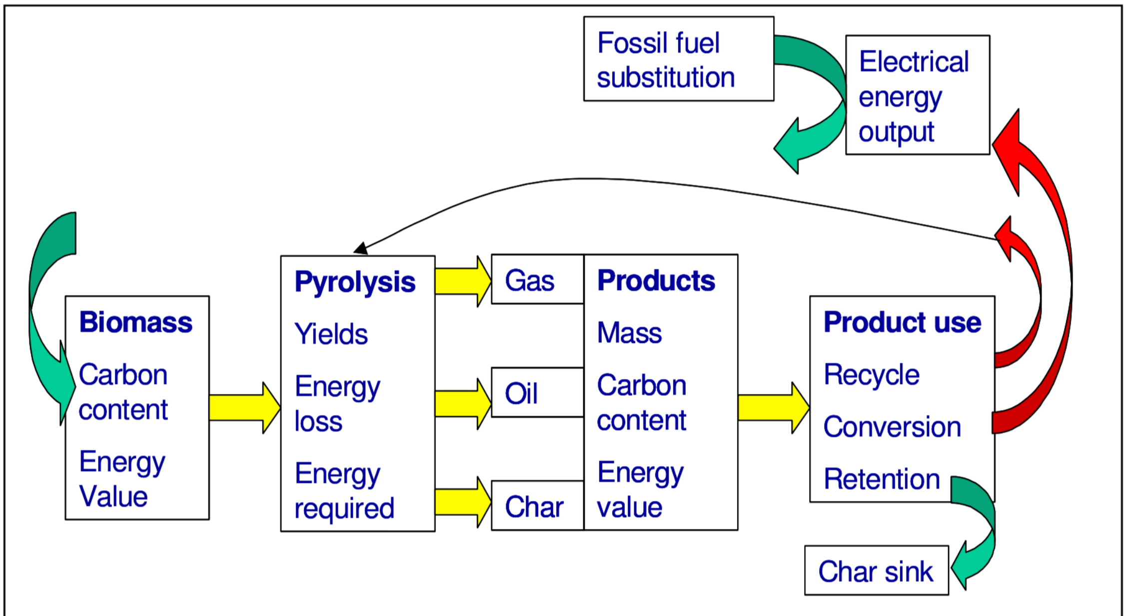


Chart 4: CO2 benefits with pyrolysis: Source: Brownsort Dissertation[3]

In regard to biochar, any factor of pyrolysis conditions that increases the contact between primary vapors and hot char, including high pressure, low gas flow, large particles or slow heating is likely to favor char formation at the expense of liquid yield. Data from scientific reports indicating that chars formed under low flow, high pressure conditions with consequent higher char yields also have higher fixed-carbon yields. This effect may be useful in maximizing the carbon sequestration potential in biochar, although there may be other changes in the char properties that are not immediately evident.



Key:
Yellow arrows represent material and energy flow though the process.
Green arrows represent carbon dioxide assimilation, avoidance or sequestration.
Red arrows represent carbon dioxide emission.
Source: Author.

Chart 5: Schematic model of pyrolysis: Source: Brownsort Dissertation[3]

Chart 5 shows the schematic model of the entire pyrolysis process, its yields, CO_2 sequestration and process flow.

From an energy process point of view, chart 6 shows the energy flow of a typical slow pyrolysis unit.

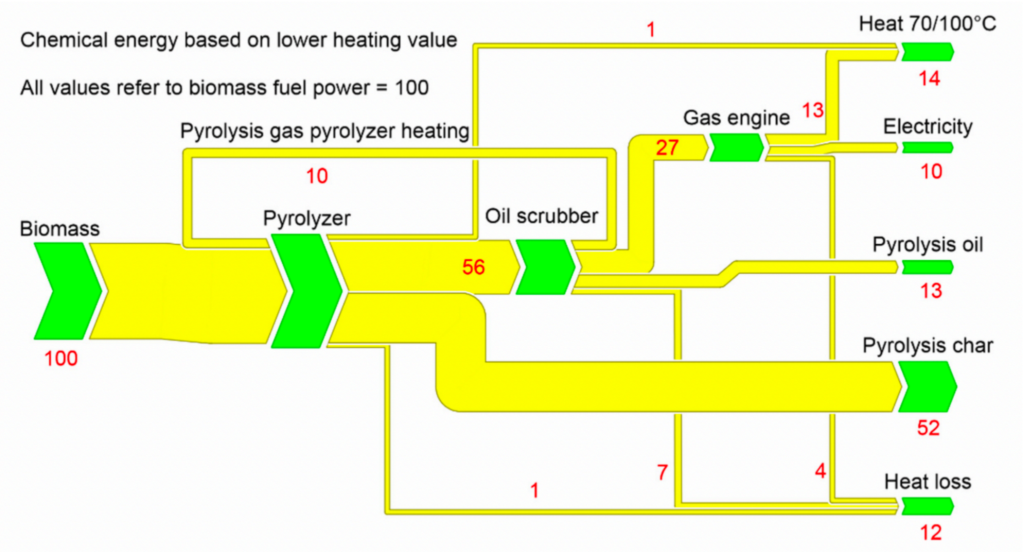


Chart 6: Energy flow diagram of pyrolysis: Source: Brownsort Dissertation[3]

Interesting are the numbers in red in chart 6. They refer to the in- and output of the system in terms of energy distribution.

Financial Aspects

The financial viability of pyrolysis systems will strongly affect their rate of establishment. An economic analysis of fast and slow pyrolysis conclude that both would be loss-making with net margins of –45 and –70 US dollars per ton of feedstock respectively, on the basis of their assumptions[3]. There are considered three income streams: 1. electricity sales, 2. greenhouse gas offset value from tradable carbon allowances and 3. biochar sales. The first two have recognized, if fluctuating, values. Biochar values depend largely on agronomic benefits that were not fully demonstrated and therefore highly uncertain at the time the analysis was published.

A simple financial analysis based on the outputs from the models described, have been carried out using UK values for industrial electricity (BIS, 2009) and EU Allowances for carbon dioxide (DECC, 2009); no values for biochar sales were included. The model outputs are shown in Chart 7.

		BEST	Haloclean	Biotherm	McCarl
Pyrolysis					
Energy value	p/kgdf	3.20	4.67	9.92	10.93
CO2 Value	p/kgdf	1.42	1.27	1.03	0.76
Total value pyrolysis	p/kgdf	4.62	5.95	10.96	11.69
Combustion					
Energy value	p/kgdf	13.09	12.24	14.63	13.86
CO2 Value	p/kgdf	0.77	0.72	0.87	0.82
Total value combustion	p/kgdf	13.86	12.97	15.50	14.68

Chart 7: Source: Brownsort Dissertation[3]

On this basis, the results suggest fast pyrolysis has around twice the income value of slow pyrolysis, but that combustion of biomass for electricity generation has a greater value than all pyrolysis processes. The sensitivity of this outcome to values used has been tested and the general conclusions are robust. The price of electricity would have to fall by a factor of ten, to less than 1p/kWh (£0.01), for the total values for fast and slow pyrolysis to become comparable with each other. Alternatively, the value of the EU Allowance for CO_2 would have to rise by more than ten times, to over 130 £/t-CO_2 equivalent, for comparable values. Even greater changes in values of incomes would be needed for the pyrolysis and combustion cases to have similar outcome values.

However, these financial considerations explain somehow, why pyrolysis has not been established in a greater extend today. In our AquaPrawnics pyrolysis business model, we achieve high profitability, even though we use slow pyrolysis, which is considered in the reviewed studies as the economic worst case scenario of all options (compared to combustion and fast pyrolysis).

After a thorough analysis of existing projects and their failures and pitfalls, we use the following considerations and evaluations to increase profitability of slow pyrolysis towards solid economic viability:

The economy of electricity generation through pyrolysis

While large waste-to-energy plants for biomass depend on bulk sale of electricity to wholesale prices, our energy production is adapted to energy consuming operations on site. Meaning, we combine energy production utilities based on slow pyrolysis with aquaculture and/or greenhouse operations in a way that energy generation meets energy demand, and our production is utilized on site. Aquaculture and greenhouse operations often suffer from high electricity prices. With other words, we cut out the electricity companies and their substantial profit margins (electricity retail prices can be up to three times higher than wholesale prices). That contributes substantially to increased overall project profitability of slow pyrolysis, both on the energy generation and the consumption side.

Another source of improved profitability derives from avoided energy losses. Both aquaculture and greenhouse operations use first of all energy in form of heat. The generated heat does not need to be converted into electricity. Syngas is used directly in aquaculture and greenhouse operations without any conversion from heat to electricity. This conversion usually causes an energy loss between 50% and 60%, which in our case contributes to the overall profitability of the combined operations.

Size and position of an economically viable pyrolysis unit

Waste-to-energy utilities are usually large in order to process high volumes of biomass, which subsequently results in higher process yields. At first sight, it is an obvious choice. However, in order to source the required amounts of biomass for such operations and to deliver electricity in the most effective way, positioning of the site is often based on a compromise. Long distance to the feedstock drive transport costs, and long distance to the electricity user diminishes the yield due to electricity transportation costs and transmission losses. We have seen projects, which went terribly wrong exactly due to this issue. With large operations, there will always be a compromise between these opposing elements, and the outcome is in most cases not advantageous for the project revenue.

Smaller units with energy consumption directly on site can be positioned close to the available feedstock. With that advantage we avoid both transportation costs for feedstock and energy.

The biochar marked

Char has been used in agriculture for thousands of years. The fertile *terra preta* (dark earth) soils of the Amazonian region result from incorporation of char into otherwise poor soils. The resulting soils have long-lasting fertility that has been related to the stability of carbon in the soil (Lehmann et al, 2009). It is this observation coupled with the search for carbon sequestration techniques for climate change mitigation that has led to recent interest in pyrolysis-derived char, or called biochar.[3]

At the time the mentioned financial investigations have been conducted, there was a very limited biochar market established yet. Meanwhile, this situation is in the process of being changed. The earlier described declining organic matter in soils have been proven to be reclaimed in relatively short time by applying amended biochar as soil amendment. An impressive demonstration was reported from the reclamation of a mine site near Aspen, Colorado. In October 2010, on a slope without any vegetation and no soil, a layer of biochar, compost and plant seeds was applied. Eight months later, the rocky slope was covert with sprouting grass, and after ten months, the site was entirely reclaimed (see chart 8).

Chart 8: Mine site reclamation with biochar and compost application.

Biochar from our production is amended with the remnants of our indoor shrimp growing operation. In addition, algae are also grown in our utilities and is used as food for shrimps and as amendment to turn the produced biochar into a highly effective organic fertilizer. With that as product, biochar has found its market, which is able to compete with conventional mineral fertilizers.

Considered this set of economic advantages combining energy and aquaculture, respectively greenhouse operations turn the entire combined operations to a highly lucrative business. With that as background, pyrolysis has finally found a way to be successfully used in agriculture projects and make slow pyrolysis operation viable.

Economics of carbon sequestration:

Carbon trade is another source of income for pyrolysis operations (at least in Europe), even though the current values of carbon certificates is too low in order to reflect the real environmental and economic advantages of carbon sequestration.

Without a doubt, the price of carbon certificates will increase during the future course of the international global warming debate. Even though not all countries are currently supporting initiatives mitigating climate change, there is an international public debate and a trend that will drive up the cost of CO_2 emissions over the coming decades. That will turn carbon sequestration, the process involved in carbon capture and the long-term storage of atmospheric carbon dioxide, to an increasingly valuable process, which subsequently will be valued in terms of increasing market prices of carbon certificates. That trend will further improve all business models where carbon sequestration is involved.

Pyrolysis process and feedstock

This section is mostly based on Brownsort[3] and puts focus on the effect of the main controllable factors influencing the outcome of pyrolysis processes. The effect of feedstock composition and preparation is discussed first followed by the effects of process operating conditions. Slow, intermediate and fast pyrolysis are all affected in a related manner, but the importance of factors and the effect of changes on product yield distribution differs between process types.

Fast pyrolysis

Fast pyrolysis is characterized by high heating rates and short vapor residence times. This generally requires a feedstock prepared as small particle sizes and a design that removes the vapors quickly from the presence of the hot solids. A moderate temperature (in pyrolysis terms) of around 500°C (932°F) is usually used. Development of fast pyrolysis progressed rapidly following the oil crises of the 1970's as a way of producing liquid fuel from an indigenous renewable resource, primarily wood, and the process is designed to give a high yield of bio-oil.

Slow pyrolysis

Slow pyrolysis can be divided into traditional charcoal making and more modern processes. It is characterized by slower heating rates, relatively long solid and vapor residence times and usually a lower temperature than fast pyrolysis, typically 400°C (752°F). The target product is often the char, but this will always be accompanied by liquid and gas products, although these are not always recovered.

Feedstock preparation

Moisture content can have different effects on pyrolysis product yields depending on the conditions (Antal and Grønli, 2003). Fast pyrolysis processes in general require a fairly dry feed, around 10% moisture (Bridgwater and Peacocke, 2000), so that the rate of temperature rise is not restricted by evaporation of water. Slow pyrolysis processes are more tolerant of moisture, the main issue being the effect on process energy requirement. For charcoal making, wood moisture contents of 15-20% are typical (Antal and Grønli, 2003). In all pyrolysis processes water is also a product and is usually collected together with other condensable vapors in the liquid product. This product has shown to be an organic pesticide.

Feed particle size can significantly affect the balance between char and liquid yields. Larger particle sizes tend to give more char by restricting the rate of disengagement of primary vapor products from the hot char particles, so increasing the scope for secondary char-forming reactions (Antal and Grønli, 2003). Hence larger particles are beneficial in processes targeting char production and small particles are preferred to maximize liquid yields in fast pyrolysis.

Temperature profile control

The temperature profile is the most important aspect of operational control for pyrolysis processes. Material flow rates of both solids and gases, together with the reactor temperature, control the key parameters of heating rate, peak temperature, residence time of solids and contact time between solids and gases. These factors affect the product distribution and the product properties.

For fast pyrolysis a rapid heating rate and a rapid rate for cooling primary vapors are required to minimize the extent of secondary reactions. These reactions not only reduce the liquid yield but also tend to reduce its quality, giving a more complex mixture, an increased degree of polymerization and higher viscosity (Bridgwater and Peacocke, 2000). Conversely, in slow pyrolysis there is some evidence that slow heating leads to higher char yields (Antal and Grønli, 2003).

Peak temperature, however, has an unequivocal effect on char yields and properties. Higher temperatures lead to lower char yield in all pyrolysis reactions. This results from the main controlling variable of pyrolysis reaction kinetics being temperature (Antal and Grønli, 2003). The effect can be thought of as more volatile material being forced out of the char at higher temperatures reducing yield but increasing the proportion of carbon in the char. Temperature also has an effect on char composition. Chars produced at higher temperatures have higher carbon contents (Antal and Grønli, 2003). This may have important implications for biochar stability in soils.

Solid residence time is also important but to a lesser degree than peak temperature, longer time at temperature leading to lower char yield (Antal and Grønli, 2003).

Peak liquid yields for slow pyrolysis are variable. Demirbas (2001) reports peak liquid yields of 28-41% at temperatures between 377°C (710°F) and 577°C (1,070°F), depending on feedstock, when using a laboratory slow pyrolysis technique. The Haloclean process yields a peak of 42- 45% liquid at temperatures of 385-400°C (725-752°F) with different straw feeds (Hornung et al, 2006).

Gas environment

Conditions in the gas phase during pyrolysis have a profound influence on product distributions and on the thermodynamics of the reaction. Most of the effects can be understood by considering the secondary char-forming reactions between primary vapor products and hot-char. The area is discussed in detail and rationalized by Antal and Grønli (2003) in the context of charcoal making; the main points are summarized here.

Gas flow rate through the reactor affects the contact time between primary vapors and hot char and so affects the degree of secondary char formation. Low flows favor char yield and are preferred for slow pyrolysis; high gas flows are used in fast pyrolysis, effectively stripping off the vapors as soon as they are formed.

Pressure has a similar effect. Higher pressure increases the activity of vapors within and at the surfaces of char particles so increasing secondary char formation. The effect is most marked at pressures up to 0.5MPa. Conversely, pyrolysis under vacuum gives little char, favoring liquid products. For pyrolysis under pressure, moisture in the vapor phase can systematically increase the yield of char, believed to be due to an autocatalytic effect of water, reducing the activation energy for pyrolysis reactions.

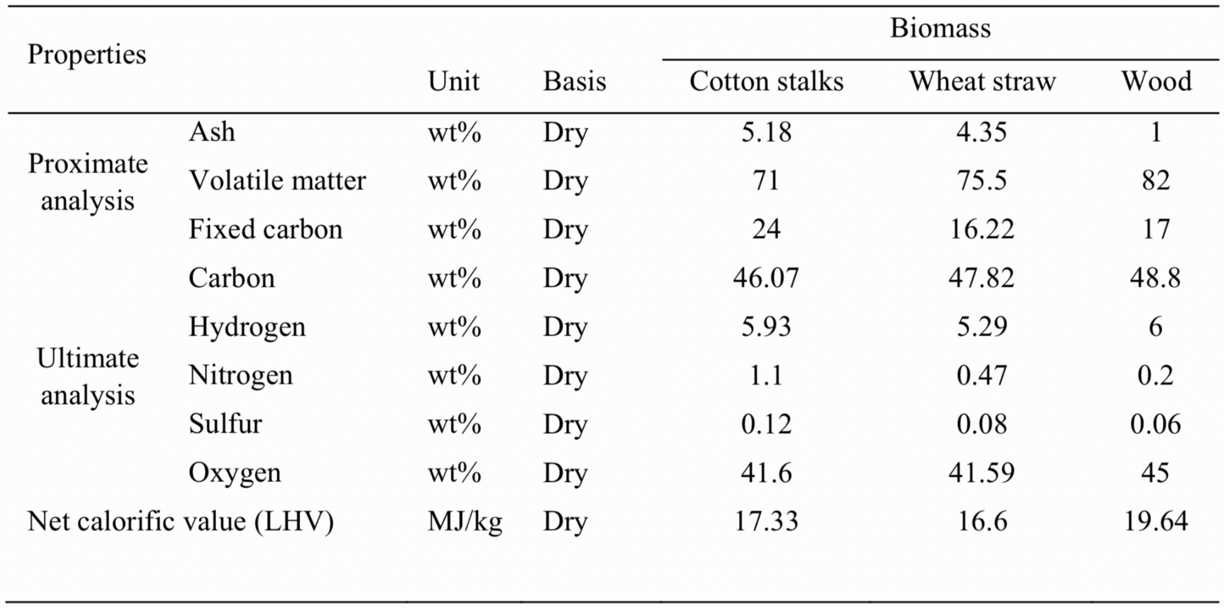
At this stage, we have not evaluated properly the economy of elevated pressure during the pyrolysis process versus the advantages achieved, such as increased yield of char and saved energy via a feedstock with higher moisture content.

The thermodynamics of pyrolysis are also influenced by gas environment. The reaction is more exothermic (heat producing) at higher pressures and low flow rates. This is rationalized as being due to the greater degree of secondary char-forming reaction occurring. Hence, higher char yields are associated with conditions where pyrolysis is exothermic; such conditions will favor the overall energy balance of processes targeting char as product.

In summary, any factor of pyrolysis conditions that increases the contact between primary vapors and hot char, including high pressure, low gas flow, large particles or slow heating is likely to favor char formation at the expense of liquid yield. Antal and Grønli (2003) provide data from their own work indicating that chars formed under low flow, high pressure conditions with consequent higher char yields also have higher fixed-carbon yields. This effect may be useful in maximizing the carbon sequestration potential in biochar, although there may be other changes in the char properties that are not immediately evident.

Feedstock issues

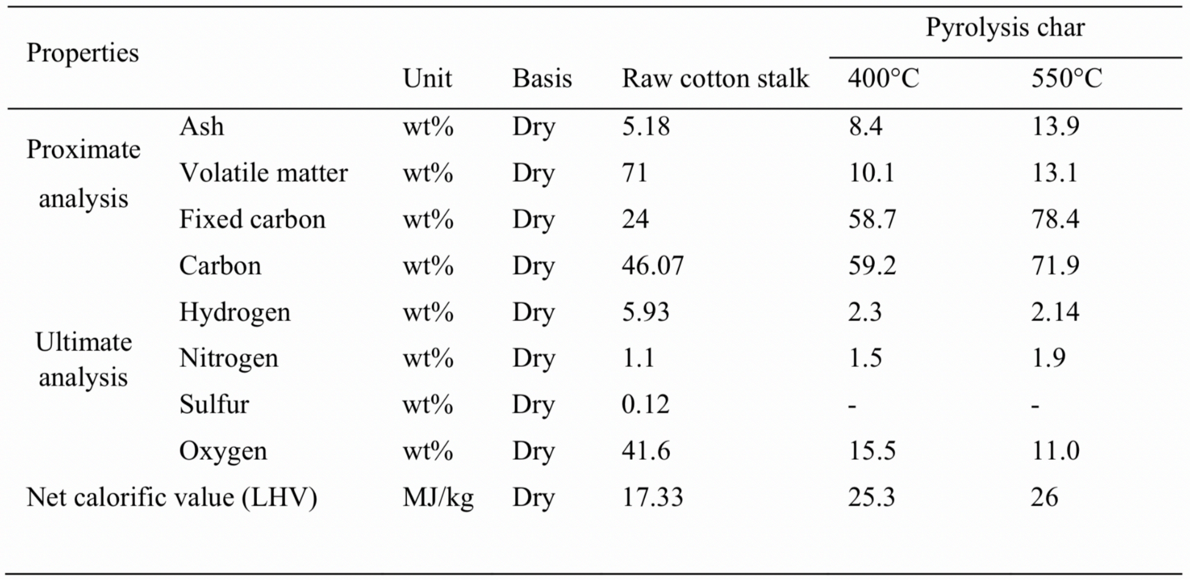
Comparative research shows the results of pyrolysis on different types of biomass. Pröll[4] compares the properties of cotton stalks, wheat straw and wood.



Properties		Unit	Basis	Biomass		
				Cotton stalks	Wheat straw	Wood
Proximate analysis	Ash	wt%	Dry	5.18	4.35	1
	Volatile matter	wt%	Dry	71	75.5	82
	Fixed carbon	wt%	Dry	24	16.22	17
Ultimate analysis	Carbon	wt%	Dry	46.07	47.82	48.8
	Hydrogen	wt%	Dry	5.93	5.29	6
	Nitrogen	wt%	Dry	1.1	0.47	0.2
	Sulfur	wt%	Dry	0.12	0.08	0.06
	Oxygen	wt%	Dry	41.6	41.59	45
Net calorific value (LHV)		MJ/kg	Dry	17.33	16.6	19.64

Chart 9: Properties of cotton stalks, wheat straw and wood.[4]

He also compares what happens when pyrolysis is run in different temperatures on the same feedstock, for example with cotton stalks.



Properties		Unit	Basis	Raw cotton stalk	Pyrolysis char 400°C	Pyrolysis char 550°C
Proximate analysis	Ash	wt%	Dry	5.18	8.4	13.9
	Volatile matter	wt%	Dry	71	10.1	13.1
	Fixed carbon	wt%	Dry	24	58.7	78.4
Ultimate analysis	Carbon	wt%	Dry	46.07	59.2	71.9
	Hydrogen	wt%	Dry	5.93	2.3	2.14
	Nitrogen	wt%	Dry	1.1	1.5	1.9
	Sulfur	wt%	Dry	0.12	-	-
	Oxygen	wt%	Dry	41.6	15.5	11.0
Net calorific value (LHV)		MJ/kg	Dry	17.33	25.3	26

Chart 10: Average values of properties of raw cotton stalk and its biochar under two pyrolysis temperatures.

Interesting to note: Higher temperatures increases ash content, but at the same time increases char production and nitrogen content.

Carbon trade in the US

AquaPrawnics is working on a proposal to push Federal carbon cap and trade carbon sequestration tax credit, as pyrolysis has definitely shown a carbon sequestration impact.

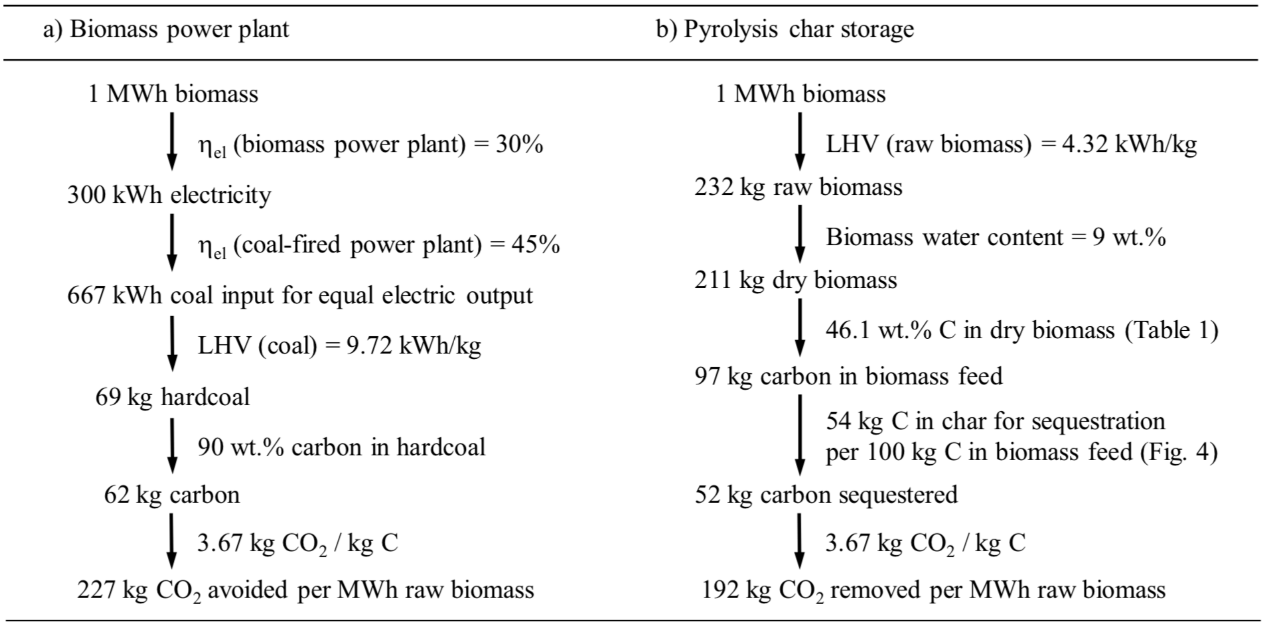


Chart 11: Comparison of pyrolysis char storage in soils to biomass-fired electricity generation.

We assume that the final calculation is done in cooperation with US authorities. This section establishes the fact of removed or avoided CO_2 emissions subject to pyrolysis operations. One report[4] compares CO_2 avoidance of biomass-fired electricity generation with char storage in soils via pyrolysis (Chart 11).

The report states that pyrolysis removes 192 kg CO_2 (423 lbs.) per one MWh electricity produced from biomass.

In terms of carbon accounting, or the overall effect on carbon dioxide emissions, one model[3] investigates the boundary of the pyrolysis process and electrical generation. A whole-life-cycle approach includes contributions from effects upstream and downstream of these boundaries. Data has been provided for these contributions by Brownsort[3] and Jim Hammond (2009, unpublished MSc dissertation) covering biomass production and transport operations, transport and spreading operations for biochar, and agronomic benefit from biochar in terms of effect on carbon dioxide emissions. The data is based on UK assumptions and covers two feedstocks, wheat straw and wood chips from UK forestry.

Model data assuming a char stability factor in the soil of 0.75 has been used and the effect of fossil fuel substitution has been separated out, but remains included. The breakdown by life-cycle stage and the overall summation are shown in chart 12. See further evaluations on biochar stability on page 14.

For wheat straw the emissions from production modify the total net effect more significantly, reducing the benefit (less negative) by 28% from the model result. This reflects the intensive nature of wheat cultivation using fossil fuel based agrochemicals. Given the differences between the feedstocks, it is not relevant to compare the two cases above as a way of comparing pyrolysis processes. Neither is it relevant to compare these outcomes with earlier figures for direct combustion, as these would also be modified by the upstream, if not the downstream, contributions.

In summary, the majority of the whole life-cycle effect on net carbon dioxide emissions offered by pyrolysis biochar systems can be related to carbon sequestered in char and emissions avoided through fossil fuel substitution. Of the other life-cycle elements (with assumptions inherent in the supplied data) transport and farm operations have relatively low significance; fossil fuel based agrochemical input to production is significant for some feedstocks. Agronomic benefit of biochar use has a small effect but is uncertain and may vary from project to project; the estimate given in the figures (chart 12) is considered conservative (Hammond, 2009).

Process	**Haloclean**	**Biotherm**
Feedstock	Straw	Wood
	kg-CO2e/kgdf	
Upstream		
Production	0.268	0.035
Transport	0.003	0.009
Sub-total	0.271	0.044
Pyrolysis and Conversion		
Biochar (at 0.75 stability)	-0.645	-0.290
Fossil fuels substitution	-0.239	-0.508
Sub-total	-0.884	-0.798
Downstream		
Transport and spreading	0.002	0.000
Agronomic benefit	-0.027	-0.016
Sub-total	-0.025	-0.015
Total Net CO_2 Effect	-0.638	-0.769

Source for upstream and downstream contributions:
Jim Hammond (2009, MSc dissertation)

Chart 12: Upstream and downstream contributions to CO2 sequestration of two type of feedstocks

Stability of biochar

The assumed stability factor of CO_2 in biochar varies over the years. Estimates of the proportion of carbon lost, and in what period, may vary (Lehmann et al, 2009). But a value of 25% loss in the first ten years has been used for assessing greenhouse gas effects (Gaunt and Cowie, 2009). The rate of loss beyond this is uncertain. A hypothetical model (Lehmann et al, 2009) suggests that if mean residence time for the so-called inert carbon is of the order of 1000 years, as expected by analogy with *terra preta* soils, the additional loss after 10 years is slow.

References

1) Die Zeit: Wie geht es dem Boden?, A. Gerdes, C. Grefe and U. Willmann, Jan. 31, 2019, No 6, p. 32 – 34.
2) David R. Montgomery: *Dirt - The Erosion of Civilizations*. 2012, S. 174.
3) Peter Alexander Brownsort: Biomass pyrolysis processes: Performance parameters and their influence on biochar system benefits. Dissertation for the degree of Master of Science, University of Edinburgh, 2009.
4) Tobias Pröll et al.: Reduced local emissions and long-term carbon storage through pyrolysis of agricultural waste and application of pyrolysis char for soil improvement. Department of Material Sciences and Process Engineering, University of Natural resources and Life Science, Vienna, Austria. Elsevier, Energy Procedia 114 (2017), 6057 – 6066, presented at 13th International Conference on Greenhouse Gas Control Technologies, GHGT-13, 14-18 Nov. 2016, Lausanne, Switzerland.