Evaluating Opportunities for Biochar Production from New Zealand Plantation Forestry Harvest Residues

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Abstract

The harvesting of New Zealand's forest plantations generated a relatively large volume of residual biomass. At the landing, these residues are typically places in piles take up valuable operational space during operations, and planting areas post harvesting. They can also become a hazard if mobilised during adverse weather events.

The process of pyrolysis can convert these residues into biochar. Biochar is a low-density, high-carbon solid with valuable soil conditioning and carbon storage properties. Biochar would be more seriously considered as a harvest residue management solution if there was a better understanding of the methods, risks and costs of production in a New Zealand forestry context.

In addition to a comprehensive overview biochar as a product, this study investigates three mobile biochar production methods: the Earth Systems Charmaker MPP40, the Air Burners Inc. CharBoss, and the Tigercat Carbonator 6050. A detailed costing model was developed to allow the calculation of biochar production unit costs under variable equipment configurations, feedstock distributions and productivity expectations. The model was applied to each production method using estimates of variables most relevant to operation in a New Zealand forestry setting. The resulting production costs per oven-dry tonne were: $1,420 for the Charmaker, $4,150 for the CharBoss and $910 for the Carbonator. These costs showed the greatest sensitivity to biochar productivity variables. The Excel-based costing model included can serve as a tool for forest managers to generate situation-specific biochar production cost and volume estimates. These can be compared with its selling price and residue management cost savings to determine the viability of a biochar operation.

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Introduction

Biochar is a carbon-rich solid, physically identical to charcoal. Formed by heating biomass to high temperatures (500°C+) with limited oxygen, it is regarded as biochar when produced for purposes other than burning. Softwood biochar is around 85% carbon (Hedley et al., 2020). It is very porous and lightweight, with an oven-dry bulk density as low as 100kg/m^3 (Oregon Biochar Solutions, 2023). One notable example of biochar's benefits goes back a thousand years to the *Terra Preta* soils of the Amazon Basin. Archaeological evidence suggests that the pre-Columbian Amazon sustained complex urban civilizations with millions of inhabitants. This was doubted, as those same tropical soils currently only provide present-day farmers with a few years of productivity; therefore, they should not have been able to feed vast cities. Exploration has found that soils surrounding the ruins contain up to 450T/ha of carbon, compared to the expected 30-130T/ha (Hawken, 2017). These carbon-rich soils contain evidence of human modification, including the addition of charred biomass, or biochar. This example shows the *use of waste biomass* to form *productive soils* by *sequestering carbon:* three contemporary goals of humanity. Biochar could be an opportunity for New Zealand plantation forestry to simultaneously address climate change, harvest residue, and soil degradation challenges.

Climate change is one of the biggest issues facing the contemporary world. To avoid irreversible adverse consequences, the United Nations Intergovernmental Panel on Climate Change (IPCC) has emphasised the need to limit temperature rise by 1.5°C above pre-industrial levels. To achieve this, 196 countries have committed, through the Paris Agreement, to reach net zero carbon dioxide (CO_2) emissions by 2050. The projected trajectory of global CO_2 emissions is shown in Figure 1. This projection highlights that even with stringent reduction efforts, sustainable carbon removals will be required to offset CO_2 emissions unavoidable by 2050. In addition to CO_2, other greenhouse gasses (e.g., methane (CH_4), nitrous oxides (NO_x) and carbon monoxide (CO)) contribute to global warming and have been given a 2070 target to reach net zero.

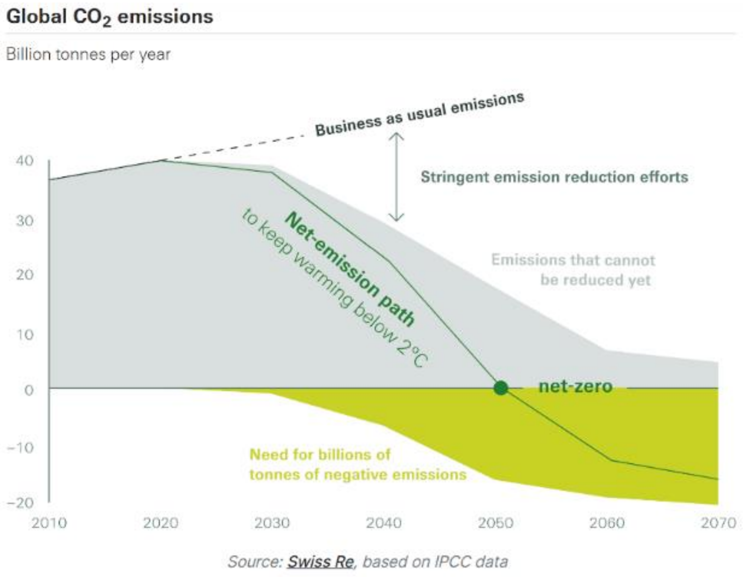


Figure 1. A projected path to net-zero CO_2 by 2050 (Swiss Re, 2019).

In July 2023, the New Zealand Government began a program to develop a carbon dioxide removal (CDR) strategy, beyond that of afforestation (Cabinet Environment, Energy and Climate Committee, 2023). Biochar could be one such strategy. As an internationally recognised negative emissions technology, it is calculated to potentially be able to sequester 0.37GT (Lehmann et al., 2006) up to 1-2GT (IPCC, 2021) of carbon per year. This is equivalent to 3-18% of 2022 anthropogenic emissions.

While emissions targets exist to avoid irreversible effects, consequences of historic warming will continue to impact society. One such consequence is an increased frequency and intensity of storms across the world (IPCC, 2021), including New Zealand (NIWA, 2018). This is especially concerning for the New Zealand forestry industry and its environmental impact, which becomes most adverse during severe storms. Mobilisation of harvest residues in heavy rain events, while not a new problem, has received more significant scrutiny in the wake of major Cyclones in 2018 and 2023. These events have highlighted the risks of woody debris to downstream communities. Potentially harmful forest harvest residues would be more willingly moved to stable locations if there were economic as well as regulatory incentives. Furthermore, whether they be wrapped around bridges or safely stored on landings, piles of harvest residues are seen as wasteful by the public. With the perceived potential of creating renewable energy from biomass to meet New Zealand's net emissions targets, the absence of an economic market is no longer an acceptable excuse for its non-utilisation. The forestry industry is expected to actively seek opportunities to utilise its harvest residues. While biochar can be made from any organic material, that made from woody biomass is known for favourably high carbon content and yield. Moreover, harvest residues can be turned into biochar with minimal pre-processing. Biochar production is not hindered (and is potentially even enhanced) by the presence of dirt, needles, or bark, unlike bioenergy operations which demand uncontaminated stem wood.

One of the most important ecosystem services provided by soil is food, 95% of which is directly or indirectly produced by soil (Forestry and Agriculture Organisation (FAO), 2015). FAO (2015) also noted that current population trends are driving the need for a 70-100% increase in food production by 2050. Amongst other strategies, this will require the fertility and stability of soil to be restored and maintained (Silver et al., 2021). Carbon content is an important characteristic of sustainably fertile and stable soils. However, modern agriculture promotes the oxidation of soil carbon at a faster rate than it can be fixed by pedogenesis, the process of soil building. Intensively cropped soils can lose 5-10 tonnes of carbon per hectare per year, reducing some from 5% to less than 1% in many places (Jehne, 2017). The application of biochar increases soil carbon, provides habitat for microbes, and helps store nutrients. It can also reduce negative soil emissions (CH_4, NO_2) and chemical leeching (nitrates, herb/pesticides) (Jeffery et al., 2017; Hedley et al., 2020; Winsley, 2017; Lehmann et al., 2006).

An international market has developed for biochar, its co-products and its carbon removal credits. The market is largest in the United States (45,000T/year (Groot, 2018)) with Australia (10,000-20,000 T/year (ANZBIG, 2023)), China, and the United Kingdom as other major producers. With just a few commercial operations contributing to the 5000T sold domestically per year, New Zealand is a laggard in the biochar industry and could be missing a valuable opportunity.

Forestry currently plays a major role in offsetting New Zealand's carbon emissions. It benefits from carbon credits earned through the Emissions Trading Scheme (ETS). Regardless of its end use, all carbon sequestered in forests is assumed to be inevitably released post-harvest. It is assumed by the ETS that the carbon fraction decreases to zero over 10 years, and Hedley et al. (2020) reported decomposition rates of pine residues on the ground of 5-17%/year. This is reflected in the carbon accounting methods of the New Zealand Emissions Trading Scheme (ETS), where long-term average net carbon removals are credited only once for new forests. Net carbon removals from forestry are limited by land available for afforestation, a finite resource competing with expanding urban centres, agriculture and permanent forestry. Biochar has the potential to break this carbon cycle, by turning the carbon in wood into a form considered permanent in many environments, such as soil, concrete, and asphalt. While not yet recognised by the ETS, carbon credits from biochar can be sold through Voluntary Carbon Markets (VCM), providing revenue in addition to the sale or in-forest application of the biochar itself.

Between sawmills, ports and thinning and harvesting operations, the forestry industry produces 3.9MT of residual biomass annually (Hall, 2021). All of this could be turned into biochar, making a useful product out of problematic residues. Most current efforts are focused on bioenergy, using wood chips in boilers or making liquid/gas/electric fuel at a fixed plant. These operations usually require mechanical comminution (chipping or horizontal grinding) of residues, a significant expense. Another major challenge to forest residue valorisation initiatives is transport costs. These increase with distance from the market, giving a radius beyond which material is uneconomic to collect.

The biochar production process is called pyrolysis and can produce useful liquid and gas co-products as well as solid biochar. While there are many potential feedstock sources (e.g., thinnings, cutover and mill residues), landing residues exist in both high volume and high concentrations. With any process, there exists a trade-off between operation efficiency and mobility. Kilns can be designed to produce biochar from any shape and size, allowing biochar to be produced on landings.

Study Objectives

Firstly, this study reviews biochar as it relates to plantation forestry in New Zealand. This includes the properties of post-harvest landing residues as a potential feedstock, the characteristics of biochar, and its applications. The review details the chemical process of biochar production and how changing temperature, and time parameters can affect the output. It identifies the equipment and techniques best suited for utilising the 2.4MT of landing residues produced annually by New Zealand plantation forestry (Hall, 2021). Three of the most promising commercially available biochar machines are then evaluated, in terms of their cost, productivity and operational considerations for use on forest landings. The system evaluation is based on Radiata pine as a feedstock, which accounts for 90% of New Zealand’s production forests (MPI, 2022). The intention is for this study to be used in conjunction with market research, to provide the basis for a biochar operation business case.

A Comprehensive Review of Biochar as it Relates to New Zealand Plantation Forestry

3.1 Feedstock sources and characteristics

To identify an appropriate biochar production method, it is necessary to characterise the target feedstock. Biochar can be produced from any biomass; however, it is recommended by the International Biochar Initiative (IBI) that biomass residues be used when available. This is to ensure operations do not compete with other productive land uses and so any carbon sequestered in the process can be considered additional. As residues give (by definition) no value to their producer and can even incur a cost for disposal, the cost of the feedstock can be assumed to be zero. While feedstock can include municipal waste and sewerage, agricultural prunings and forestry waste are more commonly used as can yield more biochar, with higher carbon content. In a study of potential biofuel feedstock in New Zealand, Hall (2021) reported that 3.9MT of woody residues are available annually, including the 2.4MT on landings.

The composition and volume of landing residue piles are dependent on many factors such as silviculture, harvesting equipment, operator skill and market conditions. Whole-tree harvesting (WTH) is where the entire tree is pulled to the landing for processing, resulting in a concentration of residues. The alternative is cut-to-length (CTL) extraction, where processing occurs in the cutover resulting in much smaller accumulations on landings. Extraction techniques such as skidding, shovelling and cable logging are most efficient when WTH. CTL extraction is only employed by forwarder operations, used in New Zealand by 16% of ground-based or 8% of all crews (Harrill & Visser, 2019). WTH is the preferred method when on steep slopes, which are a risky place to leave stem offcuts. The safe operation of traditional forwarders is also limited by slope. Poorly tended and wind-damaged stands have larger residue piles due to more material not meeting log market grades. Residue piles on flat terrain (ground-based extraction) can be more spread out, as landings tend to be larger (Visser et al., 2010) and offcuts can be pushed into the cutover without risk of mobilisation. Residues from steep terrain harvesting are often pushed temporarily off-landing into slash benches to free up valuable landing space during harvesting operations. As part of landing decommissioning, residues are ideally pulled back onto the landing.

Residue pile volume depends on the landing's setting area (area of harvest extracted to that landing). A study of piles from steep slope harvesting (Harvey, 2022), measured an average bulk volume of 170 m^3/ha harvested and 0.23 m^3/T extracted. The range of volumes measured, concurred with those from Hall (1993, 1994, 1998 and 1999), at 4 – 14% of total extracted volume. Of the bulk volume, residue piles are 25-35% solid volume (Hall, 2009). A study of landing density within small-scale woodlots found an average setting size of 12.8ha (Allum, 2020). Residue piles are composed of a variable ratio of branches to stem sections. For example, piles from an untended stand will contain a higher content of stem wood than from a value-recovery-focused crew with a nearby pulpwood market. Several residue pile studies in the '90s (Hall 1994, 1998, 1999) found piles usually contained a greater volume of stem sections than branches, with 57% of the total volume being stem wood over 1m in length.

The chemical composition of the feedstock is reflected in the yield and properties of the biochar. The carbon content of New Zealand's Radiata plantations was found to be 0.51 grams per gram of dry matter value (Garret, 2018), consistent with the IPCC guidelines (IPCC, 2006) for temperate and boreal conifers. For ETS reporting purposes, New Zealand currently assumes 0.50. While a slight underestimate on a whole tree scale, 0.5 is a better value for carbon in the stem wood (0.498), which Hall (1994) established as the greatest component of landing residues. Another characteristic of harvest residues is ash content, which is the inorganic fraction of wood remaining after combustion. This significantly varies in volume and composition between species and parts of the tree. In Scots pine, it varies between 0.2% (stem wood) to 1.8% in bark (Dibdiakova et al., 2015) and in softwoods is mostly calcium carbonate. The average ash content of radiata harvest residues was presented by Hall (2021) as 1.8% for stem sections and 4.5% for the entire pile. There have even been cases of 10% ash content (Visser et al., 2010). Such high values are a result of dirt becoming attached to the trees during the harvest process. This can be a problem for its use as biofuel, however, biochar production is relatively insensitive to inorganic contaminants.

The moisture content of radiata pine residues when first discarded is 55-60% (wet basis). Over time this decreases and settles at an equilibrium moisture content, determined by temperature but more so, by humidity (Basu, 2010). A study by Visser et al (2010), drying radiata logs during a Dunedin summer showed a large stack of logs drying to 37% over 6 months. Lower moisture contents were achieved over 4 months in smaller individual stacks of large logs (32%), small logs (23%) and split large logs (21%). Hall (2000) measured 37%, for a pile of residues after 6 months, 30-35% over the same time frame (Hall, 2007) and that 25% is possible with an extended summer of drying (Hall, 2009).

The basic density (D_b) of Radiata varies by region as shown in Figure 2. The density at a given moisture content (D_{MC}) up to 30%, accounting for volumetric shrinkage, can be found by Equation 1 (Collins, 1983).

$$D_{MC} = (1 + MC) \times \frac{3000\, D_b}{\big(3000 - (30 - MC)(0.017\, D_b + 4.7)\big)} \tag{1}$$

In practice, most residue piles are greater than 30% (fibre saturation point for Radiata pine), in which case the density at a given MC is given by Equation 2.

$$D_{MC} = D_b + \frac{D_b MC}{1 - MC} \tag{2}$$

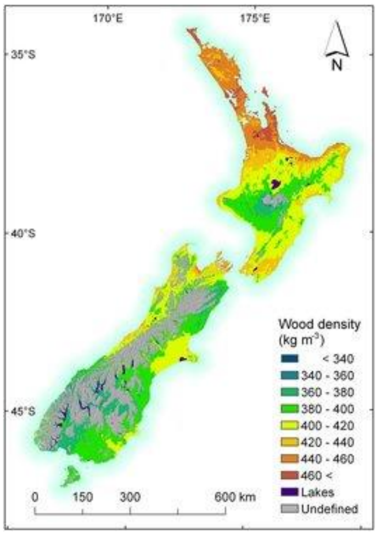


Figure 2. Radiata Pine wood basic densities across New Zealand. (Scion, 2010).

3.2 Applications for biochar

3.2.1 Carbon storage

The carbon in biochar is recalcitrant (resistance to biodegradation), making it a potential tool for combatting climate change. Much research has been conducted on biochar's degree of permanence in different environments. As suggested by *Terra Preta* soils and other available data, it is estimated that biochar's carbon has a half-life of millennia (Woolfe et al., 2010). Despite the obvious difficulty of proving this, long-term decay models extrapolated from 3-5 year experiments, have related the recalcitrant carbon fraction to the biochar's oxygen (O) and hydrogen (H) content. For example, the IBI Stable Carbon Protocol (IBI, 2013) bases the percentage of carbon in biochar with a 100-year permanency on the molar H:C ratio. If $0.4 < H:C < 0.7$, 50% of the carbon is permanent. If $H:C<0.4$, 70% is considered permanent. Camps et al. (2015) suggest these percentages are conservative, based on values of 70% and 92% for the same thresholds from Wang et al. (2013).

Whether or not this carbon sequestration provides a net climate-positive result, depends on the biochar's lifecycle, accounting for emissions released during production and transport. A best possible scenario presented by Woolfe et al. (2010) suggested biochar could reduce global emissions by 1.8 Pg of CO_2 per year (12 % of current anthropogenic emissions). Half of this comes from carbon sequestered as biochar and 30% from the replacement of fossil fuel energy with residual process heat. The remaining 20% comes from avoided CH_4 and NO_2 emissions which have global warming potentials of 30 and 273 times greater than CO_2 respectively (USA Environmental Protection Agency, 2023). A more recent global-level meta-analysis from Lefebvre et al. (2023), agrees that biochar could offset 6% of global GHG emissions.

The Kyoto Protocol Article 3.4 allows for soil carbon sequestration to be considered in countries' carbon markets. However, it is not yet included in the New Zealand ETS, possibly due to the complexity of soil carbon accounting and the fear that doing so will expose more carbon liabilities than opportunities created. The carbon removals from biochar production can be traded through VCMs such as Puro.earth, which independently verifies carbon removals and provides a trading platform. Puro's CORCs (CO_2 Removal Certificate = 1T CO_2 of removals) have become an index on the Nasdaq listings and are purchased by large companies such as Microsoft (2020). The CORC index is currently sitting at 120 Euro (Puro, September 2023). The full product lifecycle must be considered to ensure credits are only awarded for net carbon removals. Each tonne of carbon in of biochar is equivalent to about 3.67T of CO_2, however, the net CO_2 removals achieved are closer to 2.4T CO_2/T biochar (BC Biocarbon, 2023) (P. Burgess, personal communication, 2023).

3.2.2 Soil amendment

When added to soil, the incredibly porous structure of biochar creates conditions for greater fertility. A high BET surface area of up to $500m^2/g$ (Leng et al., 2021), helps retain nutrients, allowing lower rates of fertiliser application. It can improve soil physical properties like water retention, which is good for growth and can help cool the climate (Jehne, 2017). The habitat provided by its structure boosts microbial activity, increasing N_2 fixation and actively drawing down CO_2 and CH_4 (Winsley, 2017). Biochar can also reduce soil emissions. While fluxes of non-CO2 greenhouse emissions from soils are complex, it is agreed (Jeffery et al., 2017; Hedley et al., 2020; Lehmann et al., 2006), that biochar can have a positive impact by reducing CH_4 and NO_2 emissions.

The composition of inorganic elements in biochar reflects the chemistry of its feedstock. Biochar from pine stem wood has N, Ca, P, K and Mg content of less than 1% each (Hedley et al., 2020), meaning a low fertilisation value. However, the presence of bark, branches and needles in feedstock sourced from forest landings, would yield a more soil-enriching biochar. Pine biochar is alkaline, with a pH of 7-9 that can be beneficial when applied to acidic soils. This provides a liming effect of up to 5% $CaCO_3$ eq. (Hedley et al., 2020). Biochar is known for a high cation exchange capacity (CEC), although 17 meq/100g for pine biochar is not particularly high (Paul et al., 2020; Kharel, et al., 2019).

To see if biochar's improvements to soil properties resulted in improved productivity, Jeffery et al. (2017) conducted a global-scale meta-analysis of biochar addition to crop soils. The results of studies used ranged from -28% to +39% change in productivity. While they reported no significant effect on temperate soils, an average 25% increase was possible with 15 T/ha biochar application to tropical soils, mainly due to pH increase. Jeffery et al. (2017) and Hedley et al. (2020) agreed that biochar feedstock and pyrolysis technique should be tailored to the receiving soil for best results.

3.2.3 Other uses and markets

Biochar can also be used as an adsorbent in water treatment processes and as an additive to concrete and bitumen mixes. While burning technically redefines it as charcoal, it can be a renewable substitute for coal, used in industrial heating and steel-making processes. Activated charcoal can be produced by reheating with inert gasses to force open more pores, making continuous passages for even better adsorption. Biochar can be fed to animals as a dietary supplement. Adding 1-8% to the diet of young cattle increased growth and reduced methane production (Hedley et al., 2020).

Biochar is still in the early stages of adoption for many of its potential applications. The many variables involved in soil amendment (feedstock, production technique, soil type, land application rate and its effect on fertiliser and pesticide requirements) make uptake slow, as best practices are developed. A New Zealand study on grape marc biochar (Jones, McLaren, Chen, & Seraj, 2020), quantified its value as a traditional fertiliser (nutrients and liming potential) to be $87/T. Winsley (2017) reported estimates that increased carbon in soils could be worth $27–151/ha per year in increased milk solids production. Based on energy density, its value as a coal replacement was said to be from $300-675/T and if upgraded to activated charcoal, could potentially fetch $1,500/T (Jones et al., 2020). An estimate of the relative value and size of biochar's market in New Zealand and Australia are summarized in Figure 3.

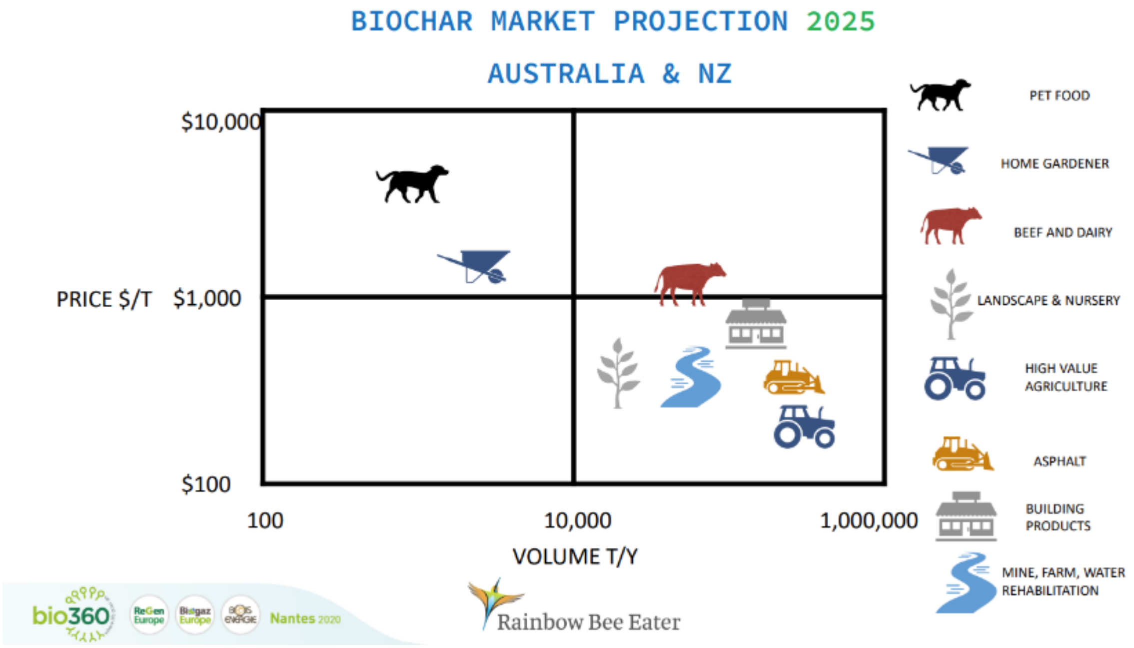


Figure 3. Relative value and volume of biochar markets in Australia and New Zealand - a 2025 projection (Burgess, 2020).

3.3 Biochar production

3.3.1 Pyrolysis chemical process

The process of producing biochar is named from the Greek words for fire (pyro) and separation (lysis). By restricting the oxygen availability while heating biomass, it is separated into new compounds, including solid biochar. The process involves heating biomass to a set temperature in a restricted oxygen environment, holding it there for a set length of time, then cooling the remaining solids before they can oxidise.

The different stages of pyrolysis and the variables affecting the products were detailed in the 'Biomass Gasification and Pyrolysis: Practical Design and Theory' handbook by Basu (2010). The stages are all overlapping and can occur simultaneously in different parts of the feedstock as the required temperatures are reached. Both endo and exothermic processes occur throughout the different stages. A well-designed system that burns condensable gasses, only needs external heat to reach pyrolysis temperature, at which point it is autothermal until all gasses have been burned off, released, or captured.

- **Drying (~ 100°C) -** Free and loosely bound moisture evaporates. Lignin begins to melt. H_2O vaporisation is endothermic, so external heat is required.
- **Torrefaction (100°C - 300°C) -** Chemical dehydration of hemicellulose and cellulose releases non-condensable gasses (H_2O, CO and CO_2). Dehydration is exothermic, so helps raise the temperature further.
- **Primary pyrolysis (200°C - 600°C**) – Condensable volatile organic compounds (VOCs - alkenes, aldehydes, esters etc.) are gasified from wood extractives and from cellulose (over 300°C). The remaining biomass solids change from long-chain molecules to aromatic ring structures, forming primary chars. This is also largely exothermic reactions (apart from early cellulose pyrolysis, which is endothermic up to 400°C.)
- **Secondary pyrolysis (300°C - 900°C) –** If heat is maintained, VOCs and condensable gasses (if not crack into non-condensable gasses (including H_2 and CH_4) and secondary char. This is slightly exothermic.

The controllable settings that determine the nature and yields of pyrolysis products are pyrolysis temperature, heating rate, residence time and oxygen availability. Pyrolysis temperature is the maximum temperature the feedstock is heated to. Temperature has a large impact on the properties of biochar, as summarized in Figure 4. Key changes in biochar properties with temperature are:

- There is high carbon retention up to 300°C degrees due to un-charred feedstock. Further carbon reduction at temperatures above 300°C, also removes H and O, resulting in char with a higher % of carbon but a lesser yield. Higher temperatures result in lower H:C and O:C ratios as well as higher aromaticity, meaning more stable biochar.
- Internal surface area increases rapidly around 450-550°C.
- The pH increases with temperature.
- Basu (2010) suggests increasing CEC with temperature. Campos (2019) and Gomez et al. (2013) concur for low temperatures, due to the existence of oxygen-containing functional groups, but suggest a CEC decrease above 350°C as oxygen is removed.

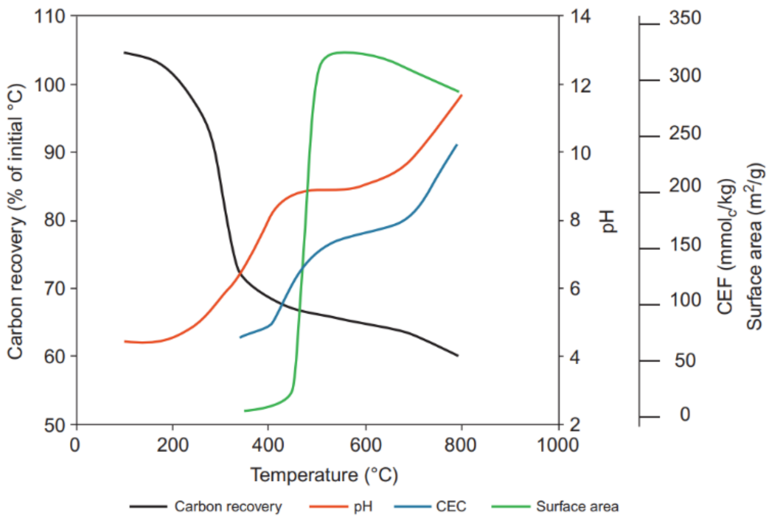


Figure 4. Qualitative diagram showing changes in biochar properties with changes in production temperature. (Lehman et al. 2007)

A high rate of heating to the pyrolysis temperature increases the degree of biomass gasification compared to solid biochar formation (Table 1). Condensable gasses can be collected straight away and cooled for maximum liquid yield while a longer residence time allows them to be cracked into non-condensable molecules for a maximum gas yield. Gasses formed in large biomass particles take longer to escape. An increased residence time facilitates the cracking of condensable gases into secondary char, increasing the solid char yield. Gasses flowing out from the centre of biomass particles, prevents inbound heat transfer by convection through pores. This leaves most heat transfer to thermal conduction which is low (~0.1W/m K), contributing to a slower heating rate for large particles. Biochar production from the large forestry residues characterised in Section 3.1, will therefore have a relatively a high yield and long residence time.

Table 1. A summary of main controllable settings to maximise pyrolysis products yield. Basu (2010).

		Controllable Setting		
		Heating rate	**Max temperature**	**Residence time**
Maximise Yield of…	**Char**	Slow (minutes-hours)	Low (400)	Long
	Liquid	Fast (seconds or less)	Med (450-650)	Short
	Gas	Fast seconds or less)	High (700-900)	Long

3.3.1 Biochar production equipment

There are many types of equipment designed to facilitate the pyrolysis process. Pyrolysis methods vary in scale and complexity, giving varying levels of control over yield or output properties. This study is focussed on biochar production on landings, so the production methods considered must be reasonably mobile. Production techniques can be broadly categorised as batch, continuous or open-air.

In batch pyrolysis, feedstock is enclosed in a chamber to exclude oxygen, and external heat is applied to initiate pyrolysis. Batch pyrolysis kilns often include mechanisms to recycle pyrolysis gasses and reduce externally fuelled heating requirements. The most common of batch pyrolysis kilns is a single chamber retort. These work much the same no matter their scale which can have a chamber up to the size of a 40ft container, like the Charmaker MPP40 (40ft mobile pyrolysis plant) (Figure 5). Feedstock size is limited only by space inside the kiln. They are not restricted by moisture content, but wetter feedstocks increase the time and external fuel required for carbonisation. Batch times can be 4 -14h depending on feedstock size, MC and char cooling mechanism. Multiple chambers can be integrated (Figure 6), so the residual heat in one chamber can be used to dry feedstock in the other, reducing external heating fuel use.

Figure 5. Charmaker MPP (left), Gongyi UT Machinery Trade Co. Ltd retorts.

Figure 6. Semi-continuous batch pyrolysis plants (from left) Charmaker FPP by Earth Systems, Custom plant by KTV Enterprises, Twin carbo retort.

Batch pyrolysis techniques focussed on biochar production from woody biomass, have reported yields (as a % feedstock's dry mass) of up to 36% (Azzi et al., 2019), 32% (Homagain et al., 2015) with 20-30% yields being common for pine (Hedley et al., 2020). According to Basu (2020), thermodynamic equilibrium can be used to calculate a maximum possible char yield of 35%.

Continuous pyrolysis uses a more complex method of mechanical oxygen restriction, to allow a continuous throughput. Instead of changing the temperature over time like batch pyrolysis, the feedstock moves through different areas of constant temperatures. The pyrolysis environment must allow feedstock to enter without the admission of oxygen and the speed of feedstock through the system must be adjusted to particle size. Therefore, continuous plants usually require small, even-sized feedstock. Using continuous pyrolysis for harvest residues would require them to be mechanically comminuted (chipped). Existing, potentially mobile continuous systems include those from Biochar Solutions Inc. in Colorado and the Charmaker CPP (continuous pyrolysis plant) from Earth Systems in Australia (Figure 7).

Figure 6. Charmaker CPP (Left) and unit from Biochar Solutions Inc.

Open-air pyrolysis methods do not use a physical chamber to enclose the burn. Flame cap pyrolysis (Figure 8) encloses a pile of biomass from the bottom and sides, then a fire is lit on the top. Flames only go upward but their heat radiates down to release VOCs from the pile below. These fuel the fire on top, helping to fully carbonise the biomass below. The 'cap of flames' on top causes smoke to be burned off. These systems allow more oxygen to enter the system, causing greater combustion of feedstock and lower yields.

Figure 7. Pit burn (left) and Ring of Fire kiln.

An open-air method that was developed with forestry in mind is the air curtain burner (ACB) (Figure 9). These work in the opposite way to traditional pyrolysis methods. Instead of excluding oxygen, the machine blows a sheet of air over an open-topped firebox, recirculating smoke and gasses back into the fire to be burned off. As it goes through its char phase, some biomass falls through a grill on the bottom, where a conveyor mechanism quenches it with water before it fully combusts. No literature was found on the chemical properties of the resulting product, however, the output is claimed to be high carbon (Air Burners Inc., 2023) and is widely sold as biochar for soil amendment purposes. ACB biochar should not be assumed of equal value in all markets to that from traditional pyrolysis.

Figure 8. Air Burners Inc. Charboss (left) and Tigercat Carbonator 6050

3.4 Biochar production risks

3.4.1 Forest nutrient removal

One concern raised about producing biochar production from forestry residues is the removal of biomass from the forest, taking with it nutrients that cannot then contribute to the growth of following rotations. While landings are usually retired from productive areas, any residues remaining on a landing before it is reused are usually pushed back into the cutover where nutrients can once again contribute to tree growth. Nutrient loss would also occur if an operation was expanded to cutover and thinning residues. These nutrient losses have been measured by multiple studies, however, at most sites, Garret et al. (2021) observed no significant change in growth between consecutive rotations, even at sites of full residue removal.

3.4.2 Pyrolysis emissions

The carbonisation of biomass into biochar prevents that wood from releasing CO_2 - a greenhouse gas (GHG) - into the atmosphere. Pyrolysis emits some CO_2, but less than if the wood would decompose naturally. However, pyrolysis also produces other gasses with global warming potential (GWP). The main gasses, CO, CH_4 and NO_2 are emitted in smaller amounts compared to CO_2 but have GWPs of 4.5, 23 and 290 times that of CO_2 respectively.

Studies on a small-scale batch pyrolysis kiln by Campos (2019) showed that without an effective abatement system, the CO_2 equivalent emissions from the CO alone were 10 times more than that sequestered in any biochar produced. It emphasized the importance for small-scale pyrolysis plants to have an efficient method of measuring and minimising greenhouse gas emissions. Batch and continuous kilns concentrate emissions through chimney flues. If these kilns do not come with an abatement method (e.g., a gas-powered flare or catalytic conversion) then it may be possible to fit one. For open-air kilns, there is less opportunity for adding additional abatement technologies. A study of five different flame cap kilns by (Cornelissen et al., 2016) found that, even without a dedicated abatement mechanism, these kilns emit more CO_2 but less of the more potent GHGs (CH_4, CH, NO_2) than an (unspecified) batch retort kiln. This is due to the greater levels of feedstock combustion and the presence of flames to burn off volatiles. According to a technical report by Ascent Environmental (2022), emissions from most air curtain burners are equal to, or less than, the Oregon Kiln (a flame cap pyrolysis method).

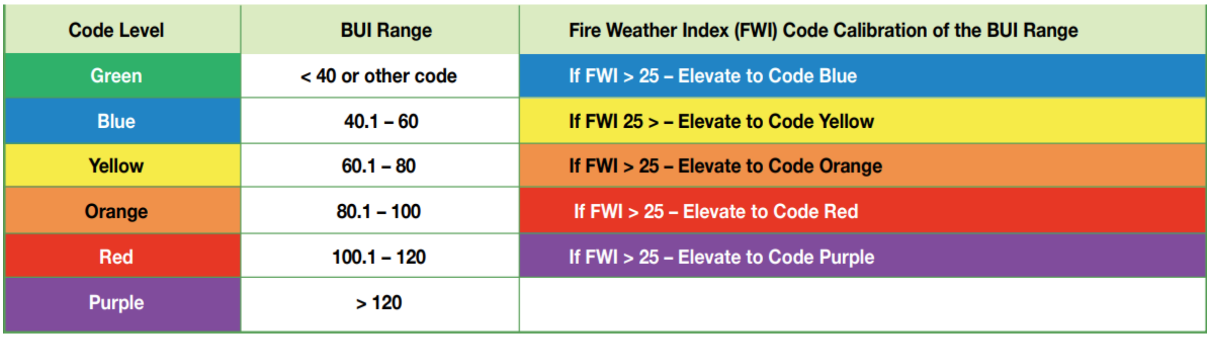
The effects of operation emissions on human health should also be considered. All gaseous emissions of pyrolysis are toxic if exposure is high enough, but the following emissions are specifically addressed in the literature. Campos (2019) identified CO exposure from operating a batch retort kiln to be safely within WorkSafe New Zealand limits of 50 ppm for 1-hour exposure. Another risk often associated with biochar, is exposure to poly-aromatic hydrocarbons (PAHs). In addition to short-term skin irritation and breathing difficulty, long-term carcinogenic, mutagenic, and teratogenic effects are possible (Buss et al., 2022). Exposure to particulate matter has also been raised as a risk of biochar production. Particulate matter of less than 2.5 and 10 micrometres respectively ($PM_{2.5}$ and PM_{10}) are the relevant measures used and have associated health and safety protocols. The technical report by Ascent Environmental (2022) showed that all major particulate and gaseous emissions were lower from flame cap and air curtain kilns than burning wood residues in piles.

3.4.2 Fire risk management

With global warming causing increased forest fire danger, operating fires of up to 1,500°C in the forest environment will raise understandable concern from forest stakeholders. Understanding the necessary controls and restrictions to manage fire risk from a biochar operation is important, for the health and safety of forest users and for obtaining insurance and permits. Controls (extra equipment/staffing) and restrictions (work areas or hours/days of operation) may also impact the feasibility and economics of a biochar operation. Recommendations relevant to on-landing biochar production are provided in The Forest Fire Risk Management Guidelines (New Zealand Forest Owners Association (NZFOA), 2018), which suggest mitigation measures for Forestry Operations in general and Hot Works specifically, based on fire indices.

Forestry Operations - Fire Indices by region are forecasted by Fire and Emergency New Zealand (FENZ) and NIWA as a function of temperature, wind, rainfall and relative humidity. Recommended mitigation measures depend on the Build Up (BUI) and Fire Weather Indices (FWI) as in Table 2.

Table 2. Forest Operations Fire Risk Management Code Levels (NZ Forest Owners Association, 2018)



Code Level	BUI Range	Fire Weather Index (FWI) Code Calibration of the BUI Range
Green	< 40 or other code	If FWI > 25 – Elevate to Code Blue
Blue	40.1 – 60	If FWI 25 > – Elevate to Code Yellow
Yellow	60.1 – 80	If FWI > 25 – Elevate to Code Orange
Orange	80.1 – 100	If FWI > 25 – Elevate to Code Red
Red	100.1 – 120	If FWI > 25 – Elevate to Code Purple
Purple	> 120	

Hot Work Operations - Biochar production would also be classified as a Hot Work Operation. In addition to those outlined for Forestry Operations, the following codes and associated measures should be implemented for Hot Works. These codes depend on the Fine Fuel Moisture Code (FFMC – from FENZ/NIWA) and grass curing (the percentage of grass that is dead or dying) as in Table 3.

Table 3. Hot Works code depending on FFMC and % grass curing (NZ Forest Owners Association, 2018)

FFMC	Grass curing		
	<40	40-80	>80
<76	🟩	🟩	🟩
76-83			🟨
84-87	🟩	🟨	🟧
88-91	🟨	🟨	🟧
92-95	🟨	🟧	🟥
>96	🟧	🟥	🟥

Some specific guidelines impacting biochar operation design under different fire risk codes include:

- *Green* - Work only on bare earth. Have hand tools, a minimum of 20 litres of water, along with an appropriate method of applying that water, within 5 metres of the work area. Patrol for 30 minutes after completion.
- *Blue* – Wet down the Hot Work area with soapy water.
- *Yellow* - No Hot Work unless on a 20-metre radius of bare ground.
- *Orange* - Consider completion of the Hot Work by 1300 hours or anticipate not working between 1230 and 1430 hours on a sunny day.
- *Red* - Patrol sites for at least one hour after machine shutdown. Consider stopping all Hot Work between 1200 and 1900 hours unless able to clear and wet down 20 metres of bare ground around the work site and maintain a good water supply on site.
- *Purple* - Stop all machines working on bare earth or processing sites at 1300 hours, unless 1000 litres of water with pump is on site, or a smoke chaser is nearby. Maintain observation presence for two hours afterwards.

FENZ can enforce open-air fire rules and permits depending on region and level of fire risk. They advise a fire season as Open, Restricted or Prohibited. Triggers for each season are unique to each region. For example, in the Tasman region, fire season is open for a BUI < 40, Restricted for BUI < 80 and Prohibited for BUI > 80 (I. Reade, personal communication, 2023). Both ACB and Flame Cap techniques would be likely categorised as ‘Burn piles/pits’, which are authorised in the Open season but require a permit in the Restricted season. They are not authorised during the Prohibited season unless a permit is granted while conditions temporarily reduce fire risk. The Fire and Emergency New Zealand Act 2017 gives FENZ the legal power to enforce this.

Air Burners Inc. promote the recommendations of Schapiro (2002) for operating ACBs: to leave a 100-foot (30m) clearance to any fire fuels, beyond which, they say there is there is little chance of large embers escaping. Very small embers can escape but generally burn completely before they hit the ground. They advise the fire could be extinguished in 10 to 20 minutes, should conditions require shutdown. An ember screen is optional to buy and helps avoid the spread of ember during the loading and burning process. The California Fire Department add, in Lee & Han (2017), that ACBs should be set up on flat ground (slope < 10%). The manual also recommends not operating at wind speeds over 32km/h.

If hot material does escape from a biochar operation, then the consequences are determined by the fuel, topography, and weather of the fire environment. The proximity and characteristics of flammable material to the biochar maker will influence the degree of restrictions and controls necessary for operation. It can be assumed the area surrounding the landing when a biochar operation moves in, is cutover. The cutover will contain fine fuels (<6mm diameter) in the form of needles, twigs, and weeds. These fuels respond rapidly to changes in relative humidity, and if dry, will readily ignite. The concentration of medium (branches, scrub) and heavy (stem sections) fuels around the landing depends on the logging crew's residue management techniques. The presence of medium and heavy fuels gives the potential for a more intense, less easily extinguishable fire. Cutover residues, especially if worked into windrows, are relatively contiguous, allowing a fire to easily spread. The landing surface can be assumed to have been bladed free of organic material and considered 'bare land', except for the residue pile itself. Residue piles are mainly composed of stem wood (heavy fuels) (Hall, 1998) and are generally not contiguous with other residues, meaning a lower risk of ignition and spreading, compared to the surrounding cutover. The average area of landings in New Zealand is 3900m^2 with a length-to-width ratio of 2:1 (Visser et al., 2010). An elliptical landing of this size would allow a biochar machine up to 25m separation from the cutover. This can be visualised in Figure 10.

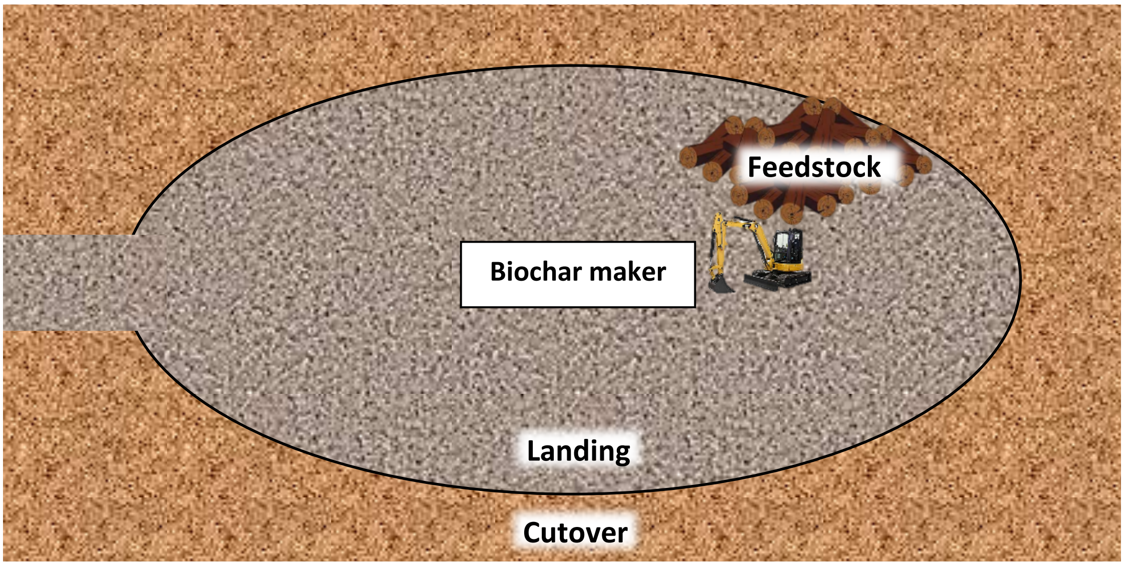


Figure 9. Operation layout plan view.

The probability of a fire starting in the cutover can be a function of aspect and elevation. Sunnier north-facing slopes will be drier and lower elevations generally have a lower relative humidity and warmer temperatures. Once a fire is started, its spread is determined by slope. For every 10% increase in slope, a fire will double in speed and half its speed for every 10% decrease (FENZ, 2017). Air temperature, rainfall, wind speed, and relative humidity (RH) all affect fire risk. Warmer temperatures dry fuels out, while rainfall makes them wet and less flammable. Higher wind speeds will transport more suspended solids further from the source, potentially into the cutover or residue pile. If an ember does reach the cutover, of all the weather factors, RH has the biggest impact on whether a fire will start. According to Wier (2007), there is only a 4% chance of a Spot-fire above 40% RH, compared to a 40% chance if below. If RH is less than 25% there is a 100% chance of ignition.

Evaluation of Forest Landing Biochar Production Systems

The New Zealand biochar market is still developing, meaning lower capital systems would likely be of most interest to early in-forest operations. Continuous pyrolysis operations would require a chipper or horizontal grinder, adding extra capital and operating expenses compared to batch or open-air methods. Initial calculations showed that these extra costs would not likely be offset by the increased productivity of biochar alone. While flame cap kilns can take unprocessed feedstock and have a very low capital cost, they were also not considered for this project. There is little productivity data on their use at a scale relevant to the volumes of forestry slash. While markets develop, the value of an operation could come more from residue removal than from sale of biochar and its carbon removals. With landing residue volumes of 2.4MT being produced and just 0.26MT being recovered annually (Hall, 2021), the availability of feedstock is unlikely to be a limiting factor. In many cases, especially where residues are too far from, or too dirty for biofuels markets, feedstock can be assumed to come at zero cost. Therefore, the low feedstock conversion efficiency (yield) of ACBs was not a concern.

Three commercially available mobile pyrolysis plants best suited for use on New Zealand forestry landings were selected for evaluation. Amongst potential batch pyrolysis kilns, the Charmaker MPP40 from Earth Systems was selected as the best option. This is due to its ability to process large sizes of feedstock, the ability to adjust temperature settings and its inbuilt quenching system. Having been designed with forestry in mind, the Air Burners Inc. CharBoss and Tigercat 6050 Carbonator ACBs were also considered to have high potential. These three promising biochar production methods were evaluated in terms of their cost, productivity and operational considerations for safe utilisation. A costing model was developed to obtain an operation day cost for each biochar machine. This was divided by estimates of daily biochar production to yield a unit cost.

4.1 Biochar operation system design

The following sections outline the main equipment requirements and methodology for operating each biochar machine. It provides justification for choice of equipment which contributes to the cost of each operation.

4.1.1 Air Burners Inc. CharBoss

Dimensions (LxWxH): 6.60 x 2.34 x 2.03m
Weight: 7.9T
Origin: Florida, USA
Cost: $270,000 NZD (inc. freight and port fees)

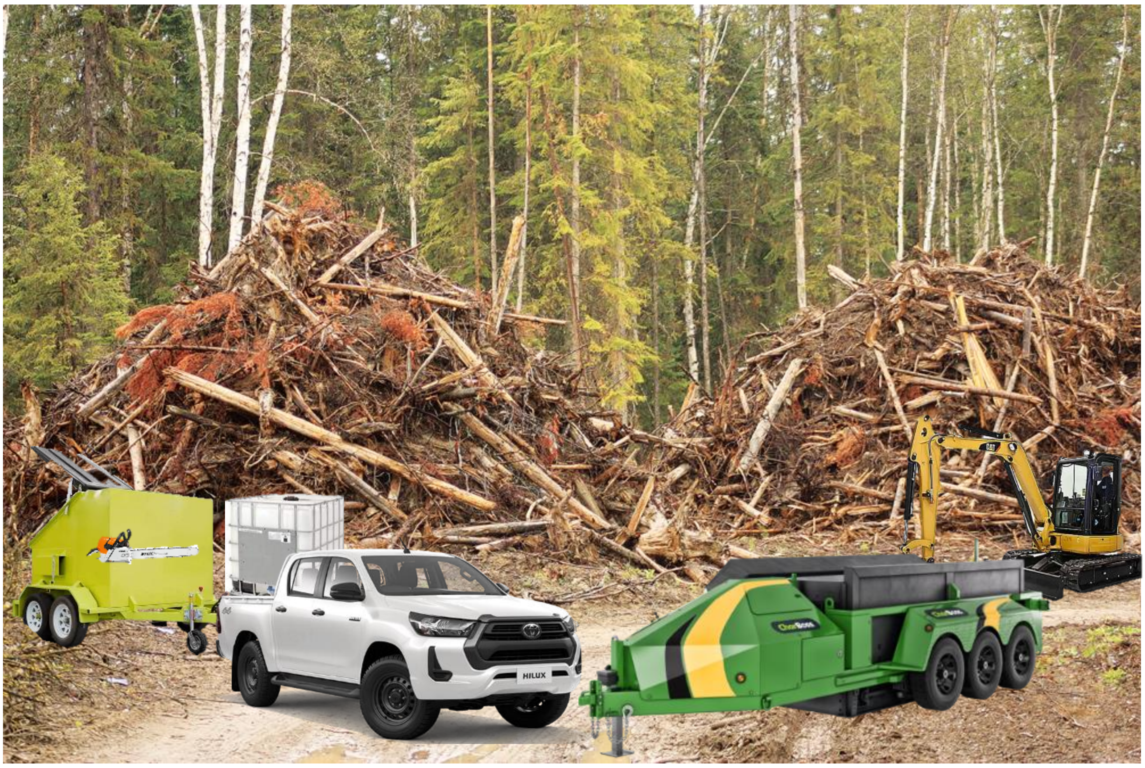


Figure 10. CharBoss operation supported by 1 x operator, 5.5T digger, 1000L water tote and a crew Ute with trailer

Operation of the CharBoss initially requires a fire to be established in the firebox before the 'air curtain' fan is gradually brought up to full speed. It is expected to take one hour to reach full operating capacity (Fountain Engineering Ltd, 2000). This will depend on the operator's fire building expertise and the use of accelerants - 3 gallons of diesel is recommended in the manual (Air Burners Inc., 2023). The CharBoss can burn through up to 2T of biomass per hour (Lee & Han, 2017), which is loaded in through the top of the firebox. A 5.5T digger was decided to be the most cost-effective machine for loading, considering feedstock would be no greater than 0.5T (firebox length limits feedstock to 3.6m). In the event of feedstock being too large for the firebox, it can be trimmed to length with a chainsaw. As the feedstock burns it goes through a biochar phase. Some of this hot char falls through the shaking grill in the bottom of the firebox, where a conveyor delivers it into a tray of water which halts further combustion. The water tray loses 50L per hour through evaporation and adsorption into the biochar. The 400L/day of water required can be bought onto site by the operator each day in a 1000L tote on or towed behind a Ute. The 2.1m^3 (0.63T when wet) of biochar produced in a day can be transported out of the forest in the back of the Ute or trailer. Consuming feedstock at a rate of 1T/hour, the CharBoss would take 10 weeks to process an average 340T residue pile (reasoning in Section 4.3)

4.1.2 Tigercat 6050 Carbonator

Dimensions (LxWxH): 12.19 x 3.61 x 3.66m
Weight: 41.7T
Origin: Canada
Cost: $1.4 million (estimated)

As of 2023, the Carbonator has been taken off the market for redevelopment but is expected to be back in production in 2025. Specifications for this updated machine are therefore not available but have been estimated using previous model specifications, product representative's expectations, and comparison to other ACBs.

Figure 11. Carbonator operation supported by 2 x crew, 14T digger, 5000L water truck and a bulk truck.

The same start-up procedure as for the Charboss can be assumed for the Carbonator. Once up to full productivity, the Carbonator can burn through up to 20T of biomass per hour (Tigercat, 2020). The firebox dimensions limit feedstock length to 9m, so one tonne would be the maximum piece size. To load this into the 3.7m tall Carbonator, a 14T digger was decided to be the best machine. As in the CharBoss, biochar falls through the grill on the bottom of the firebox. It is quenched by a plumbed-in water supply and augers carry it from the machine and onto a conveyor into the bulk truck. The Carbonator uses up to 1200L of water per hour, which could be serviced by a 5000L water truck, with one refill per day. The 35m^3 (11T when wet) of biochar produced in a day can be transported out of the forest in a 4-axle bulk truck. This truck would also serve as transport for the two crew while the water truck remains in the forest. Consuming feedstock at an average rate of 13T/hour, the Carbonator would process a landing in 4 days.

4.1.3 Earth Systems Charmaker MPP40

Dimensions (LxWxH): 12.19 x 2.44 x 2.59m
Weight: 20T
Origin: Australia
Cost: $760,000 (landed in New Zealand, plus an estimated $20,000 for a second set of cages)

Figure 12. Charmaker operation supported by 1 x crew, 20T front end loader, 5.5T digger, 15m^3 skip with truck.

The Charmaker comprises a 40ft container filled with 36m^3 of steel cages. These cages are filled with feedstock and then loaded into the container. According to the manufacturer, the weight of a full cage can be up to 5T. The operation should utilise a 20T front-end loader to load and unload the cages. Two sets of cages would be used, so one set can be filled while the other is pyrolyzed. With seven hours to wait for one batch, filling 36m^3 of cages would not come under time pressure. The productivity of a batch, however, is proportional to the solid volume of feedstock. The packing ratio (solid volume/bulk volume) of the feedstock should be maximised within the time available. The cages can be loaded with feedstock up to 3m in length, meaning some lengths will need a chainsaw to trim down. The loading of feedstock could be accomplished with a 5.5T digger.

Once the pyrolysis of a batch is complete, cages can be partially quenched by an internal sprinkler system to reduce combustion once doors are opened. They are then dunked in a tank of water to fully quench. This operation could use a skip truck with a 15m^3 skip. It could cart water from the nearest source, serve as the quench tank, and then backloaded with the 12m^3 of biochar produced by the single batch per day. Processing 36m^3/8T of feedstock per day would mean spending 10 weeks per landing.

4.2 Operational considerations

4.2.1 Fire risk management

In a machine like the Charmaker, the pyrolysis reaction is physically contained. The only potential risk of hot material escaping is from any biochar not quenched by the internal sprinklers before opening. The Charmaker is not an open-air fire so would not be subject to Restricted or Prohibited fire season restrictions. It would still be classified as a Hot Work operation so should be guided by the NZFOA Guidelines (2018), or the most recent local equivalent. These guidelines have been interpreted in the context of a Charmaker operation in Table 4. The fan in an ACB reduces but does not eliminate the risk of hot solids from leaving the firebox. Some burning material can escape when the fire is agitated during the loading of feedstock. Effort should be made to reduce the height from which feedstock is dropped. Table 4 also suggests specific measures for operating ACBs (CharBoss and Carbonator) under different levels of fire risk. Risk levels (Fire season, Forestry and Hot Works codes) do not necessarily correspond as below, and measures corresponding to the highest level of code should be applied.

Table 4. Suggested fire risk management measures for forestry landing biochar production.

Fire Season	**Hot Works Code**	**Forestry Operation Code**	**Measure**	
			Batch Pyrolysis (Charmaker)	**Air Curtain burners**
Open	🟩	🟩	Firefighting hand tools (shovel, cordless water blaster + water backpack, Diesel pump system with at least 60m hose. Mobile, full 1000L tote on site in addition to water for biochar quenching (Figure 14). Patrol for 30 minutes after completion.	
Restricted	🟨	🟦	Wet down the area between the Charmaker and the quench tank before opening the chamber.	Permit required. Wet down the area within 4 meters of the worksite before starting.
		🟨		Install a steel ember screen (Figure 15) around the firebox. Do not operate in winds above 25km/h.
			Ensure a 20m minimum distance from the cutover.	
	🟧	🟧	No opening of the chamber between 1230 and 1430h on a sunny day.	No operation between and 1230 1430h on a sunny day. A crew member with boots on the ground watching for escaping sparks is required at all times.
🟧	🟥	🟥		Wet down slash pile, especially any fine fuels while ACB is in operation. Patrol site for 1 hour after shutdown.
Prohibited		🟪	Between 1200-1900h wet down area of machine use (log trimming and cage loading)	No operation

Figure 13. Suggested firefighting equipment to be always on-site.

Figure 14. An ember screen fitted to an Air curtain burner to reduce the risk of hot solids escaping (Lee & Han, 2017).

The degree of controls and restrictions on a Charmaker operation would depend on the operator's and forest owner's appetite for risk. Assuming the measures suggested in Table 4 are followed, the implications for the operation's economics are:

- Extra operating supply costs for firefighting equipment.
- Extra fuel use to collect the extra water for wetting down areas on higher-risk days.
- Operation time-of-day adjustment to avoid chamber opening during windy or hot conditions.
- It is assumed for operation costing that there are zero workdays lost due to fire risk.

As open-air fires, ACBs would be subject to FENZ fire season restrictions. In an Open fire season, there are no enforceable restrictions, so measures would again be up to the crew and forest owner. In a Restricted fire season, a permit will be required for each site of operation. The conditions of a permit will likely enforce the measures suggested in Table 4. In addition to Forestry and Hot Works Code levels, controls and restrictions will also depend on the fire environment of the operation. The characteristics of surrounding fuels and topography, as well as current and recent weather conditions, will determine if and how operation is possible. Restrictions would likely include thresholds on windspeed (25km/hour) and RH (40%). The Guide to Pile and Windrow Burns as a Land Management Tool (FENZ, 2017) is a useful document for further developing a risk management plan.

Fire season elevation thresholds vary by region, but considering those for the Tasman region (Open up to 40 BUI, Restricted up to 80 and Prohibited above), the implications on operation economics include:

- Extra operating supply costs for firefighting equipment.
- Extra fuel use to maintain the water supply for wetting down areas on higher-risk days.
- Operation time-of-day must be adjusted to avoid windy or hot midday conditions.
- During the Restricted season, with good planning and management around timing and location, it should be possible to meet permit conditions and lose zero workdays.
- The BUI is above 80 for around 11 days per year (average since 2000 from Nelson Aero and Hira weather stations) which means no operation.

4.2.2 Pyrolysis emissions

Despite both batch pyrolysis and ACBs being cleaner burning than traditional burn piles, being a commercial operation and a daily occurrence, could mean a resource consent is required for 'Discharges to Air'. The emissions from ACB have been well studied as part of their spread throughout North America. Table 5 presents the emissions per tonne of feedstock (Ponderosa Pine) published by Ascent Environmental (2020) and translated into hourly emissions from the Carbonator (at 13T/h feedstock) and the CharBoss (at 1T/h feedstock). Batch pyrolysis emissions abatement technology can vary greatly. The Charmaker technology appears to be similarly advanced compared to a unit that underwent emissions testing by Sørmo et al. (2020). Their emissions measurements 'per kg of biochar' were converted to 'per tonne of 30% MC Radiata' and spread over the expected seven-hour batch time, for an hourly rate comparable with ACBs.

Table 5. Hourly pollutant discharges to air from each biochar maker studied.
***Emission data not found*

	Pollutant							
	CO_2	CO	CH_4	VOC	PM_{10}	NO_x	SO_2	N_2O
Air Curtain Burner emissions (kg/T feedstock) **(Ascent Environmental, 2022**)	738	1.3	2	0.45	0.65	0.5	0.05	0.07
Carbonator emissions@ 13T feedstock/ hour (kg/hour)	9588	16.9	26	5.9	8.5	6.5	0.9	0.65
CharBoss emissions@ 0.8T feedstock/hour (kg/hour)	590	1	1.6	0.4	0.5	0.4	0.06	0.04
Batch pyrolysis emissions (kg/T feedstock) **(Sørmo, et al., 2020)**	251	1.2	0.7	0.2	0.1	0.1	**	**
Charmaker emissions (kg/hour)	35.9	0.18	0.1	0.22	0.02	0.16	**	**

Details on permitted emission levels were not found in any region plans, so the Tasman District Council was contacted for comment. These predicted emissions did not raise any concern from their air quality expert, especially as discharge would most likely be to relatively rural airsheds. According to their regional plan, a Consent would be required if feedstock less than seven days old was used, likely because traditional burning techniques are not as clean when the material is green. If a biochar maker can be proven to process green material with similar emissions to those above, then permission should be granted without the need to regularly reapply for consent.

4.4 Productivity estimation

The productivity of the three operations is highly dependent on the moisture content and geometry of the feedstock. Published productivity numbers rarely state the characteristics of the feedstock used. Nor do they often define the particle size or moisture content of biochar produced, making output weights or volumes difficult to compare. The feedstock, as characterised in 3.1 is assumed to be piles of Radiata pine residues with a moisture content of 30%. Full data, including sources and reasoning for the following productivity estimates are outlined in Appendix A and summarised in Table 6.

One batch from the Charmaker is expected to take 7 hours of pyrolysis, plus an hour for loading and unloading, meaning an 8-hour day onsite. Assuming a 25% yield, one batch is expected to produce 1.3T of oven-dry biochar. ACBs take one hour to reach full operating capacity and one hour to cool down after the last feedstock is loaded. Unlike the Charmaker, ACBs provide continuous production, so the workday length is flexible. To maintain a realistic workday, and allow best comparison with the Charmaker, ACB operators will also be on-site for 8 hours. Assuming 30 minutes of set-up and 50% production from the first and last hours of operation, there will be the equivalent of 6.5 fully productive hours per day. Both ACBs are assumed to yield 6% biochar. The Carbonator will process 85T of feedstock into 3.6T of biochar per day. The CharBoss is expected to process 6.5T of feedstock into 0.29T of biochar per day.

Table 6. Biochar productivity comparison.

	Feedstock input (T/8h workday)		**Yield (Oven dry mass biochar/ feedstock)**	**Biochar output (T/8h workday)**	
Method	30% MC	Oven-dry		Oven-dry (100kg/m^3)	Post-quench (300kg/m^3)
Charmaker	7.35	5.14	25%	1.29	3.86
CharBoss	6.50	4.55	6%	0.22	0.66
Carbonator	84.5	59.2	6%	3.55	10.65

The Charmaker allows the biochar's properties to be fully customised by the adjusting the pyrolysis conditions (temperature, residence time and oxygen supply). When maximised for % carbon, the H:C ratio can be as low as 0.3 (Earth Systems, personal communication 2023). The biochar produced by the Carbonator is claimed by the manufacturer to be 80-90% carbon (Tigercat, 2020). This suggests a similarly low H:C ratio. A video from a Carbonator demonstration revealed some unburned needles and twigs mixed in with the biochar produced (MissoulianVideo, 2022). It is possible that small feedstock could fall through the grill before being fully charred. If their feedstock conversion efficiencies (yields) are four times lower than from batch pyrolysis, the biochar output from ACBs would contain a 4 times higher ash content than from the Charmaker. Techniques for optimising the yield and biochar properties can be developed with experience (S. Joseph, personal communication, 2023), but in general, the output from ACBs will be a lower percentage of pure biochar and have less predictable characteristics.

4.3 Estimating operational costs

The cost of each biochar operation was derived using a costing template from the Logging Industry Research Organisation (LIRO, 2019). It accounts for machine rates, operating and overhead costs, labour and transport of equipment, biochar and crew, to give a day cost for each operation. GST was excluded from all costs. Assumptions regarding the average feedstock distribution and the biochar output were made to give a unit cost of producing biochar from each method.

Using online marketplaces, product manuals and industry contacts, the necessary variables (such as those in Table 7) were estimated and used to derive the fixed and running costs for all equipment. Justification and references for values are given in the costing model spreadsheet (Appendix C).

Table 7. Key machine and vehicle costing variables used for biochar operation costing.

Machine	**Purchase price ($)**	**Daily use (hours)**	**Depreciation time to 10% Purchase price (years)**	**Fuel consumption (L/hour)**	**Day Cost ($/day)**	**Transport cost ($/hour)**
Charmaker	780,000	7	10	5.7	640	200
Carbonator	1,400,000	7	10	20	1,465	340
CharBoss	270,000	7	10	4.2	295	120
Digger – 5.5T	135,000	6	11	5.8	155	120
Digger – 14T	250,000	6	11	13	320	280
Front end loader	200,000	1	20	26	145	220
Vehicle	**Purchase price ($)**	**Lifetime (km)**	**Used price ($)**	**Fuel use L/100km)**	**Road user charges ($/100km)**	
Crew Ute	60,000	250,000	25,000	9.5	76	
Water truck	95,000	250,000	30,000	13	126	
Bulk truck	300,000	750,000	120,000	36	350	
Skip truck	200,000	750,000	70,000	22	126	

The lifespan and salvage value of forestry equipment are dependent on many factors, such as operating conditions, build quality, utilisation, and second-hand market. Sourcing depreciation values for each machine seperately would be both difficult and subjective, especially for biochar technology which is relatively new to the market. For simplicity and consistency, depreciation was assumed to be to 10% of its purchase price over 10 years for a full-time (7 hours of utilisation/day) machine (R. Visser, personal communication, 2023). Repairs and maintenance (R&M) is another variable that was standardised across machines and vehicles as being 30% of depreciation. An interest rate of 5.94% was used, weighted to assume a 25% equity in the average capital invested (ACI), a 7% borrowing rate and a 2.75% lending rate. The insurance cost used was 6% of the ACI in each machine. The price of diesel used was $2.00/L. These assumptions are summarised in Table 8.

Table 8. Cost variable assumption summary

Depreciation of full-time machine	R&M % of depreciation	Diesel price	Interest rate (weighted to ACI)	Insurance cost (% of ACI)
10% over 10 years	30%	$2.00	5.94%	6%

All operations were assumed to be run as a stand-alone business. Overhead costs such as office equipment, administration, accounting, and finance charges were included, amounting to $13,000/year. The cost of operating supplies covers the depreciation of equipment beyond the main machines and vehicles. It includes firefighting equipment, water pump, personal protective equipment (PPE), radios and training costs, summing to $5,100.

Transport of machinery, feedstock and biochar can all influence the economics and carbon footprint of an operation. In this study, operations occur on the landing, therefore feedstock transport cost is zero. The impact of feedstock's geographical distribution on an operation's cost and carbon footprint is an important element of this system evaluation. To allow the costing model to be applied to different situations, the feedstock distribution has been simplified to be in terms of five variables (Figure 16).

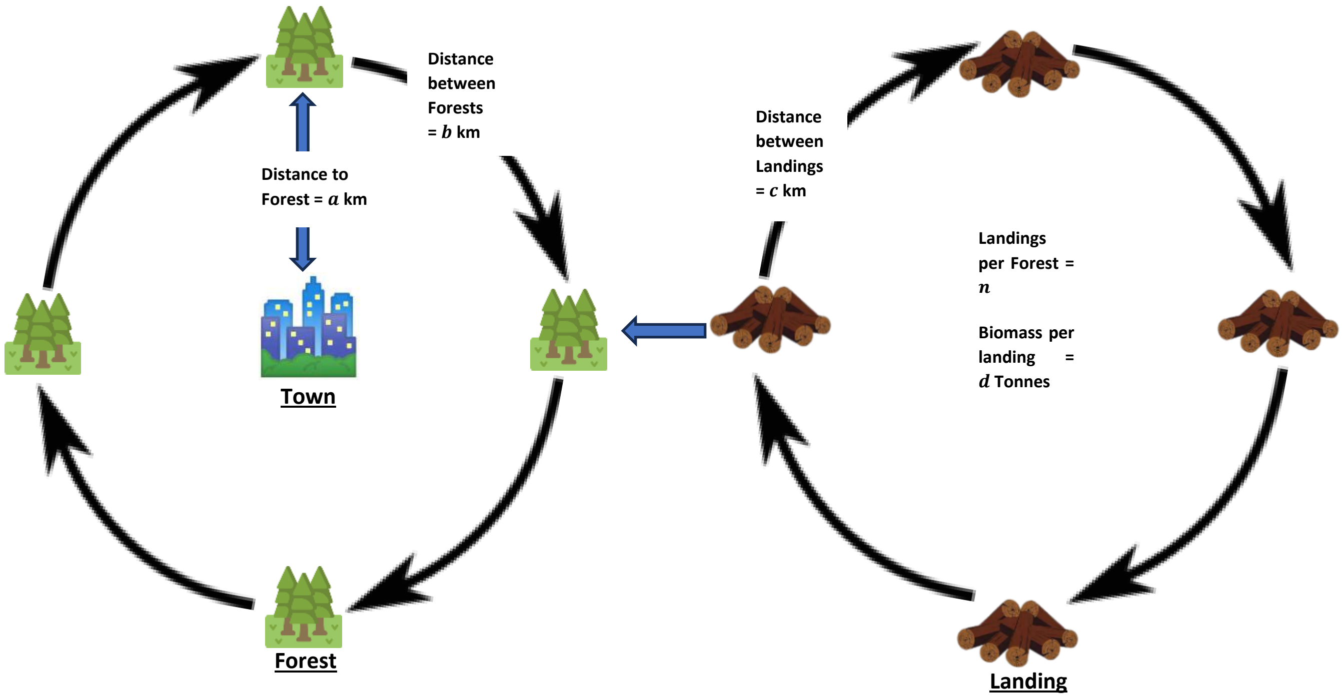


Figure 15. Diagram showing variables used to model geographic distribution of feedstock.

- Each forest landing contains a harvest residue (feedstock) pile of constant mass ***d***.
- Each forest contains ***n*** landings, assumed to be spaced at **c** distance from each other.
- Each forest is located at ***b*** distance from the next forest and ***a*** distance from Town.
- Town is home to the crew, machine transport providers and the biochar market.

Each machine in an operation has an in-forest and inter-forest transport cost and fuel consumption. In-forest shifts are assumed to be short enough for machines to walk themselves, except for the Charmaker which requires a truck. Inter-forest shifts are assumed to require trucks to move all machines. For the results presented in this study, the average distance of a forest to town was assumed to be 50km, and the distance from one forest to the next 30km. Each forest was assumed to have 10 landings with appropriately aged residue piles (dry but not rotten, likely between 6 months and 2 years,) at an average of 500m spacing.

Yield statistics for biochar production are generally based on feedstock weight. An average mass of feedstock per landing is therefore an important metric. Using the values in Table 9, (based on section 3.1) a typical landing residue pile will contain 340T of biomass.

Table 9. Feedstock properties assumptions

Species	Radiata pine
Basic density (D_b)	420kg/m^3
Aged Feedstock Moisture Content	30% (after at least 6 months of drying)
Feedstock density (D_{30})	618kg/m^3
Landing residue volume	170m^3/ha (of harvest setting)
Harvest setting area	13 ha

It is assumed that the operations are run by full-time staff who are paid $35/hour for 260 days/year. Daily work hours are 8 hours on-site plus travel time, which is a function of the 'distance to town' and an average driving speed of 75km/h. Paid non-workdays include statutory holidays, annual leave, and sick days. For the ACBs, it accounts for days where work may not be possible in the event of prohibited fire season or extreme wet weather. Air Burners Inc. (personal communication, 2023) claim their ACB can operate in the rain. However, it was judged that operation would be unrealistic for at least 5 days per year. The resulting workdays (summarised in Table 10) were used to calculate daily labour and fixed equipment costs.

Table 10. Summary of paid vs work days assumptions

	Charmaker	**CharBoss**	**Carbonator**
Total paid days	260	260	260
Less: Statutory holidays	12	12	12
Annual leave	20	20	20
Sick leave	10	10	10
Fire risk days	0	11	11
Wet days	0	5	5
Leaves workdays:	**218**	**202**	**202**

The parameters discussed above were input to an Excel-based costing model (Appendix C). The outputs most relevant to determining the feasibility of a biochar operation are presented in Table 11. The unit costs for producing biochar on a forest landing are lowest for the Tigercat Carbonator at $907/T, followed by the Charmaker at $1,419/T (0.6 times higher) and the CharBoss at $4,146/T (4.5 times higher). Value for a biochar operation can be not only realised from the biochar product, but also from the removal of residues. The cost of removing air-dried harvest residues from a landing by extracting it as biochar is also the lowest using the Carbonator, at $38/T. It costs 4.5 times more if using the CharBoss and 6.5 times more using the Charmaker. Harvest residue quantities are most often visualised as green Tonnes, so the cost for removing the green equivalent weight is also given in Table 11.

Table 11. Comparison of key biochar operation costs

	Charmaker	CharBoss	Carbonator
Capital cost	$1,327,000	$486,000	$2,057,000
Day cost	$1,825	$1,132	$3,218
Cost/T biochar produced	$1,419	$4,146	$907
Cost/T feedstock **(Equivalent green feedstock)**	$248 ($154)	$174 ($108)	$38 ($24)

A potential source of income from biochar is from carbon dioxide removals. Voluntary carbon markets like Puro.earth award net removals, therefore emissions from the operations are of interest. The costing model calculates fuel consumption data, which is presented in Table 12.

Table 12. Operation fuel consumption comparison

	Charmaker	CharBoss	Carbonator
Fuel use/day	133L	86L	281L
Fuel use/T biochar	103L	314L	79L

4.5 Sensitivity analysis

The assumptions used to calculate the costs in Table 11 were made with varying levels of certainty. Some variables would be relatively predictable to a contractor setting up an operation. They would have real quotes (prices, wages, financing, and insurance), specific equipment knowledge (depreciation, R&M) and local feedstock distribution and characteristics data. Some variables, such as fuel price and unfavourable weather conditions, are subject to more change over time, but can be forecasted. Assumptions for other variables, notably those governing biochar machine productivity, will not change significantly over time but significant epistemic uncertainty. The data informing assumptions for Charmaker batch time, ACB throughput and ACB yield are both limited and based on highly variable productivity data (Appendix A). This variation comes from both uncertainty in measurement conventions (dry vs wet moisture contents) and the inherent variation of productivity with feedstock moisture content and geometry.

The significance of any assumption's uncertainty depends on the objective function's sensitivity to that variable. The effect on biochar production unit cost of key variables was investigated through sensitivity analysis. For each variable, a realistic high and low value was chosen, leading to either a favourable or unfavourable change in unit cost. The reasoning for these high and low values can be found in Appendix B. The sensitivity of biochar production unit cost to key operational cost, feedstock distribution and productivity variables are quantified and compared in (Figures 17-19).

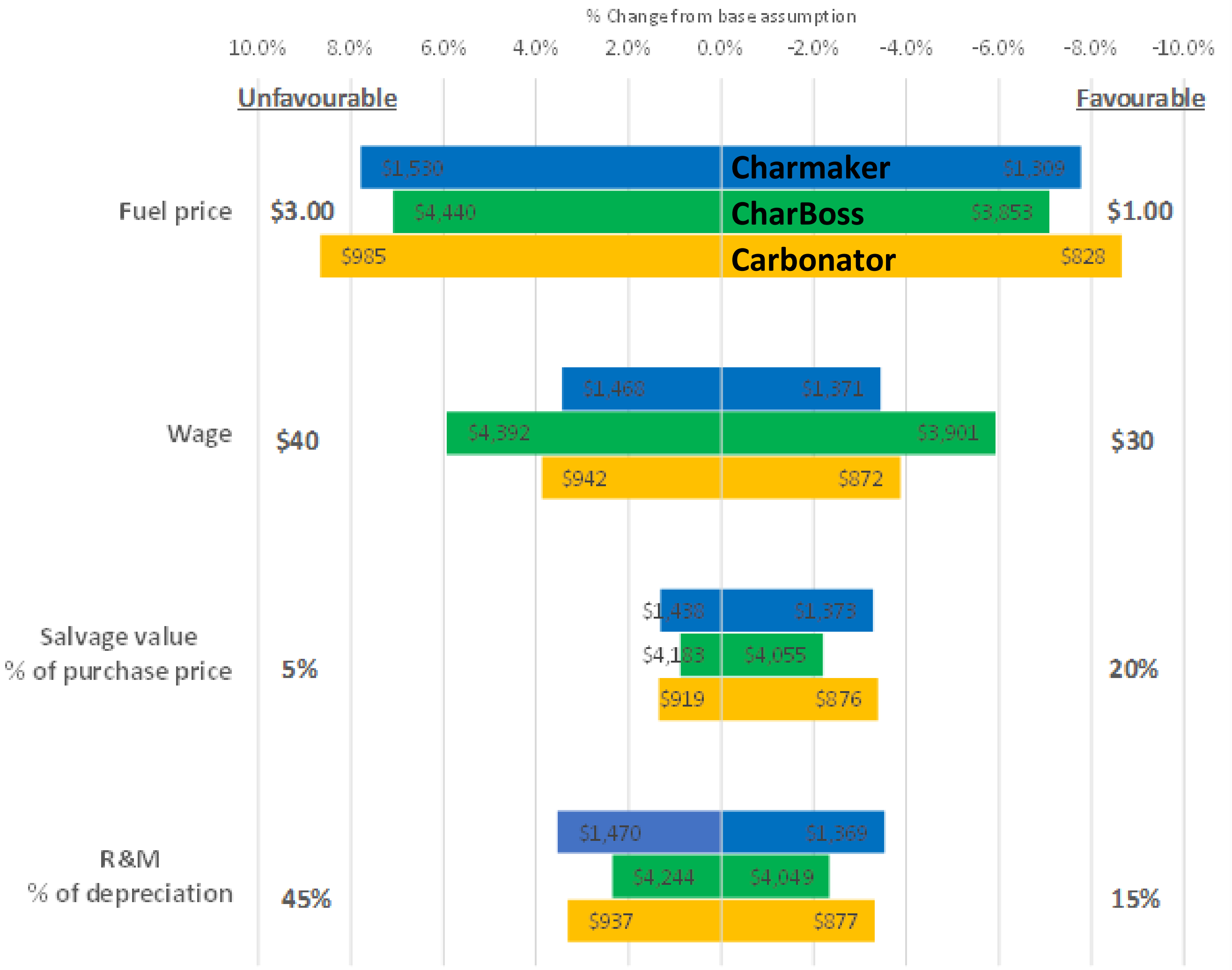


Figure 16. Biochar production cost sensitivity to operational cost variables.

While fuel is only around 15% of total operation costs, it has a relatively high unit price variability, as evident in recent years, so can have a high influence on production unit cost. Wages account for 25-40% of total costs, yet any changes will be relatively small and predictable. The machine feed rates are not likely to demand high productivity from the operator, but the high risks involved warrant the need for a quality crew. Either operation would be the first of its kind in New Zealand, meaning a substantial learning/training period is likely for any operator. This makes staff retention important, which could encourage a higher wage.

Figure 17. Biochar production cost sensitivity to feedstock distribution variables

Forest spacing affects the duration, and forest size affects the frequency of machine transporter hire. Forest spacing has a bigger impact due to the fixed costs per shift. This explains the higher sensitivity of the Carbonator operation, where higher throughput means it will move between landings and forests 12 times more frequently. As expected, the unit cost increases with forest 'distance from town'. This significance of distance to market would most likely be lower for a biochar operation compared to residue recovery operations such as for biofuel, where whole or chipped residues are extracted. This suggests that biochar could be a more feasible option for forests in remote locations.

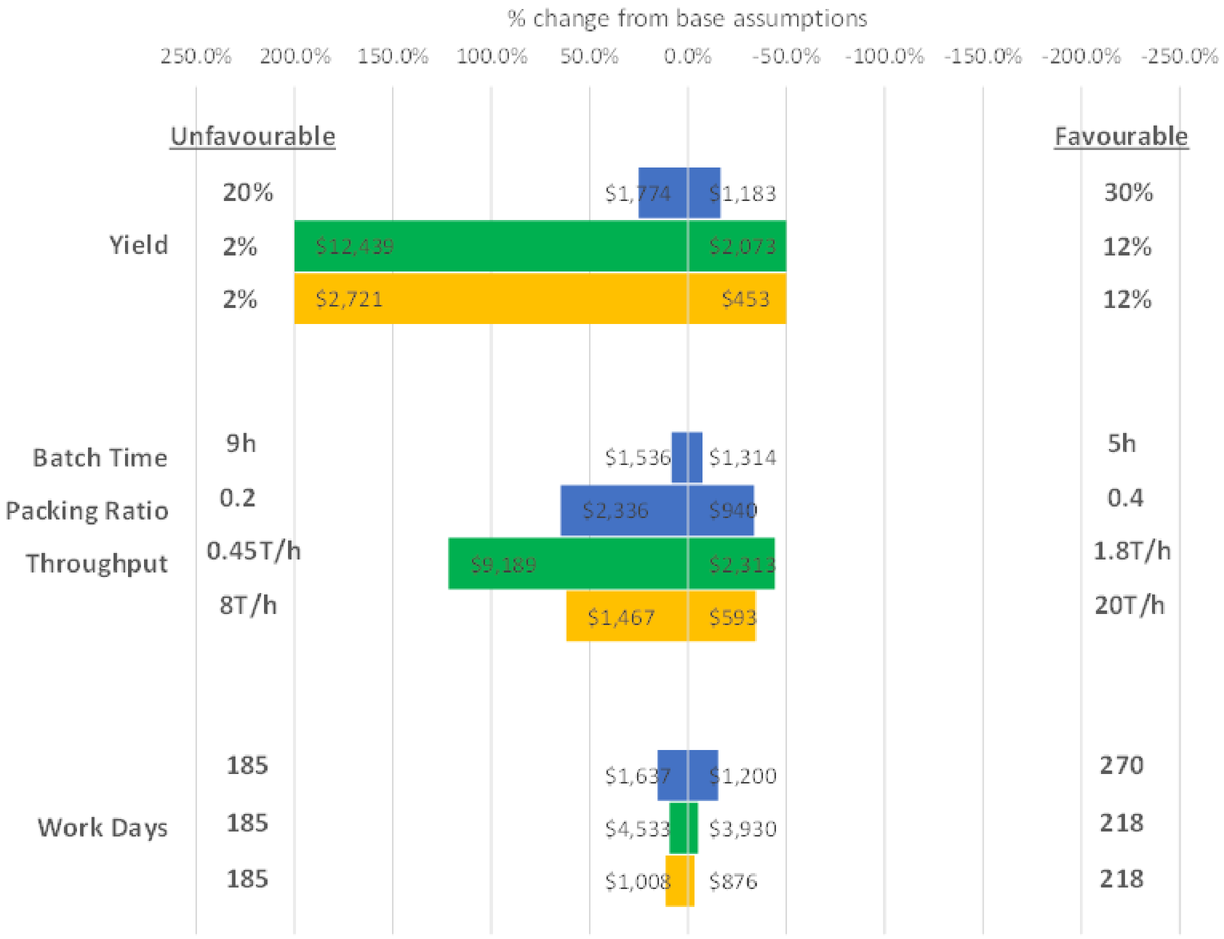


Figure 18. Biochar production cost sensitivity to productivity variables.

The yield, packing ratio and throughput variables are all inversely proportional to biochar production unit cost. Packing ratio, is more significant than batch time with respect to total cost, suggesting efficient feedstock trimming, and arrangement should be a priority, even if it results in extra labour costs. The Charmaker unit cost's low sensitivity to batch time suggests that wetter feedstock would be relatively insignificant. The extra diesel used to dry wetter material would negatively influence the operation's carbon footprint and potential revenue from VCMs.

Discussion

5.1 Reconciliation of results

The results of other mobile biochar production studies are presented in Table 13. While the context of each study and assumptions used all vary, they show a similar range of unit costs to those presented by this study. These studies all performed a sensitivity analysis and also found that production costs were most sensitive to biochar production rates.

Table 133. Summary of results from similar techno-economic studies

Study	Feedstock	Method	Cost (real NZD/T)
Nematian et al. (2021)	Orchard biomass	Unspecified \$460k pyrolysis unit with horizontal grinder	\$1,068 - 2,720
Keske et al. (2019)	2m lengths of Black Spruce	Charmaker (20ft version) (optimistic productivity)	\$1,456
Sahoo et al. (2019)	36% MC woodchips	Biochar Solutions Inc. continuous pyrolysis plant (\$684k) for 16h/day	\$2,036 (oven-dry)
Chung et al. (2015)	Green 3-inch chips of beetle-damaged Ponderosa pine	Biochar Solutions Inc. continuous pyrolysis plant for 8h/day	\$5,187

5.2 Quantification of biochar value

Despite the many useful properties of biochar, the market in New Zealand is still emerging. A barrier to adoption is limited understanding of the types and volumes of biochar best suited to specific soil types. Biochar is an investment to soil health, and unlike fertilisers, the benefits are not always immediately apparent. The cost to buy biochar may also be a barrier if current selling prices exceed the perceived benefits. As well as the cost of production, selling prices need to reflect the cost of handling, marketing, certification, testing and a profit margin. Therefore, the unit production costs identified by this study are not necessarily the break-even prices for sale to the consumer. The lack of published data on biochar selling values and volumes, meant the revenue side of operation economics was not a focus of this study. Even so, indications of some present-day revenues are useful to put the costs of production in perspective.

On the New Zealand retail market, biochar is sold by the litre. For example, Biogrow sells 1000L bulk bags for \$6,450 (Biogrow, 2023) and CharBro sells 100L for \$205 (CharBro, 2023). By the assumptions used in this study, there are 10,000L per oven-dry tonne of biochar, making these selling prices equivalent to \$64,500 and \$20,500/T respectively. In the better-established US market, biochar can be bought by the 88m^3 truck load at NZD 1,200/T (Oregon Biochar Solutions, 2023) and in Australia averages NZD 850/T (Straight, 2022). These international prices are better indications of what the New Zealand market would potentially pay, for the bulk volumes produced by the techniques in this study.

An indication of biochar's CDR value can be given by considering the Puro.earth VCM. CORCs awarded per unit biochar are a function of the following variables (assumptions):

- Cabon content (85%)
- H:C ratio (0.3)

- Soil temperature (12°C)

Assuming these biochar properties are yielded from each method, 1T of oven-dry biochar is assumed to permanently fix 2.64T of CO_2. If the pyrolysis is assumed to emit the same CO_2 eq. as in-situ decomposition of residues, net operation emissions per unit biochar can be assumed to come purely from the diesel used (2.68kg CO_2/L). The net CO_2 removals and corresponding VCM value for $212/T (Puro.earth, 2023) are shown in Table 14.

Table 14. Comparison of the carbon value of each system's biochar under the Puro.earth methodology

	Charmaker	**CharBoss**	**Carbonator**
Fuel use CO_2 emissions/T biochar	280kg	810kg	210kg
Net CO_2 removals/T biochar	2.37T	1.80T	2.43T
CDR value/T biochar	$503	$382	$516

These net CO_2 removal figures are consistent with those achieved by Rainbow Bee Eater in Australia (2.5 T_{CO2}/T_{bc}) (P. Burgess, personal communication 2023)) and BC Biocarbon in Canada (2.4T_{CO2}/T_{bc} (BC Biocarbon, 2023)).

Anyone developing a business case should not only consider biochar and its CDR value, but also the value of savings on harvest residue management costs and the value of a marketable 'environmentally friendly' image. While the market size for biochar in New Zealand is uncertain, there should be no shortage of market for CDR credits. This is reasoned as large companies like Microsoft have been buying biochar CORCs as part of efforts to offset their current and historic emissions. (Microsoft, 2022).

5.3 System comparison

The Carbonator produces biochar at the lowest unit cost and is likely to do so for most New Zealand plantation forestry applications. While unit cost is an important metric for comparing the three systems, other considerations could influence the preferred option for a given situation. Full utilisation of the Carbonator requires 85T of feedstock per day, 12 times that of the other systems. Some regions may not have the feedstock supply within a reasonable radius to justify a machine of the Carbonator's size. As unlimited, zero-cost feedstock availability was assumed, the feedstock conversion efficiency alone was not important. If a positive cost was put on feedstock, then the ACB systems (6% yield) would be disadvantaged compared to the Charmaker (25% yield). A break-even analysis comparing the Charmaker and Carbonator showed that the Carbonator would still have the lowest unit production cost up to a feedstock cost of $23/T. The Carbonator system has the greatest capital expense but is still an investment of similar scale to other forest machinery. For a forestry application, the ability to finance any of the three biochar systems would not likely influence preference.

The Carbonator has slightly more fire risk than the smaller-sized Charboss, however, both ACBs have far more risk than the fully enclosed Charmaker. More workdays were assumed to be lost due to fire risk each year from ABC operations compared to the Charmaker. However, the difference could be greater, depending on the local fire environment and forest owner's appetite for risk. Wet and windy weather conditions would also affect the ACB operations more negatively than the Charmaker. Break-even analysis suggests that the Carbonator could work just 98 days per year and achieve the same unit cost as the Charmaker working for the assumed 218 days.

The properties and value of each system’s output may also differ. While much is known about the biochar from batch pyrolysis, the biochar from ACBs is less understood. The Charmaker allows the control of some biochar characteristics, which can potentially be tailored for higher-value markets. More research on ABC outputs would help quantify value differences. The marginal value gain with increased levels of biochar production, may not be linear. A system should be selected to suit the market’s volume as well as quality demands. While this study considers each system as a standalone operation around a single biochar unit, there is an opportunity to run multiple units or to integrate biochar production into existing operations such as harvesting. Systems may achieve differential gains in efficiency from upscaling or integration. For example, a second Charmaker would not likely need a second crew, but a second CharBoss likely would.

5.4 Further research and development

Biochar production trials with residues like those found on New Zealand forestry landings are needed to reduce uncertainty in productivity estimates. This would provide more certainty on yield and batch time/throughput variables and allow a more accurate cost estimation. The yield of batch pyrolysis methods is already nearing the theoretical limit of 35% (Basu, 2010), so has little room to be improved. The yield from ACB is never going to match that of enclosed pyrolysis methods, however, there is potential to develop yield-improving technology and techniques. For example, T. Miles (personal communication, 2023) suggested that 15% was possible by coating feedstock with clay and maintaining a low fan speed. The throughput of ACBs could be increased with more mechanisms to separate biochar from unburned feedstock, as is achieved by the shaking grill of the CharBoss. Tigercat will be releasing the redeveloped Carbonator, which is rumoured to be more robust and compatible with an ember screen. It would not be surprising if Air Burners Inc. added biochar extraction capabilities to their existing Carbonator-sized Firebox range of ACBs.

There are other promising mobile biochar systems beyond those investigated in the scope of this project. A relatively low-capital system that can be sized to a forestry scale, is the pit-burn. A type of flame-cap pyrolysis performed in a pit dug into the ground. The Biochar Network New Zealand (BNNZ) have trialled this method on windrowed wilding pine residues near Lake Pukaki (Richards, 2023). A higher-capital system worth investigating is the Earth Systems Charmaker FPP (fixed pyrolysis plant), essentially 2 Charmaker MPP units working semi-continuously. Such systems are less mobile, which then introduces the cost trade-off between feedstock transport distance and plant relocation frequency.

Conclusion

The production of biochar can remove harvest residue accumulations from forest landings and create a valuable product. The Earth Systems Charmaker MPP40, Air Burners Inc. CharBoss and Tigercat Carbonator 6050 are commercially available biochar production units well suited for use in a New Zealand plantation forestry context. Designed for mobility, they can be taken directly to the source of feedstock, avoiding any transport cost of raw feedstock. These systems are also compatible with the irregular and often large piece size, moisture and ash content of harvest residues. A review of the biochar production process suggested that the batch pyrolysis method employed by the Charmaker would yield the most valuable biochar, due to its controllability and predictability. The Charmaker can achieve a much higher conversion efficiency than the CharBoss and Carbonator methods, which rely on a high degree of feedstock combustion.

The high volume of unutilised residues on New Zealand forestry landings, justified the assumption that they would be available at zero cost and in volumes exceeding the capacity of a single biochar operation. The day cost of operating standalone operations around each unit was acquired using a comprehensive Excel-based costing model. The model was populated with estimates for cost parameters such as labour, fuelling, depreciation and equipment financing. Machine, crew and biochar transport costs were linked to feedstock volumes and distribution parameters and were given relevant values. The expected productivity of each system was deduced using published figures and expectations of their relevance to a New Zealand forestry application.

Cost and productivity estimates were combined to yield biochar production unit costs of $1,419/T for the Charmaker, $4,146/T for the CharBoss and $907/T for the Carbonator. These costs do not vary significantly with realistic variation in operation relocation frequency and distance and are moderately sensitive to the operation's distance to town. The significance of distance to town, however, is expected to be low relative to alternative biomass recovery operations such as biofuels, which do not achieve such a large in-forest volume reduction. Unit production cost was most sensitive to biochar yield and throughput. These variables, whose estimates contained high uncertainty, should be the focus of further research to quantify the relationship between productivity and both feedstock geometry and moisture content. This study provides a guide to the methods, risks and costs of biochar production in a context relevant to New Zealand plantation forestry. The costing model included in Appendix C, can be used by forest managers to provide accurate, situation-specific costs. Costs can be compared to the expected selling price for biochar, its CO_2 removals and the value of avoided residue management costs, to determine if a biochar operation is economically viable.

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Appendix A - Productivity derivations

Biochar density

- Bulk density 100kg/m^3 (Green Houston, 2023).
- 170-250kg/m3 dry bulk density, up to 500kg/m3 wet and holds up to 3 x its weight in water.(Earth Systems, personal communication, 2023).
- Rogue Biochar in Oregon states their product ranges from 96-110/m3 (small particle size).
- Pacific Biochar 98kg/m3 bone dry or 196kg/m3 delivered.

Assumption: 100kg/m^3 dry, and 300kg/m^3 for transport out of the forest after quenching.

Yield convention

Percentage yields are conventionally given as:

$$Yield = \frac{Mass\ biochar_{\ Oven\ dry}}{Mass\ feedstock_{\ oven\ dry}} \times 100\%$$

(S. Joseph, Personal communication 2023)

Carbonator

- Would assume also 1h to get started and 1h to cool down.
- 10T in 1T out per hour (Tigercat product rep). This suggests a 10% yield.
- 4-5 yards (3-3.8m3) BC per 17-20T of feedstock in 1 hour. (Tigercat Brochure). This suggests a 2.5% yield.
- The same sized Air Burners Inc. Firebox model claims to burn 11-13T/hour of feedstock.
- 5-7% yield (Stephen Josepf, Personal communication 2023).

Assumption: The Carbonator can process 13T feedstock/hour at 30% MC and give a biochar yield of 6%. The yield for both ACBs are on the conservative side to account for a reduced yield on rainy days.

CharBoss

- On average 1,500 lbs to 1 US Ton (680-900kg) of vegetation waste an hour to 400 lbs (180kg) of biochar. (USFS test numbers – Email from AB Sales rep). (This 27% yield suggests wet biochar weight used in calculation. If 300kg/m^3 is assumed for wet biochar, these numbers relate to a conventional 9% yield).
- 1000-2000lbs (450-900kg)/hour to 4-5cubic feet/h (0.11-.14m^3) (AB spec sheet). This suggests a 1-3% yield.
- 9% yield up to 17% with big dry pieces. (Quoted by Dr Han in article (Skabelund, 2023).
- 6-8% yield and 1.5-2US Ton/hour (900-1800 T/hour) (US Biochar Initiative, Personal communication 2023)
- The fire box volume is 11 times smaller than that of the Carbonator.

From report on Burnboss (Lee & Han, 2017)

- Combustion rate of disposal ranged between 0.6 (fresh) to 1.7 (12-month-old) GmT/SMH
- Burning consumption didn't change considerably (just .1T/h) between 10-20 and <10 cm diameter feedstock.
- Burning consumption rates were 70% greater for 12-months-old residues (17% MC), compared to fresher fuels with a higher moisture content (27% and 36% in 2 different sites).

- Softwood residues was 15% more efficient than hardwood, and mixed species.

Assumption: The Charboss will process 1000kg/hour of 30% MC radiata pine harvest residues and yield 6% biochar.

Charmaker

From manufacturer

- 36m^3 of volume is available for feedstock
- 20% biochar yield by weight (unsure if wet or dry char)
- 25% MC 10t will take 6 - 7 hours
- 10T/42m3 packed (given in specs for higher volume FPP) = .238T/m3 bulk density. If 0.714T/m3 solid density @30%MC (from 1T/m3at 50%MC), packing density (bulk/solid volume) = .238/.714 = 0.333333333. This suggests the same solid density assumptions of 0.714T.m^3 were used by the manufacturer and agrees with the estimates from Hall (2009) and Harvey (2022).

Other literature

- Wrobel-Tobiszewska et al (2009)u assumed a productivity of 4 tonnes of 12%mc wood material into 1 tonne of biochar in 4 h operation with MPP20.
- The Charmaker works as a traditional batch kiln, so assuming good oxygen exclusion, it should yield within the 20-30% identified by Hedley et al., 2020.

Assumption: If loaded at a 33% packing ratio with 618kg/m^3 (Radiata at 30% MC, 420kg/m^3 basic density) feedstock, the 36m^3 Charmaker MPP40 would hold 7.35T of feedstock. At a yield of 25%, 5.14T of dry feed would produce 1.29T of dry biochar.

Appendix B – Sensitivity analysis bounds

Machine and operating costs

Fuel

Description	Diesel price ex GST. Does not account for change in machine transporter costs, however these are only 1-3% of total operation fuel consumption.		
Assumptions	High = $3.00	Base = $2.00	Low = $1.00
Reasoning	Current price from industry contact, high and low from 5-year min and max values Retail fuel prices in New Zealand - Figure.NZ		

Labour cost

Description	Hourly wage to operation employees		
Assumptions	High = $30	Base = $35	Low = $40
Reasoning	Range suggested by industry contact		

Repairs and Maintenance

Description	Cost as a % of depreciation		
Assumptions	High = 45%	Base = 30%	Low = 15%
Reasoning	Range suggested by industry contact		

Depreciation

Description	Machine value as % of purchase price after 10 years. Does not include vehicle depreciation.		
Assumptions	High = 2%	Base = 10%	Low = 20%
Reasoning	Range suggested by industry contact		

Feedstock distribution

Distance from town

Description	Distance for crew commute and biochar extraction to market.		
Assumptions	High = 100km	Base = 50km	Low = 25km
Reasoning	An average forest distance from port is 92km (Manley, 2016). Towns capable of supporting a biochar operation in terms of market and labour are more common than ports.		

Forest spacing

Description	Distance between forest harvest areas where transporters are required for machines.		
Assumptions	High = 60km	Base = 30km	Low = 15km
Reasoning	NZ forests appear to be closer to each other than they are from town.		

Forest size

Description	Number of landings per harvest area.		
Assumptions	High = 30	Base = 10	Low = 3
Reasoning	Considering a 13ha average harvest setting size (for woodlots (Allum, 2020)) and a single crew pulling 300T/day from a 650T/ha forest for 1.5 years, the harvest area would have 10 landings. A small 50ha woodlot might have only 3 landings while a large plantation with multiple crews working close by may have 30 landings harvested within a 2-year period		

Landing spacing

Description	Average distance machines have to walk between landings within a forest. *Reasoning:*		
Assumptions	High = 1000m	Base = 500m	Low = 300m
Reasoning	Assuming 30m road per ha (also for woodlots, (Allum, 2020)) and 13ha setting size there would be 390m between landings. With adjacency constraints for harvest areas being introduced, the number of landings per harvest area will reduce. Assuming the same volume of harvesting in a forest, the average distance between landings will increase.		

Residue pile size

Description	Mass of residue on each landing		
Assumptions	High = 975T	Base = 342T	Low = 54T
Reasoning	Mainly a function of setting size, landing residues/ha and packing density (solid volume/bulk volume. Base value of 342T uses (13ha, 170 bulk m3/ha and .25). 95% of setting sizes ranged 11 and 15 between (Allum, 2020), residue pile volume ranged between 40 and 350m3/ha (Harvey, 2022) and 0.2-0.3 is a reasonable range for packing ratio. Using the min and max of each variable, high and low pile weights were derived.		

Machine productivity

Yield

Description	Mass of oven dry biochar/ mass of oven dry feedstock %.		
Charmaker			
Assumptions	High = 30%	Base = 2%	Low = 20%
Reasoning	The range of yields published in the literature review by Headly et al. (2020) are 20-30%.		
CharBoss, Carbonator			
Assumptions	High = 12%	Base = 6%	Low = 2%
Reasoning	Base cases are a realistic value estimated for harvest residues. High and low case scenarios are maximum and minimum values published for each machine.		

Packing ratio

Description	Solid volume/bulk volume of feedstock packed into Charmaker cages.		
Assumptions	High = .5	Base = 0.33	Low = .2
Reasoning	Base case assumes 33% packing ratio fits 7.35T of residues ito the 36m3 chamber. This is equivalent to 0.92T/h. A reasonable range of packing density is 0.2-0.5 depending on feedstock geometry and effort put into packing it efficiently.		

Batch time

Description	Time from closing to opening of Charmaker chamber		
Assumptions	High = 9h	Base = 7h	Low = 5h
Reasoning	Base case assumes a 7-hour batch time. The batch time could realistically be as high as 10h and as low as 5h, on top of the 1h/day for setup and un/loading.		

Throughput

Description	Mass of oven dry biochar/ mass of oven-dry feedstock %.		
CharBoss			
Assumptions	High = 1.8T/h	Base = 1T/h	Low = 0.45T/h
Carbonator			
Assumptions	High = 20T/h	Base = 13T/h	Low = 8T/h
Reasoning	Base cases are a realistic value estimated for harvest residues. High and low case scenarios are maximum and minimum values published for each machine.		

Workdays

Description	Number of productive days per year

Charmaker			
Assumptions	High = 270 days	Base = 218	Low = 185
Reasoning	Worst case scenario, the prohibited fire season does apply to the Charmaker and a high number of prohibited days (30 = Highest annual # of days above 80 BUI in Tasman region). Base case assumes no restrictions, so a better case scenario could be if someone operated it 6 days/week		

CharBoss, Carbonator			
Assumptions	High = 18	Base = 204	Low = 218
Reasoning	Worst case scenario, a high number of prohibited days (30 = Highest annual # days above 80 BUI in Tasman region). Best-case scenario, no lost days due to fire or rainy days.		

Appendix C – Biochar Operation Costing Model

Biochar Costing spreadsheet.xlsx