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Carbon Footprint of Forest Harvesting Operations in New Zealand

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EXECUTIVE SUMMARY

The forest industry is currently experiencing the early stages of pressure to measure and report emissions. Currently, there is little research, particularly in New Zealand, on the emissions produced by harvesting operations or options for crews to reduce emissions. This report provides an estimation of the carbon footprint for harvesting crews in New Zealand, of which values can be used to estimate emissions. The report demonstrates the application of a simplified methodology for emissions reporting, outlines the potential advantages and disadvantages for forest managers and harvest crews to measure emissions and collates relevant specific research addressing innovation and improvement options to reduce carbon footprint.

For reporting carbon footprint of any business, an important step is to set the ‘scope’. The Scope defines the extent that carbon is included or excluded in the analyses. ‘Scope 1’ is typically used in reporting carbon footprint and specifically focuses on ‘direct GHG emissions and removals’. Scope 1 for forestry operations is primarily focused on fuel use and includes only the harvesting operation itself, including the travel of the crew to and from the site. It does not include other operational aspects such as the construction of infrastructure to prepare the area for harvest, the transportation of the logs from site, or the manufacture of the equipment itself.

Data collection on fuel use was primarily through a survey of forest managers and crews. This was then broken into swing yarder, tower yarder (hauler) or ground-based, according to the primary method of extraction. The data collected included 30 ground-based, 13 swing yarder and 12 tower yarder crews with an average number of machines of 4.8, 8.1 and 7.4. Fuel use ranged from 1.2 - 11.2 L/m^3 (average of 3.67) for ground-based, 2.8 - 9.1 L/m^3 (4.3) for swing yarder, and 2.0 - 11.3 L/m^3 (5.0) for tower yarder crews.

Carbon footprint is reported in tonnes of CO_2 equivalent (tCO_2e). Published fuel to CO_2e conversion factors are used. The tower yarder (*hauler*) crews had the highest average carbon footprint both per annum and per m^3 harvested, with an average of 935 tCO_2e/annum and 14.7 kgCO_2e/m^3 respectively. Swing yarder crews averaged the next highest (782 tCO_2e/annum and 12.6 kgCO_2e/m^3) with ground-based resulting in the least (693 tCO_2e/annum and 10.7 kgCO_2e/m^3).

The key benefits of GHG reporting were to prepare for potential disclosure requirements, potentially reduce costs long term, have better investment/financing opportunities and help reach the nation's net-zero targets. The negatives were costs, time, and reporting not necessarily making reduction action occur. The consensus from survey responses was that reporting of carbon emissions was being done by forest management companies, with no pressure on harvest crews to measure or report their emissions. Four of the six forest management companies reported they currently measure their carbon footprint, including the collection of harvest crew’s fuel data. Most companies are in the quantifying and goal setting stages, so currently do not have reduction plans in place.

INTRODUCTION

As the world transitions to a low carbon economy, companies that are at the forefront of this change will be in a position to offer benefits and competitive advantages. This is the point of view that a lot of companies in New Zealand are adopting, partially in response to the global climate crisis, but more so as an immediate effort to try to meet New Zealand's ambitious emissions reduction targets for 2030 and 2050. There is now a wider expectation for other industries to become accountable for their carbon emissions.

In response to the international climate crisis, in 2019 the New Zealand government introduced the Climate Change Response (Zero Carbon) Amendment Act (NZ Govt, 2019). This details a net zero 2050 target in which "*net accounting emissions of greenhouse gases in a calendar year, other than biogenic methane, are zero by the calendar year beginning on 1 January 2050 and for each subsequent calendar year*". Biogenic methane emissions reduction by the same year is targeted at 24% to 47% less than 2017 emissions levels.

The latest guidance on New Zealand's Projected Greenhouse Gas Emissions to 2050 has indicated that with existing measures only, gross emissions will gradually decrease from 79.7 million tonnes of carbon dioxide equivalent ($MtCO_2e$) in 2020 to 66.6 $MtCO_2e$ in 2050 (MfE, 2022a). Carbon dioxide equivalent (CO_2e) is the contribution of all greenhouse gas emissions quantified by carbon equivalent. New Zealand's target accounting emissions are projected to decrease from 74.4 $MtCO_2e$ in 2020 to 44.7 $MtCO_2e$ in 2050.

This outlines a disparity between the currently projected measures and the target values. Forestry sequestration and international offsets can only do so much in terms of bridging this gap - the final solution will involve cooperation from all sectors within New Zealand, including forest managers and workers.

There is little research, particularly in New Zealand, on the emissions produced by harvesting operations, as well as on ways to improve current harvest machines or systems, or utilise innovative alternatives. Being able to estimate harvesting emissions, and benchmark against collective averages, will be valuable for contractors and management companies. There are four objectives of this research:

1. Review literature and consult with industry professionals to establish the benefits and disadvantages of GHG reporting for a company within New Zealand.
2. Investigate and present current and future methods to mitigate GHG emissions for harvest crews within New Zealand.
3. Provide a fuel-based estimation of the carbon footprint equivalent for harvesting crews in New Zealand (tower yarder, swing yarder and ground-based).
4. Demonstrate a concise methodology for forest companies wishing to measure and report their harvest operation carbon footprint in New Zealand.

LITERATURE REVIEW

Greenhouse Gas / Carbon Footprint Reporting

New Zealand guidance around Greenhouse Gas (GHG) measurement and reporting is provided by the Ministry for the Environment (MfE, 2021 and 2022a). The guidance itself is extracted from international frameworks for GHG reporting, detailed below (ISO, 2018). The GHG Protocol separates emissions based on their source into the following categories (WBCSD, 2001):

- Scope 1: Direct GHG emissions from sources owned or controlled by the company (i.e., within the organizational boundary). For example, emissions from the combustion of fuel in vehicles owned or controlled by the organization.
- Scope 2: Indirect GHG emissions from the generation of purchased energy (in the form of electricity, heat, or steam) that the organization uses.
- Scope 3: Other indirect GHG emissions because of the activities of the organization but generated from sources it does not own or control (e.g., air travel).

A criticism of scope 3 emissions is that double counting can occur. Scope 3 emissions are also someone else's scope 1,2 or 3 emissions (Ryan & Tiller, 2022). In that study of 237 large New Zealand entities, one third reported GHG emissions, half providing the organisational boundaries, with the reporting of scope 1, 2 and 3 emissions being inconsistent. It is important to note that almost all GHG reporting is based on estimates and emissions conversion factors.

GHG reporting can be conducted either internally or externally. Within New Zealand there are several external services and agencies that provide carbon foot printing. The Ministry for the Environment keeps an up-to-date record of such companies that can provide different levels of service (Ministry for the Environment, 2022b). Some of these include:

- Deta Consulting https://www.deta.global/ provide both carbon foot printing and strategies to reduce footprint in a 'carbon kickstarter' package. Recently conducted a footprint for a forestry crew in the Central North Island.
- Toitu Envirocare https://www.toitu.co.nz/home makes available both their Carbon reduce and Carbon zero programmes that give you the 'guidance, tools, and software to calculate your full carbon footprint'. Essentially these programs help and assist you to conduct your footprint.
- Ekos NZ https://ekos.co.nz/ is a 'Business Calculator' or 'Business Calculator lite'. Your inputted information with assistance from the Ekos team generates your carbon footprint.
- Oxygen Consulting https://www.oxygen-consulting.co.nz/carbon-management is a consultancy service operating specifically in the carbon space, and offers either a 'carbon efficient' or 'carbon neutral' package.
- Morphum Environmental https://www.morphum.com/sustainability-services is another consultancy tservice available to conduct/verify GHG reporting.

For internal measuring, there is guidance from the Ministry for the Environment (MfE) titled "Measuring and Reporting Greenhouse Gas Emissions: Guide for Organisations" (MfE, 2022a). There is also the 2022 Measuring Emissions Interactive Workbook which is a tool that companies can use to calculate their full carbon footprint. Many of the above companies refer to the values used in this workbook. If a company chooses to measure themselves then following the methodology used in this MfE report is a good starting point and it is recommended to get this verified by a third-party organisation.

Harvest Emissions

Forests act positively in three ways during the carbon cycle. They act as a carbon sink, provide storage of carbon through products and can be used as a substitute for fossil fuels (IPCC, 2014; Wakelin *et al,* 2020). Harvest operations produce direct (CO_2, CH_4, N_2O NO_x, CO) and indirect (CO_2, CH_4, NO_x, CO) emissions (Sonne, 2006). The harvesting operations make up around 45 - 60% of emissions from the production of a domestic log (McCallum, 2009; Weyrens *et al.* 2022). Fuel usage for different machines in New Zealand has been studied (Amishev, 2010; Oyier & Visser, 2016). Oyier & Visser (2016) found an average of 3.04 L/m^3 for ground-based systems and 3.18 L/m^3 for cable yarding systems. Sandilands *et al.* (2009) and Karalus (2010) support the idea that hauler mechanical crews use more fuel per m^3 harvested than ground-based crews. Whilst Sandilands *et al.* (2009) identified a 14% increase in the fuel used by mechanical hauler crews (2.47L/m^3) over ground mechanical crews (2.16L/m^3), Karalus (2010) identifies a 9% difference.

International research has shown that mechanised harvesting crews produce significantly more emissions than more manual based operations (McCallum, 2009; Engel *et al*, 2011; Sonne, 2006; Athanassiadis, D. 2000; Klvac & Skoupy, 2009). McCallum, (2009) is the only completed New Zealand harvesting carbon emission study publicly available. It found an average of 8.8 kgCO_2e/m^3 (kilograms of carbon dioxide equivalent released per metre cubed of logs produced) for harvesting operations. The ground-based mechanical (8.5 kgCO_2e/m^3), yarder mechanised (9.7kg CO_2e/m^3) and yarder motor manual (9.0kg CO_2e/m^3), were all significantly higher than ground-based manual emissions (6.6 kgCO_2e/m^3). Engel *et al* (2011) recorded partially mechanised, highly mechanised and fully mechanised emissions as 4.1 kgCO_2e/m^3, 6.8 kgCO_2e/m^3 and 7.4 kgCO_2e/m^3. Both Athanassiadis (2000) and Klvac & Skoupy (2009) studied fully mechanised (harvester and forwarder) crews as well and found emissions of 7.8 kgCO_2e/m^3 and 9.0 kgCO_2e/m^3 respectively. A more recent study from Haavikko *et al*. (2021) from Finland found 7.34 kgCO_2e/m^3 and 3.14 kgCO_2e/m^3 for first thin and final felling operations. Interestingly, internal forest machine relocations were also studied which resulted in an additional 0.33 kgCO_2e/m^3. A further study out of Finland by Kärhä *et al*. (2022) reported an average footprint of 5.7 kgCO_2e/m^3 across 29 machines (harvesters and forwarders) for the 2020 year of ground-based CTL operations.

Several variables influence emissions in harvest operations such as stand and terrain conditions, operator skill, tree species, management methods, fuels/oils used and machine type (Van Belle, 2006; González-García *et al.*, 2009; Vusić *et al.*, 2013; McCallum, 2009; Cosola *et al.*, 2016). International studies on carbon emissions relate to the operation of different machines and systems than are used in typical NZ harvesting operations, hence direct comparison with the international studies should be used with caution.

Oyier & Visser (2016) determined that terrain had a significant impact on fuel usage by harvesting crews with an increase from 2.22 L/m^3 to 3.18 L/m^3 from flat to steep terrain. Management practices such as applying the most efficient harvest plan including road layout, as well as optimising logistics has a significant impact on environmental and emission impact reduction (Cavalli & Grigolato 2010). Cosola *et al.* (2016) found that using semi-mechanised crews for selective harvesting had low emissions (2.27 kgCO_2/m^3) when compared to manual harvest in shelterwood.

Operator skill and technique have also been proven to have a high effect on carbon emissions (Cosola *et al.*, 2016; McCallum, 2009; Mercier & Makkonen, 2004). Minimising fuel consumption at the crew level is an obvious initial step for reducing the carbon footprint. McCallum (2009) states that minimising idle time through effective planning in advance of harvesting, optimising payloads to ensure that machines are not under or overloaded, and ensuring tyres are inflated optimally for the conditions are ways that harvest crews can reduce their carbon footprint. Fuel consumption by machines that use large amounts of fuel (yarder, mechanised felling, processing, skidders, excavators) can be reduced through operator training and preventative maintenance. This can also occur during the planning stage by ensuring workers are well trained and optimising the skid layout and positioning of machines to reduce movement.

Reducing Harvesting Carbon Footprint

Diesel is the primary fuel used in forestry and makes up over 90% of the emissions from harvesting operations (McCallum, 2009). A number of technologies that could reduce the harvesting footprint are presently available, but not yet commercially successful. This includes biofuels as a direct substitute for fossil fuels in current equipment, but also possible conversions to either hydrogen or electric equipment. While lubrication oils represent less than 5% of the total footprint, bio-oils are also a possible step towards a lower carbon-based operation.

Biofuels

Biofuels include any energy-enriched chemicals generated directly through the biological processes or derived from the chemical conversion from biomass of prior living organisms (Rodionova *et al*., 2017). The main direct advantages of biofuel use include its renewability, non-toxicity, higher flash point and higher biodegradability. In contrast, its main disadvantages are higher viscosity (impracticalities for both direct injection and indirect type diesel engines), lower energy content and higher price (Kralova & Sjöblom, 2010).

Hall & Gifford (2007) stated 'It's theoretically possible for New Zealand to be self-sufficient in terms of liquid [bio] fuels by using sustainably managed forests, while having a low impact on domestic and export food production'. Jack & Hall (2009) identified that forestry biomass was a key resource in replacing fossil fuels, Large-scale energy, economic and environmental impacts were assessed by Hall *et al*. (2009). Forest biomass has been recognised as the most promising renewable resource for the production of biofuels and biochemicals, which can substitute those presently derived from fossil fuels (Suckling, 2015; Hall 2013; Pang, 2019). However, due to the complicated physical structure and chemical composition of the biomass, there are technical challenges for the commercialisation of the new technologies and processes (Pang, 2019).

While production of conventional biofuels (i.e. bio-diesel) is well established, Suckling (2015) found that use remains low in New Zealand with it being less than 0.1% of total transportation energy. There is a NZ blend mandate stated for 2023 (Ngā Kora Koiora - Biofuels, 2022), and Steer (2015) noted that a forestry led biofuel industry could provide Māori landowners with an opportunity to secure long term financial, cultural and spiritual benefits.

Hydrogen technology

Stępień (2021), Onorati *et al.* (2022) and Das (2002) all agree that hydrogen can meet growing energy demands and is considered 'one of the most important fuels of the future'. However, to become a worldwide alternative to fossil fuels, aspects such as production methods, storage, safety, and engine optimization are yet to be settled. Currently, the hydrogen internal combustion engine is the only known internal combustion engine that meets the latest EU 'zero emission' standards (producing less than 1 g CO_2/kWh). The only significant unwanted by-products are Nitrous Oxides (NOx), which already have a treatment and mitigation methodology inbuilt into the latest engines.

It is possible to blend hydrogen into current fuels for internal combustion engines, however, the power, torque, and brake thermal efficiency all decrease (Shadidi *et al.*, 2021). Hydrogen fuel cell engines pose a recent and exciting new opportunity. A fuel cell utilises an electrochemical reaction to generate electricity which in turn can be used for propulsion in a similar method to current electric vehicles (Manoharan *et al*., 2019). As an energy carrier, hydrogen fuel cells pose an efficient alternative to traditional battery systems.

Research and development is still required to further either hydrogen internal combustion or fuel cell engines reaching mainstream markets (Boretti, 2020). Whilst most of the research for both hydrogen fuel cells (Camacho *et al*., 2022) and internal combustion engines (Verhelst, 2014) has been conducted for on road vehicles (primarily trucking), there are few advances in the space of forestry specific harvesting vehicles (I.e., excavators, skidders and other large-scale harvesting machinery).

Electric technology

Electric hybrid engines have been researched for over 30 years (Burke, 1992). Carlini (1997) noted that maximum power is often only required for a small amount of time for logging equipment, thus a hybrid electric system, instead of an internal combustion engine may be able to improve performance by saving fuel, reducing pollutant emissions and decreasing noise. To try to reduce emissions from forestry and agriculture machines in the EU, there has been an increase in restrictions on internal combustion engines (Scolaro *et al*, 2021). Forestry machine manufacturers have looked at integrating electric and hybrid drives into a range of machines to replace hydraulic and mechanical systems (Shen *et al*. 2017; Silvaş *et al*. 2012).

Currently, the most common hybrid design uses electricity to solve the issue of smaller engines that might lack of power for short periods of time (Mergl *et al*., 2021). Literature refers to this as the electro-hybrid drive. For example, the Logset machines use the electro-hybrid drive system in their 8H GTE and 12H GTE harvester models. Johnsen (2021) found 20 to 25% fuel savings for the 12H GTE model in comparison to non-electro-hybrid harvesters and Eniola (2013) found similar fuel savings with the Elforest forwarder.

A study on the Koller K507H-e hybrid cable yarder by Cadei *et al*. (2021) found the machine had an average fuel consumption rate of only 0.56 to 0.8 L/m^3. The Koller K507H-e uses electric winches driven by a diesel-electric motor and has the ability to store energy in batteries when braking is applied to the drums. Visser (2015) stated that during normal operation the engine only runs 30% of the day, mainly working from the battery and the engine needs to run only when pulling and the battery stores the braking energy from slowing when returning.

Ponsse, a Finnish machine manufacturing company, recently released a fully electric forwarder EV1 model (Ponsse, 2022), but no performance data or battery specifications have been provided in their release.

Even though hybrid engines have been available for over 30 years, hybrid electric technology is in the initial stages of development in forestry (Burke, 1992; Scolaro *et al*. 2021). Some of the issues included a complex gearbox with high gears needed to adapt the internal combustion engine to varying conditions, traction requirements and high loads as part of the power demand. Both Scolaro *et al*. (2021) and Mergl *et al*. (2021) agree that strong development in this area is expected in the coming years. The main advantage of electric hybrid machines is the fuel savings of up to 30% compared to conventional powertrains (Poikela and Ovaskainen, 2022). There is also a decrease in environmental impacts and lower machine maintenance is required (Pandur *et al*. 2020).

Biodegradable oils

Nowak *et al*. (2019) reported on the key environmental issues of using conventional lubricating oils and their biodegradability, with over 60% of lubricants used around the world put into the environment (Tkáč *et al*., 2014). Schneider (2006) reported on the environmental threat due to high ecotoxicity, but lubricants manufactured from biological compounds have less effect than those from fossil origins (Stanovsky, *et al*., 2013; Schaffer & Buchschacher, 2002). Mineral oil is not only environmentally harmful, it also makes up around 6% of the emissions for forestry operations (McCallum, 2009).

Bio-oils are organic-based substitutes for mineral-based lubricants. Biodegradable lubricants are available for many applications including engine, hydraulics, gear, chain, electrical insulation, and grease applications. They have been used in European countries for forestry applications for many years, with France, Germany, Sweden and Austria now making it compulsory. Research has shown that bio-oil retains a lower temperature, which provides better performance (Skoupy *et al*., 2010; Ignea *et al*, 2017). With forestry harvesting applications being in an uncontained environment, one benefit is the reduced impact of oil spills into the environment. Burst lines, incorrect usage and lack of care or effort are the greatest risks (Yun Hsien, 2015).

New Zealand provides limited government incentives for the uptake, with no target or mandate on usage (Suckling, 2015). Visser (2018) noted that none of the New Zealand forestry companies surveyed had plans to implement the use of bio-oil across their harvest crews. There was hesitance due to the higher labelled cost, limited access, efficacy, and the risk of damage to equipment.

METHODS

Fuel data and information regarding carbon footprints was primarily collected from forest managers and harvest crews across all regions of New Zealand. An initial goal of 10 crews from each primary extraction method (ground-based, tower, swing yarder) was set. The source of information provided was kept anonymous in final reporting. Some larger companies were able to provide data for multiple crews, and each crew's data was kept as a unique entry.

For evaluation of the data, a crucial first step was to interview an expert in the field of carbon measurement and reporting to ensure a good level of understanding of the standardised national guidance provided (MfE, 2022a) as it relates to New Zealand. A senior engineer from Lumen, an engineering consultancy specialising in carbon management, provided insight into the GHG reporting systems and the differences between the Scopes (now referred to as Categories). The traditional Scope 1 through 3 are being replaced with Categories 1 through 6, whereby Scope/Category 1 through 3 remains the same, but a further Category 4 through 6 are added.

For a full and total analysis of carbon equivalent footprint, every category should be considered, including indirect GHG emissions from the use of products and equipment. In general, broad assumptions are made where appropriate for lack of specific data. A key takeaway from the interview is remembering that it is important to focus on what you can control.

Category 1:

- Fuel and oil usage from all vehicles/processes (including personnel fleet).
- Any gas usage on site or in the office (or leakage).

Category 2:

- Electricity used both on site and in the office.

Category 3:

- External travel of employees (air travel, business commute outside day-to-day operation), or working from home consideration.
- Refrigerant use on site or in the office (chilled transport, office air conditioner).
- Upstream emissions from fuel manufacture and distribution (well to tank)

Category 4:

- Waste materials and water (landfill waste)
- Emissions generated through leased assets.

Categories 5 & 6 are less relevant for harvesting operations, as the responsibility of the end of life of the product (logs) is generally passed onto the subsequent processor or end user, and the carbon removal itself is accounted for under the ETS.

For an average forestry crew in New Zealand, it may be reasonably difficult to capture an in-depth carbon footprint (i.e., using all Categories 1-4) for their operation. For this study, Category 1 was used that simplifies the carbon equivalent footprint of the harvesting operation only, and hence the primary contributors were fuel and oil use as these will account for most of the emissions. The scope boundary for this investigation is defined as the edge of the forest harvest ground, with the exception of personnel vehicles to and from the site. Thus, trucking and external emissions associated with the organization (e.g., office spaces) are not considered.

Although the data was requested, it was assumed few crews would have detailed record of oil consumption, and if absent it was estimated to be equal to 7% of the total fuel used (Klvac *et al*., 2003; McCallum, 2009). The emissions from crew transportation to and from site were estimated using the average distance to site and number of machine operators for each crew, collected in the survey.

The emissions calculation is as follows:

$$E = Q_{Diesel} \cdot F_{Diesel} + Q_{Petrol} \cdot F_{Petrol} + 0.07 \cdot Q_{Diesel+Petrol} \cdot F_{Oil}$$

Where E = emissions from the source in kgCO2e per year

Q = activity data (the quantity of fuel and oil used)

F = associated emission factor for source

The emissions factors (F) used are shown below in Table 1. These factors are consistent with those used in the UK and by the United States Environmental Protection Agency (EPA, 2022).

Table 1. Emissions factors (MfE, 2022a; DBEIS, 2022)

Emission Source	**Unit**	**kgCO_2e/unit**
Transport Fuel - Diesel	Litres	2.69
Transport Fuel - Petrol	Litres	2.46
Oil	Litres	2.96

RESULTS

Crew composition

The data collected for harvest crews were classified based on the primary method of extraction: being either swing yarder, tower yarder (*hauler*) or ground-based. Data for two production thinning crews are also presented. While each harvest system was unique in terms of equipment used, the following is a generalised summary of the composition of the crew by harvest system type. For each machine a corresponding power rating (in KW) was found and also averaged.

Tower Yarder Crew – Average of 7.4 machines

- Tower Yarder (330kW)
- Bulldozer/other tail hold machine (Variable)
- 2(+) Falling (and/or processor) machines (210kW)
- 2(+) Grapple machines (130kW)
- 2(+) Excavator machines (may have winch) (150kW)

Swing Yarder Crew – Average of 8.1 machines

- Swing Yarder (320kW)
- Bulldozer/other tail hold machine (Variable)
- 2(+) Falling (and/or processor) machines (210kW)
- 2(+) Grapple machines (130kW)
- 2(+) Excavator machines (may have winch) (150kW)

Ground-based Crew – Average of 4.8 machines

- Skidder (or Forwarder) (170kW)
- Falling (and/or processor) machine (210kW)
- 2(+) Grapple machines (130kW)
- 1(+) Excavator machines (may have winch) (150kW)

Production Thin – Average of 4.5 machines - (No specific machine data)

Fuel and Productivity Data

Table 2 below shows the raw data collected including the ranges of diesel burned, production volumes per metre cubed as well as the per litre productivity. Ground-based crews (GB) depict the lowest average diesel use with highest average volume harvested, leading to the lowest per metre cubed fuel efficiency, compared to Swing Yarder (SY) and Tower Yarder (TY).

Table 2. Annual fuel and production data (minimum, maximum and average across crews)

	Diesel Use (L x 1000)			Volume (m^3 x 1000)			L/m^3		
System	**Min**	**Max**	**Avg**	**Min**	**Max**	**Avg**	**Min**	**Max**	**Avg**
GB	91.1	376.0	238.4	9.8	216.2	85.0	1.16	11.20	3.67
SY	152.5	478.0	269.0	30.8	150.3	67.1	2.82	9.07	4.34
TY	174.6	459.7	320.7	29.4	198.1	78.7	1.98	11.31	5.04

Data collected on fuel usage and production data have been analysed to give a total and a per m^3 carbon footprint, per calendar year. All data included is based on a full year equivalent period, of which FY2020 is the oldest dataset (i.e., all data was recorded within the last 3 years).

In total, data for 30 ground-based harvesting crews were received, which included two 'production thin' crews (these are shown in green in Figure 1 below). Total tonnes of CO_2e for the recorded year period is shown on the left axis (bar graph), whilst the $kgCO_2e/m^3$ values are seen on the right (orange line). This allows for a visual comparison of the two metrics, helping to identify that a large carbon footprint does not necessarily mean the 'carbon efficiency' in kg per m^3 was also large. The clearest example of this is seen in crews 1 through 14, where the average footprint of 8.84 $kgCO_2e/m^3$ is much smaller than that of the remaining ground-based crews (average = 12.38). This even suggests that a higher total carbon footprint (bigger operation) may result in a lower per metre cubed carbon footprint (i.e., better efficiency) Other notable features include crew 19 having a very large value of 32.5 $kgCO_2e/m^3$. This can potentially be attributed to a very difficult block to harvest. This is likely as the fuel usage was average, as shown in the blue (Figure 1), it just had low harvest volume.

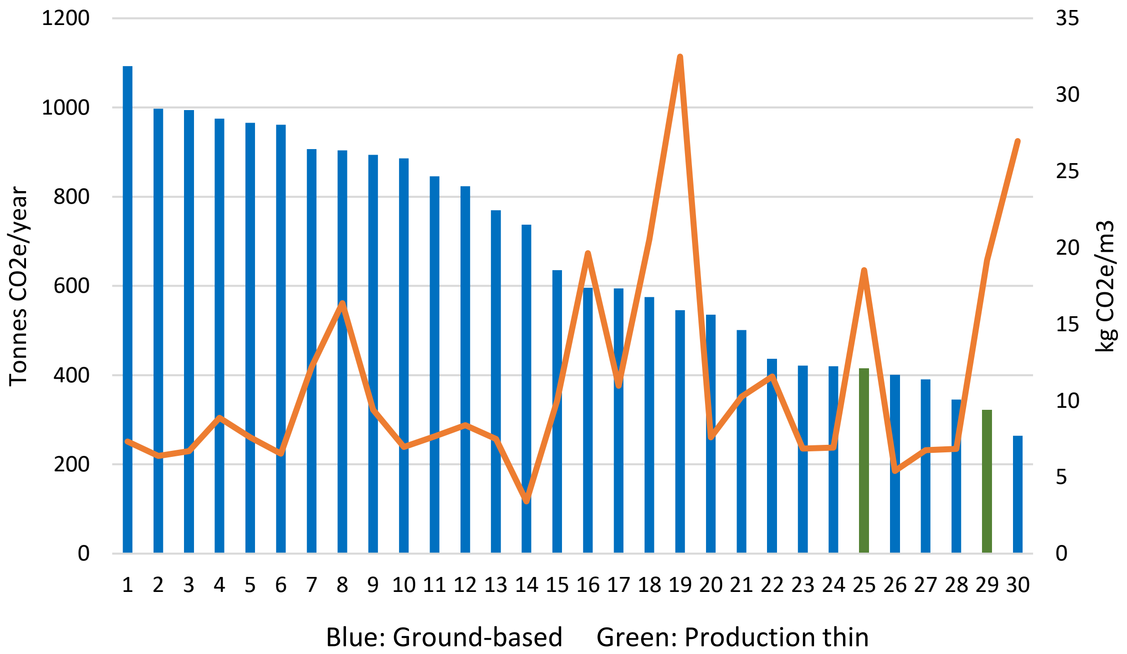

Figure 1: Carbon emissions of ground-based crews

The per year results for cable harvesting crews are indicated below in Figure 2. This dataset includes 25 crews, of which 12 involve a tower yarder or hauler crew (green) and 13 swing yarder-based crews. Once again, a large spike is observed – one in the swing yarder group of 26.3 $kgCO_2e/m^3$, and one in the tower yarder crews of 32.8 $kgCO_2e/m^3$.

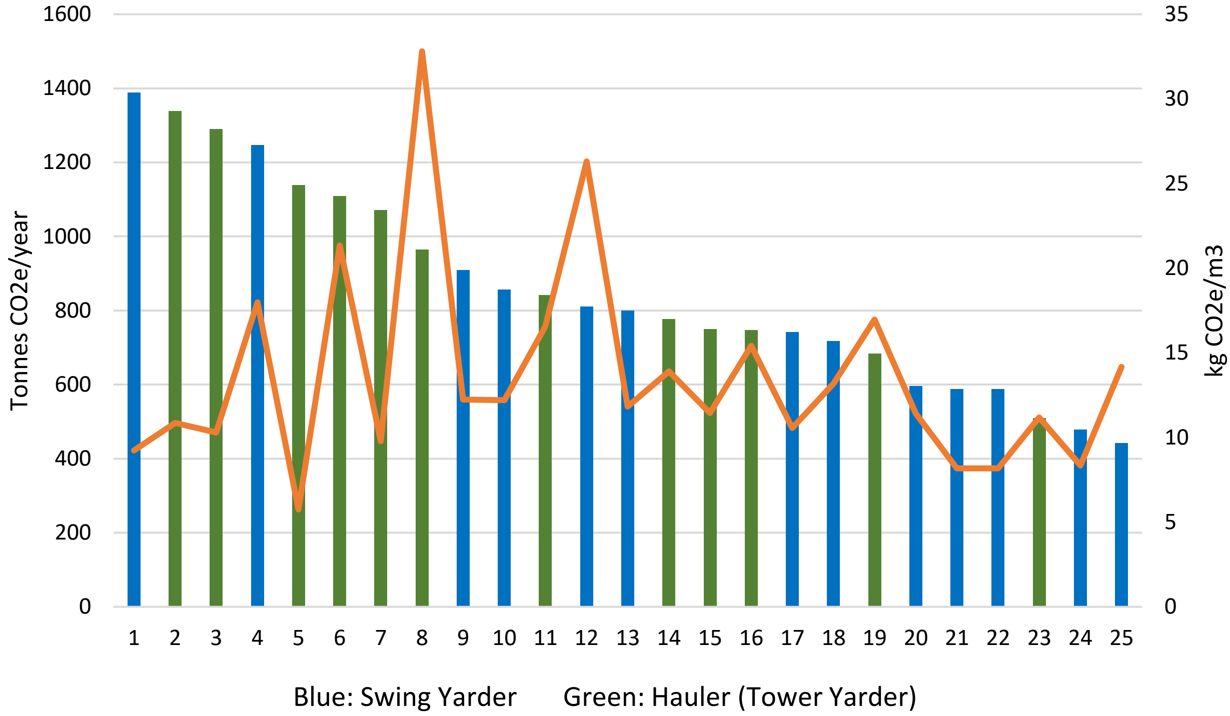

Figure 2: Carbon emissions of cable harvesting crews

The average values for both equivalent annual carbon footprint (based on fuel/oil usage alone) and per m^3 emissions are presented in Table 3 below. Data is segregated by crew configuration and arranged in ascending order (in terms of mean per m^3 carbon emissions) for ground-based, swing and tower yarder. There is the most variability in the ground-based data, with a coefficient of variation of 62% It is not appropriate to calculate variability for the production thin data (as there are only 2 results).

Table 3: Statistics for each crew configuration

	Mean Tonnes CO_2e/annum	**Mean (kg CO_2e/m^3)**	**StDev (kg CO_2e/m^3)**
Ground-based	693	10.7	6.6
Swing Yarder	782	12.6	4.8
Tower Yarder	935	14.7	6.7
Production Thin*	369	18.9	-

**Values are indicative only (based on 2 crews, further study required to confirm)*

These results are visualised below in Figures 3 and 4 for the three crew types identified. Table 3 indicates that hauler crews have the largest carbon footprint per annum, followed by swing yarder and ground-based crews. Outlier values can be seen in both figures.

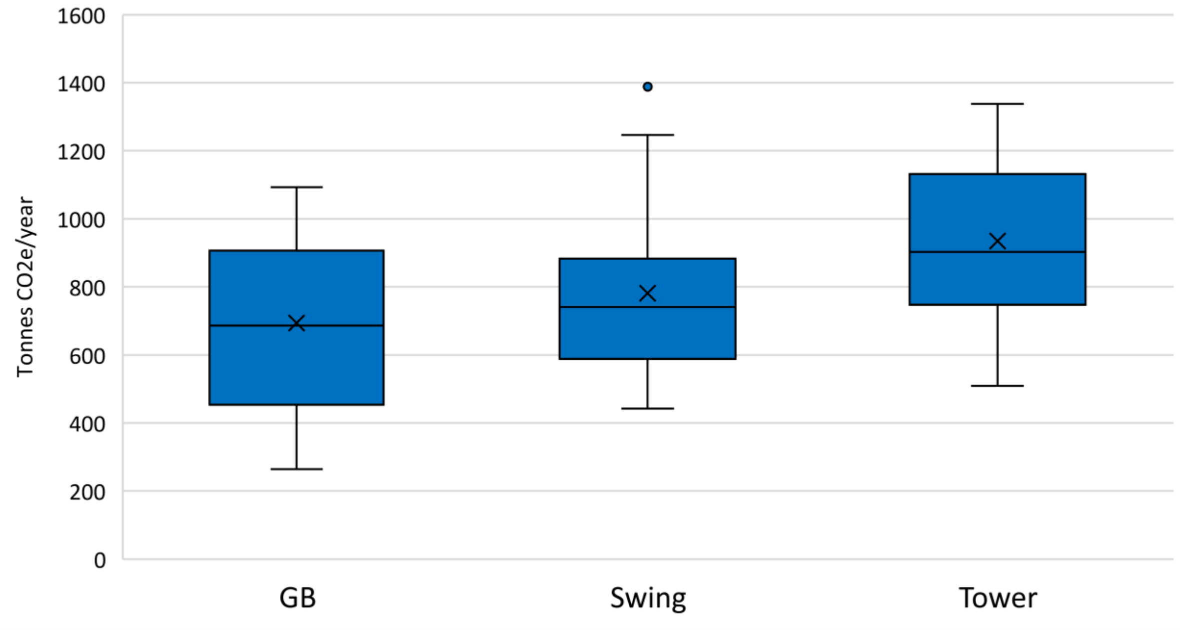

Figure 3: Equivalent footprint per annum by crew type

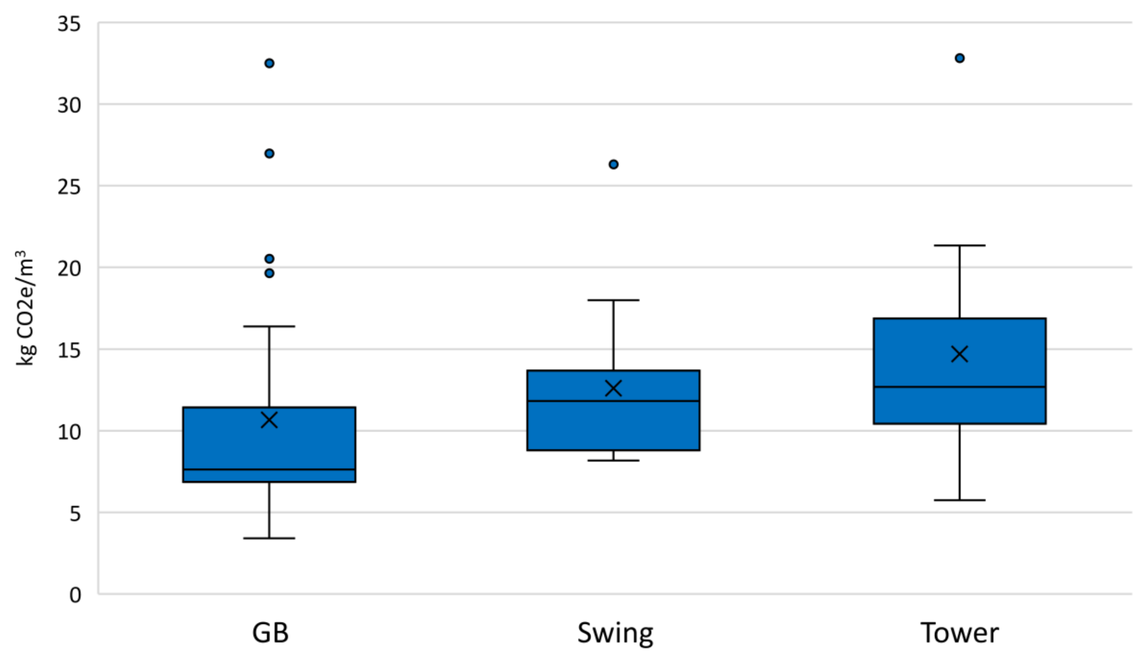

Figure 4: Carbon emissions per m3 logged by crew type

Comparison with past literature

Oyier and Visser (2016) considered a similar investigation wherein the fuel consumption of timber harvesting systems (cable yarder and ground-based) was compared throughout New Zealand. Whilst the purpose was primarily to quantify fuel use by machine and production, total fuel volumes and harvest volumes from the 2013/2014 years can be extracted for analysis of carbon equivalent emissions. Fuel data for 16 cable yarding and 9 ground-based operations have been applied using the relevant emissions factors utilised in this study to provide results for comparison. The oil usage and crew vehicle usage were estimated as well. Figures 5 and 6 below indicate the total annual equivalent carbon footprint in tonnes (fuel, oil) as well as this equivalent metric in kg per meter cubed of logs harvested. An average of 9.2kg CO_2e/m^3 for ground-based and 9.3kgCO_2e/m^3 for cable-harvesting systems is observed (note that this is from the 2013 - 2014 calendar years).

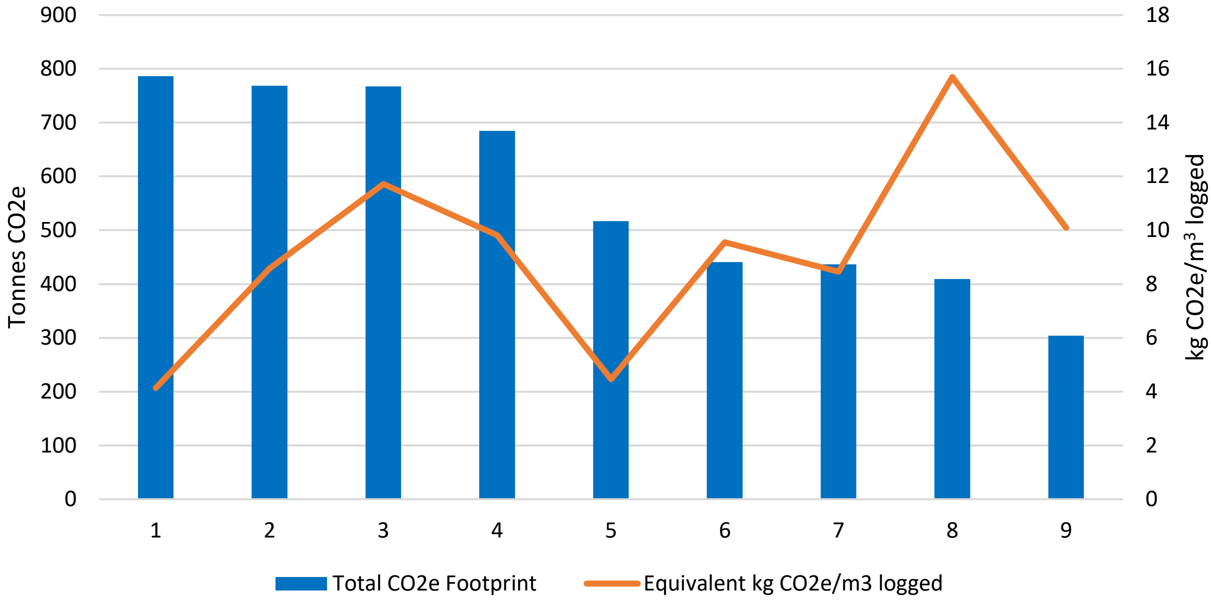

Figure 5: 2015 Ground-based harvesting carbon emissions NZ – Fuel data from Oyier (2015)

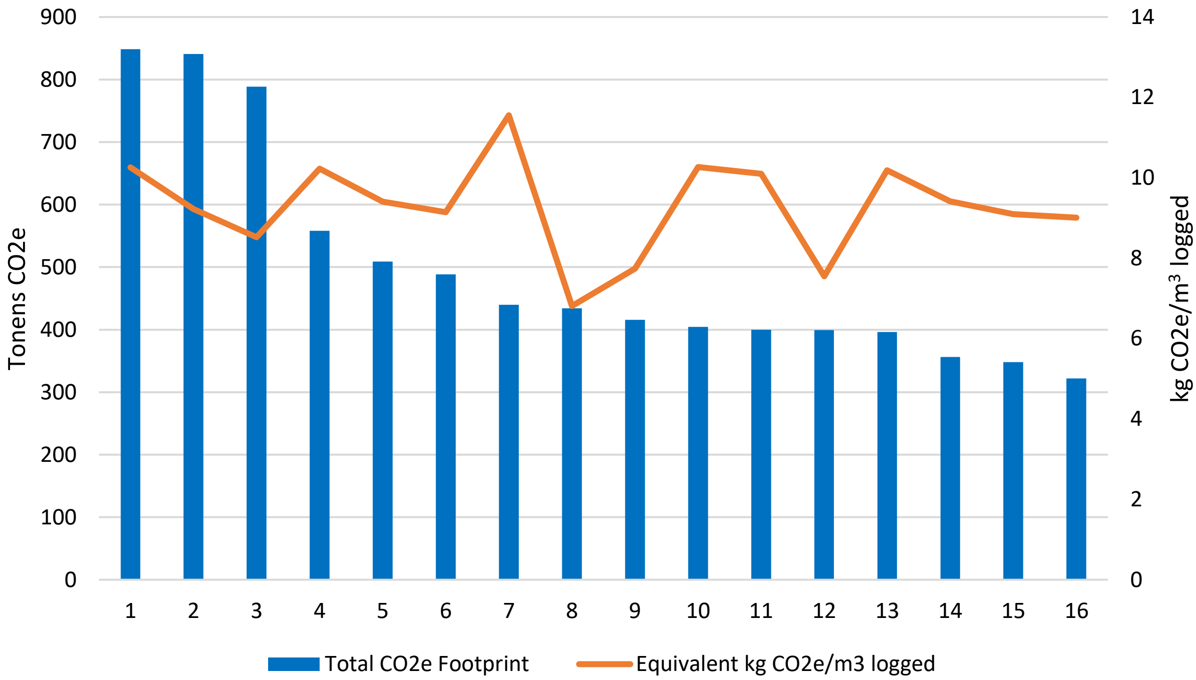

Figure 6: Cable yarder harvesting carbon emissions NZ - Fuel data from Oyier (2015)

One observation is the large increase in fuel usage/carbon emissions since Oyier and Visser (2016) of data in 2013/14. This study indicates that both ground-based and cable yarding crews are burning significantly more fuel (resulting in greater carbon emissions) per m^3 of logs harvested (20% increase in GB systems and up to a 53% increase in cable yarding systems). This is consistent with mechanisation rates across the industry increasing, with mechanised felling on steep slopes increasing from 20% in 2005 to 70% in 2020 (NZ Logger, 2021). The results identified in this study are also above those of the 2009 study from McCallum (2009), which found ground-based and hauler mechanical crew emissions of 8.5 kgCO_2e/m^3 and 9.7 kgCO_2e/m^3 respectively.

Oyier and Visser (2016) found just a 1.2% difference between ground-based and yarder crews, and hence the CO_2e footprint difference were minimal. In this study cable yarding systems were differentiated into tower and swing yarders to help identify a potential difference. There was a 24%

difference in carbon emissions per m^3 between ground-based and swing yarder systems, and a 32% difference between ground-based and tower yarder crews.

Three international studies on the carbon footprint of fully mechanised ground-based crews all reported lower values than found in this study with 7.41 $kgCO_2e/m^3$ (Engel *et al.* 2011), 7.79 $kgCO_2e/m^3$ (Athanassiadis 2000) and 9.00 $kgCO_2e/m^3$ (Klvac & Skoupy 2009). Two recent ground-based studies out of Finland (Haavikko *et al.* 2021; Kärhä *et al*. 2022), utilising different felling techniques/growth regimes, reported average carbon equivalent footprints of 7.1/3.1, 5.7 $kgCO_2e/m^3$, lower than the 10.7 $kgCO_2e/m^3$ found in this study.

A recent study out of northern Italy from Spinelli *et al*. (2022) examines the fuel consumption from 12 tower cable yarding operations (all Valentini type yarders), each with a corresponding processing machine (crew size of 3-4). The investigation includes fuel consumed for ‘yarding and processing’ as well as crew commuting to and from work. Their average across all sites for these selected processes was 3.52 L/m^3. This equates to 10.2 $kgCO_2e/m^3$ logged and is 20 to 40% lower than the results of this study, where the cable yarding systems of swing and tower resulted in emissions of 12.6 and 14.7 $kgCO_2e/m^3$ respectively. One aspect that can help explain the difference is that the new Valentini yarders used are smaller (~130kW) than the larger (and generally older) tower yarders used in New Zealand (~300kW). However, their harvests were also more complex with just ~139m^3 of timber removed per hectare. Two interesting points were that the processing unit was the biggest contributor to fuel burn (50% contribution compared to the yarders 39%) and the commuting fuel burn accounted for 9% of overall usage for the Italian harvest operations.

Survey results and GHG reporting benefits

Four of the six forest management companies reported that they currently measure their company carbon footprint and four report on their harvesting crews. Most companies were in the quantifying and goal setting stages and did not have initiatives in place to use this information. In terms of future goals for companies there was a stronger interest in both electric and hydrogen trucking, but harvesting machines were mentioned. All companies stated they currently put no pressure on the crews to report emissions. However, they believe that with improved machine tracking/recording data available this will be possible to do more accurately in the future. The consensus with regard to the best ways to reduce emissions for harvesting crews in the short term was to reduce machine idle time, more efficient usage of machinery and carpooling. In the long term (5+ years), they saw the electrification of machines being the most likely reduction strategies to be used.

In line with forest manager responses, of the crews that were spoken to, none have or are currently measuring their carbon footprint. However, some did keep good records of their fuel and oil usage, so could easily calculate their yearly emissions. In this survey, the only crew with plans and taking action on the plans to reduce emissions was Hurring Logging Ltd, with the importation of the Logset 12H GTE in 2021.

There are several benefits and disadvantages to reporting GHG emissions. Financial, social and environmental implications should be considered when deciding if to report emissions. To help reach the government’s national net zero targets, all industries should make changes to help reduce emissions. Measuring and reporting emissions is the first step, so by reporting emissions usage forestry can take the first step in helping reach our national targets and obligations. This will also help forestry be viewed more positively in society as it demonstrates social responsibility. It is a great public relations tactic to be seen to be reducing emissions. There may be an increase in the eagerness for planting trees if the harvest is seen as less impactful on the environment. One forest company making changes may motivate other companies to follow.

There is also an opportunity to save money as establishing the carbon footprint can help identifies cost saving and business opportunities. Measuring emissions increases awareness and encourages reductions. Reporting prepares the company for potential disclosure requirements in the future or if forestry operations are one day entered into the emissions trading scheme (ETS) or another scheme.

Factoring in the purchase cost of new forestry machines, businesses will struggle to invest in new emissions reduction equipment. However, if emissions are being recorded and the improvement from a new machine can be estimated, this may help with achieving a better loan rate or investment. Investors are attracted to proficient measuring and reporting as it will be a more sustainable company, thus is seen as a better long-term investment. BNZ are looking at two forms of sustainable lending, sustainability linked loans and green/social loans. For these to be provided, banks must gain a good understanding of the project, so GHG reporting will aid this. For these loans, the bank would offer a higher loan amount and/or a lower interest rate.

If the reporting is conducted externally by a consultant, forestry companies will have to bear the cost of their services. If done internally, there will be time spent understanding how reporting is done, collecting data, processing data and then presenting the results of the analysis. This may take significantly longer than an external provider and may end up costing more.

It is stated in Defra (2010) that the connection between reporting and acting on reducing emissions is indirect and that many other variables affect emissions reductions. As there are no current pressures for forestry companies to act on reducing emissions, action will be delayed.

Hydrogen energy poses a long-term alternative to fossil fuels and could reduce emissions significantly. Hydrogen fuelled harvesting machinery requires further research and development before it becomes commercially available and a viable option for harvesting crews within New Zealand. That being said, companies such as Hiringa Energy are actively looking into the space, with the trucking sector as the first step. Electric hybrid machines are a technology that is already commercially available for forestry specific application. Elforest is contributing to the development of a hybrid forwarder. Logset is leading the way with their 12H GTE and 8H GTE hybrid harvester models. Discussions with Logset determined that the application in New Zealand conditions is still relatively unknown, with just one harvester machine here.

Biofuel has been described both in literature and by the forest industry as a ‘transitionary fuel’ before hydrogen and/or electric technologies have established themselves. Biofuel is still very expensive compared to fossil fuels and the demand for quality feedstock for biofuel production is high.

CONCLUSION

The analysis of data from 55 crews showed tower yarder crews producing the largest quantity of emissions with 935 tCO_2e/annum, normalised by production data to give 14.7 $kgCO_2e/m^3$. Swing yarder and ground-based crews were significantly lower with 782 and 693t, normalised to 12.6 and 10.7 $kgCO_2e/m^3$ respectively. These results were significantly higher than those reported in other studies. However, this coincides with the increase in mechanisation of harvesting operations.

It was found that measuring and reporting of carbon emissions was being done by forest management companies, with no pressure on harvest crews. Most companies were in the qualifying and goal setting stage with not much progress on reducing emissions. Key GHG reporting advantages were to aid the government’s national net zero target, prepare the company for potential disclosure requirements and being able to acquire better investments and loan rates for sustainable equipment. The main disadvantage is the time it takes for a company to collect and analyse data. Research and survey responses have shown that measuring and reporting does not necessarily incite change for the company.

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APPENDIX 1: SURVEY QUESTIONS

[Forest Managers]

- Does your forest company currently attempt to measure/report its Carbon Footprint? (if so, please provide some details)
- Does your company currently have plans in place to reduce your emissions, or to offset them? (if so, please briefly describe)
- Have you undertaken any of these plans? (if so, please provide some details)
- Are you, and or your logging crews, currently measuring the carbon footprint of harvesting operations? If so, briefly explain how.
- Within the next 5 years, what might your expectations be for your contracted harvest crews in terms of measuring/reporting carbon footprints?
- What do you believe are the best ways to reduce the carbon footprint of logging crews? Currently (Right now) and longer term (5 years).
- Any other comments on carbon footprints/emissions for harvesting crews or this study?

[Crew Managers/Owners]

- Are you currently measuring the carbon footprint of your logging crew? (if so, please provide some details)
- Are there any incentives to measure your carbon footprint currently, or to offset them? (if so please provide some details)
- Does your company currently have plans in place to reduce your emissions or to offset them? (if, so please briefly describe)
- Have you undertaken any of these plans? (if, so please briefly describe)
- What do you believe are the best ways to reduce the carbon footprint of logging crews? Currently (Right now) and longer term (5 years).
- Do you know (or can you estimate) your crew's current diesel and/or petrol consumption? (per month or per year)
- If not, can you at least estimate the amount of diesel and/or petrol you use each day (or week?)
- What is the corresponding production (m^3/t or truck loads if not possible) for this period of fuel use?
- If recorded, please state how many litres of oil and lube would you use (again, per month or year?)
- On a typical day, how many hours would you work? (or just list start and finish time)
- Can you please list your machines used (and power rating if possible). For example: Harvester (160kW), Grapple Skidder (125kW), Processor (180kW), Loader (110kW).
- On a typical work day, how many crew vehicles would you use and what is the distance to a typical worksite?
- As part of running your logging crew, do you also operate an office and (or) workshop?
- Any other comments on carbon footprints/emissions for harvesting crews or this study?