Understanding the Emissions of New Zealand's Logging Operations

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Abstract

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 a simplified methodology for emissions reporting, outlines the potential advantages and disadvantages for forest managers and harvest crews to measure emissions and a collation of relevant specific research addressing potential innovation and improvement options.

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 fuel use.

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}), and a published fuel to CO_{2e} conversion factors are used. Based on expert advice, this study also includes the 'well-to-tank' carbon footprint. That is, the carbon used in extracting, processing and delivering the fuel to the logging site. There remains debate about the justification of including this in Scope 1 analyses, but effectively it adds about 20%.

The highest carbon footprint both per annum and per m^3 logged were the tower yarder (hauler) crews, with an average of 1153 tCO_2/annum and 18.1 $kgCO_2e/m^3$ respectively. Swing yarder crews averaged the next highest (964 tCO_2/annum and 15.5 $kgCO_2e/m^3$) with ground based resulting in the least (855 tCO_2/annum and 13.1 $kgCO_2e/m^3$).

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 don't currently have reduction plans in action.

Hydrogen, hybrid/electric, biofuels and biodegradable oils are possible improvement options that were explored in this report. Hydrogen is in the 'keep an eye on' stage with retrofitting without original equipment manufacturer (OEM) integration as the only feasible solution currently for onsite forestry equipment (without the introduction of external new fuel cell lines, such as those in development from JCB), thus trucking poses the most obvious first step. Hybrid electric systems are available for harvesting machines, with reasonable fuel savings possible.

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1. Introduction

As the world transitions to a low carbon economy, those that are at the forefront of this change will be in a unique position that can offer many benefits and competitive advantages. This is the outlook that a lot of companies in New Zealand are adopting going forward, 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. Whilst this effort is mainly being led by the corporate and financial sectors, there is now a wider expectation for other industries to become accountable for their carbon emissions.

The forest industry is currently experiencing the early stages of pressure to measure and report emissions, particularly from overseas stakeholders. This is only expected to increase. This pressure could be placed on harvesting crews, to monitor their emissions and employ methods to try to reduce them. Two of New Zealand's largest forest management companies, Manulife and Timberlands, stated they consider cost, environmental and social aspects when selecting harvest crews. They both expect to include harvest crews' sustainability (in terms of carbon footprint) as part of their business in the next 5 years. 'Carbon footprint' is defined as the amount of carbon dioxide released into the atmosphere as a result of an organisation's activities. Individual crews understand that fuel usage makes up the majority of this footprint but are not well informed as to how much and with what variables does it change.

Currently, there is little research, particularly in New Zealand, on the emissions produced by harvesting operations and formal research on ways to improve current machines or utilise innovative alternatives. Having a resource that crews can use to estimate their emissions and a collation of relevant and specific research addressing ways to improve, will be very valuable for harvest contractors and management companies. There are four objectives of this research:

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

2. Literature review

This literature review summarises research of relevance to the New Zealand forest industry in regard to reducing harvest operation carbon emissions. This includes a summary of GHG reporting in New Zealand, past literature on harvest emissions and improvement/innovation options.

2.1 Greenhouse Gas reporting in New Zealand

In response to the international climate crisis, in 2019 the New Zealand government introduced the Climate Change Response (Zero Carbon) Amendment Act (New Zealand Government, 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 (New Zealand's Projected Greenhouse Gas Emissions to 2050, 2022) has indicated that with existing measures only, gross emissions are projected to gradually decrease from 79.7 million tonnes of carbon dioxide equivalent ($MtCO_2e$) in 2020 to 66.6 $MtCO_2e$ in 2050. 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.

New Zealand guidance around GHG measurement and reporting is provided by the Ministry for the Environment (MfE). Companies within New Zealand (including logging operations) report their GHG emissions in accordance with this guidance (Ministry for the Environment, 2022a). The guidance itself is extracted from international frameworks for GHG reporting, detailed below (International Organization for Standardization, 2018).

The GHG Protocol separates emissions based on their source into the following categories (World Business Council for Sustainable Development & World Resources Institute, 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, so can be counted multiple times (Ryan & Tiller, 2022). Almost all GHG reporting is based on estimates using emissions factors, thus is important to note that almost all GHG reporting is inaccurate, in some way.

Ryan & Tiller (2022) was a study which sampled 237 large New Zealand entities, none of which were forestry, to determine the level of reporting currently being done. They found one third reported GHG emissions, half providing the organisational boundaries, with the reporting of scope 1, 2 and 3 emissions being inconsistent.

2.2 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, 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 for the production of a domestic log (McCallum, 2009; Weyrens, Therasme & Germain, 2022). Fuel usage for different machines in New Zealand has been studied (Amishev, 2010; Visser & Oyier, 2016). Visser & Oyier (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 crews can produce significantly more emissions (McCallum, 2009; Engel, Wegener & Lange, 2011; Sonne, 2006; Athanassiadis, D. 2000; Klvac & Skoupy, 2009). McCallum, (2009) is the only New Zealand harvesting carbon emission study completed publicly available, which 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), hauler mechanical (9.7kg CO_2e/m^3) and hauler motor manual (9.0kg CO_2e/m^3), were all significantly higher than ground based manual emissions (6.6 kgCO_2e/m^3). Engel, Wegener & Lange (2011) recorded partially mechanised, highly mechanised and fully mechanised emissions as 4.1 kgCO_2e/m^3, 6.83 kgCO_2e/m^3 and 7.41 kgCO_2e/m^3. Both Athanassiadis (2000) and Klvac & Skoupy (2009) studied fully mechanised (harvester and forwarder) crews as well and found emissions of 7.79 kgCO_2e/m^3 and 9.00 kgCO_2e/m^3 respectively. A more recent study from Haavikko et al. (2021) from Finland found a carbon equivalent per m^3 footprint of 7.34 and 3.14 kg 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. Several other variables also 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). It should be noted that international studies on carbon emissions have largely different variables to a typical NZ forestry operation, thus are expected to be varied.

Visser & Oyier (2016) determined 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 best harvest plan and using tools to improve management logistics, particularly with roading, 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 the smallest production of emissions (2.27 kgCO_2/m^3).

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). McCallum (2009) states 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 improve. Reductions made at the crew level by minimising fuel consumption is an obvious initial step for reducing the carbon footprint. Machines that use large amounts of fuel (hauler, mechanised felling, processing, skidders, excavators) are able to have a reduced consumption through operator training and preventative maintenance. This can also occur during the planning stage by ensuring workers are well trained and optimising the skid and positioning of machines to reduce movement.

2.3 Hydrogen technology

Stępień (2021), Onorati et al. (2022) and DAS (2002) all agree that hydrogen possesses the ability to 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 there are several aspects of its use that still need to be finalized, including production methods, storage, safety, and engine optimization. That being said, 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 of hydrogen engine combustion are Nitrous Oxides (NOx), which already have a treatment and mitigation methodology inbuilt into the latest engines to keep these close to zero. By adding hydrogen as a blend to internal combustion engines, the power, torque, and brake thermal efficiency all decrease (Shadidi et al., 2021). However, due to the replacement of diesel or other hydrocarbon fuel sources, direct emissions of CO, UHC, CO_2 and soot all decrease (with an expected increase in NOx emissions).

Hydrogen fuel cell engines pose a recent and exciting new opportunity (as opposed to merely burning an injected amount of hydrogen in an internal combustion engine). 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 which can produce a sustainable hybrid car (and by extension other vehicles). However, modest expenditure is required for research and development to further the chances of 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). This presents an opportunity for further research into this area.

2.4 Electric hybrid engines

Electric hybrid engines have been researched for over 30 years (Burke, 1992). Early research by Carlini (1997) stated that maximum power is 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, there has been an increase in restrictions on internal combustion engines in the non-road mobile machinery category in recent years (Scolaro et al, 2021). An example is the regulations for machines with engines above 56W in stage 5 European regulation (EU: Nonroad Engines, 2017). 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). The industry has done this with solutions taken from the automotive industry (Mergl et al., 2021).

Currently, the most common hybrid design uses electricity to solve the issue of smaller engines with a lack of power, for example in harvesters (Mergl et al., 2021). Literature refers to this as the electro-hybrid drive. The Logset machines use the electro-hybrid drive system in their 8H GTE and 12H GTE harvester models. Johnsen (2021) found 20 to 25% for the 12H GTE model 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) and found the machine had a mean fuel consumption rate of 0.56 to 0.8 L/m^3. This is significantly lower than traditional diesel engine cable yarders, which range from 2.35 to 3.98 L/m^3 (Oyier and Visser, 2016). The main difference between the Koller K507H-e and other models is the electric winches driven by a diesel-electric motor, and the ability to store energy in batteries. Visser (2015) stated 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.

Ponsee, a Finnish machine manufacturing company, is also working in this space, with a fully electric concept forwarder EV1 model released in August 2022 (Ponsse Launches New Technology: An Electric Forest Machine, 2022). No performance data or battery specifications have been provided in their release.

Even though forestry has been researching applications of hybrid engines for over 30 years (Burke, 1992), Scolaro et al. (2021) state hybrid electric technology is in the initial stages of development in forestry and in comparison to road vehicles, it is significantly more challenging. Scolaro et al. (2021) reviewed technical electrification research, focussing on the feasibility from a mechanical perspective in agriculture and forestry machinery. 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. However, they found it to be a feasible solution to reducing emissions. However, 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), which saves money on fuel and associated costs of getting the fuel to the site. There is also a decrease in environmental impacts and often requires less maintenance (Pandur et al. 2020).

2.5 Biofuels

Biofuels have been a large topic in the energy debate over the last several years with forestry being one industry that has taken a particular interest. New Zealand, being an isolated island, is currently importing fossil fuels. Diesel is the primary fuel used in forestry and makes up over 90% of the emissions from harvesting operations (McCallum, 2009). Jack (2009) identified that forestry biomass was a key resource in replacing fossil fuels, so large-scale energy, economic and environmental impacts were assessed by Hall et al. (2009). 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'. Since then, 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).

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 disadvantages are higher viscosity (impracticalities for both direct injection and indirect type diesel engines), lower energy content and higher price among others (Kralova & Sjöblom, 2010). There are many ways to convert wood biomass to a fuel that is ready for commercial use. 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).

Production of conventional biofuels is well established, however, Suckling (2015) found that use remains low in New Zealand with it being less than 0.1% of total transportation energy. However, with forestry being an already existing industry, providing carbon sequestration, year-round supply (Hall, 2013) and the blend mandate stated for 2023 (Ngā Kora Koiora - Biofuels, 2022), there is huge potential for additional revenue for forestry companies (Suckling, 2015). Steer (2015) also stated that a forestry lead biofuel industry could provide Māori landowners with an opportunity to secure long term financial, cultural and spiritual benefits.

2.6 Biodegradable oils

Over 60% of lubricants used around the world are put into the environment (Tkáč et al., 2014). Nowak et al. (2019) reported on the key environmental issues of losing conventional lubricating oils and their biodegradability. Schneider (2006) also reported on the threat due to high ecotoxicity to the environment. 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 when used in an un-contained site, 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. However, New Zealand provides limited government incentives for the uptake, with no target or mandate on usage (Suckling, 2015). Therefore, the New Zealand forest industry hasn't had a huge uptake in usage, with most operators in New Zealand still using petroleum-based oils (Ministry of Agriculture and Forestry, 2016).

Visser (2018) stated that of the New Zealand forestry companies surveyed, none had plans to implement the use of bio-oil. He stated there is hesitance due to the higher labelled cost, limited access, efficacy and the risk of damage to equipment. Tkáč et al. (2014), Rajamaeki (1993) and Visser (2018) found the per litre price to be the biggest barrier to uptake, with it being around three times compared to mineral oil. However, in New Zealand conditions, it was found to cost 6% less due to the reduction in the volume needed (Visser, 2019). LubEco's bio-oil products are also carbon neutral, as the CO_2 emitted during decomposition equals the CO_2 captured when the oil was produced (Orton, 2017).

Since forestry is in an uncontained environment and is becoming more mechanised, there is also an increased probability of oil spills into the environment. Burst lines, incorrect usage and lack of care or effort are the greatest risks (Yun Hsien, 2015). Research has shown that bio-oil retains a lower temperature, which provides better performance (Skoupy et al., 2010; Ignea, Ghaffaryian, & Borz, 2017).

3. Method

3.1 Data collection

Data collection was conducted primarily through a survey of current practices within New Zealand, collecting data from forest managers and harvest crews. This took place early in the investigation to allow companies to respond and provide the information necessary in time. An initial goal of 5 crews from each primary extraction method was set (ground based, tower, swing yarder). Information provided is kept anonymous in final reporting to give an unbiased representation in which participating entities are comfortable.

A survey questionnaire was created using Google Workspace (appendix B) – one for forest management companies and one for individual crews. An initial email similar to the one attached (appendix A) was sent to several forest management companies (and subsequently to their crews). The Google Form questionnaire was then forwarded to willing managers/crews that replied. Overall, the survey was aimed to reach companies across all regions of New Zealand. For larger forestry companies where they had several crews' records of fuel and production data, this was sent through as an excel spreadsheet and manually input into the dataset.

3.2 Analysing data

A crucial first step of the investigation involved contacting and interviewing an expert in the field of carbon measurement and reporting. This was necessary to synthesize the guidance given by MfE (Ministry for the Environment, 2022a) and get an understanding of how most companies here in New Zealand are approaching the task. A senior engineer from Lumen (an engineering consultancy specialising in carbon management) provided insight during a short zoom interview. It was identified that many companies (including one of the main auditors, 'Toitu Envirocare') are moving away from the traditional scope 1 through 3 categories of what to include within a footprint and are replacing it with a modified 'category' system. This difference is seen below in Table 1.

Table 1: Inclusion of factors in emissions footprint: scope and categories

Scope 1	Category 1	Direct GHG emissions and removals	Fuel
			Refrigerant and medical gases*
			Agriculture, forestry, and other land uses
Scope 2	Category 2	Indirect GHG emissions from imported energy	Purchased energy
Scope 3	Category 3	Indirect GHG emissions from transportation	Business travel
			Employee commute (travel)
			Freight transport
			Refrigerant use (from chilled transport or air conditioner)
			Working from home
	Category 4	Indirect GHG emissions from products an organisation uses	Transmission and distribution losses
			Water supply and wastewater treatment
			Materials and waste
	Category 5	Indirect GHG emissions (use of products from the organisation)	
	Category 6	Indirect GHG emissions (other sources)	

Whilst most companies who report in New Zealand are proficient with categories 1 through 3, 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, for example, if determining the life cycle analysis of a skidder, one can consider a similar sized truck vehicle. A key takeaway from the interview is remembering that it is important to focus on what you can control. The first step usually involves collecting year-to-year data and starting from there.

Regarding the above table, the sections for consideration for a full business carbon footprint that relate to a forestry crew here in New Zealand are as follows. For this study, category 1 was used.

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 for their operation (e.g., not many crews may be able to estimate their electrical use). This report simplifies the carbon equivalent footprint of the harvesting operation to the primary contributors of fuel and oil use, as these will account for the majority of the emissions. Note that oil consumption per crew has been 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.

Both fuel and oil are considered contributors to carbon footprint, with the 'well-to-tank' (WTT, emissions associated with the production, processing and delivery of the fuel/oil) included. 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.

The calculation methodology used was

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

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 + WTT values

The emissions factors (F) used are shown below in Table 2. These factors are consistent with those used in the UK and by the United States Environmental Protection Agency (Department for Business, Energy & Industrial Strategy, 2022b; GHG Emission Factors Hub, 2022).

Table 2. Emissions factors (Ministry for the Environment, 2022a; Department for Business, Energy & Industrial Strategy, 2022)

Emission Source	Unit	$kgCO_2e$/unit	WTT $kgCO_2e$/unit
Transport Fuel - Diesel	Litres	2.69	0.63
Transport Fuel - Petrol	Litres	2.46	0.60
Oil	Litres	2.96	0.70

3.3 Research improvement options

In terms of the research side of the project (objectives 3,4), the methodology includes further analysis of relevant literature as well as consultation with industry and third parties. Expanding on both objectives 3 and 4, the report synthesises information relevant from the following industry sectors:

- Machine and equipment manufacturers
- Bank/Financing sources
- Forest management companies
- Forest harvest crews
- Carbon consultancy firms

Meetings with appropriate industry sources are held throughout the project, with initial email contact being conducted during the first few weeks of the project timeline. Email contact was conducted in a similar approach to that outlined in Appendix A, however, specified for each industry sector. All feedback from industry representatives was synthesised with literature and presented clearly and concisely.

As discussed, several variables within forest harvest operations have been studied and proven to have an impact on emissions. However, more research needs to be done with a range of operators, while working in New Zealand conditions and with modern mechanised practices to get a better understanding of a baseline for expected values that harvest crews and managers can then use to estimate their footprint. As shown in the literature review there is also little formal research into ways to reduce the emissions produced by crews through the improvement of the operator or machine, nor feasible innovation options. For this reason, an overview of realistic options for harvesting crews was also completed to give foresters an idea of future innovations within the space.

4. Results

4.1 Carbon footprint for harvesting crews

4.1.1 Crew composition

The data collected for harvest crews were classified into either swing yarder, tower yarder (hauler) or ground-based, based on the primary method of extraction. Data for two production thinning crews are also presented. Feedback from crews on exact machine composition was varied, thus a general estimation based on the information received was drawn.

The average composition of what a crew consists of, and relative power ratings are as follows:

Tower Yarder Crew – Average of 7.4 machines contributing to direct harvest on site

- 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 contributing to direct harvest on site

- 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 contributing to direct harvest on site

- 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 contributing to direct harvest on site

- (No specific data, assume similar to ground-based composition)

4.1.2 Raw Fuel and Productivity Data

Table 3 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 depict the lowest average diesel use with highest average volume harvested, leading to a lower per metre cubed fuel efficiency.

Table 3. Raw Fuel and production data (minimum, maximum and average across crews)

	Diesel Use (L)			Volume (m^3)			L/m^3		
	Min	Max	Avg	Min	Max	Avg	Min	Max	Avg
GB	91120	376016	238370	9800	216164	84992	1.16	11.20	3.67
SY	152544	478033	269036	30800	150285	67064	2.82	9.07	4.34
TY	174576	459700	320672	29402	198104	78661	1.98	11.31	5.04

4.1.3 Carbon equivalent analysis

Data collected on fuel usage and production data have been analysed to give a total carbon footprint and a per m^3 number, 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 was received for 30 ground-based harvesting crews, 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' per m^3 was also large. The clearest example of this is seen in crews 1 through 14, where the average $kgCO_2e/m^3$ footprint of 10.17 is much smaller than that of the remaining ground based crews (16.13). This even suggests that a higher total carbon footprint (bigger operation) may result in a lower per metre cubed carbon footprint (better efficiency) Other notable features include crew 19 having a very large value of 40.1 $kgCO_2e/m^3$. This can potentially be attributed to an incredibly difficult block to harvest. This is likely as the fuel usage is average, as shown in the blue (figure 1), it just had low harvest volume.

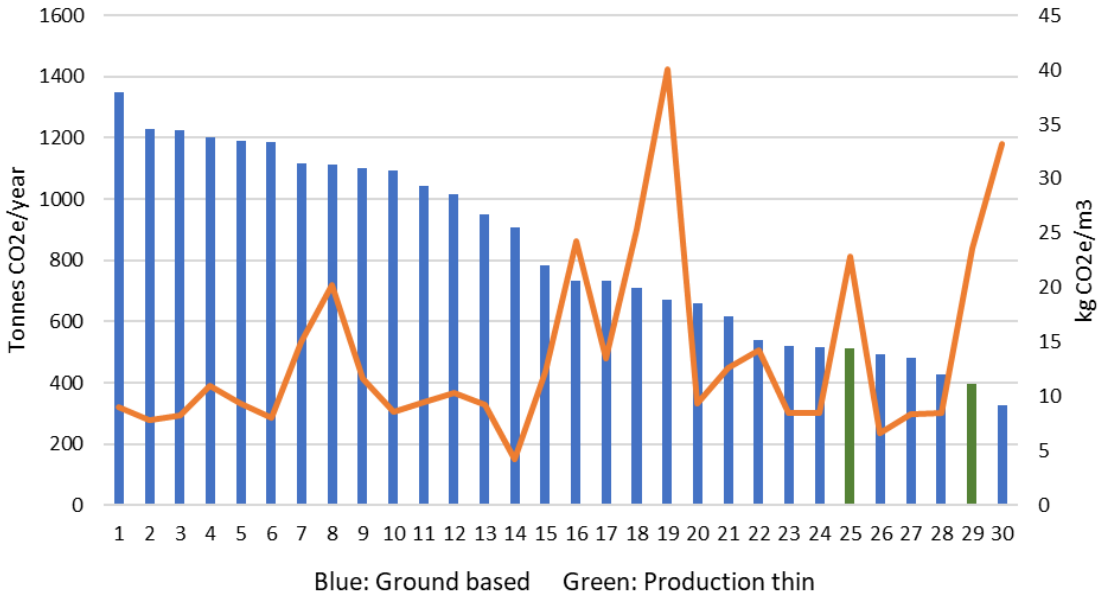

Figure 1: Carbon emissions ground-based crews

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 32.5 $kgCO_2e/m^3$, and one in the tower yarder crews of 40.5 $kgCO_2e/m^3$.

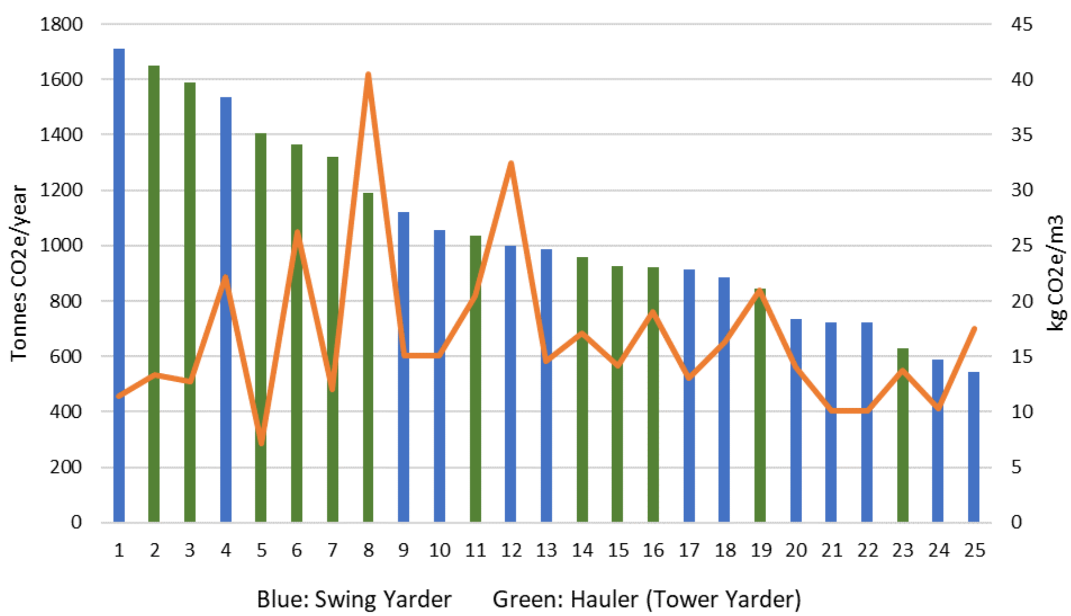

Figure 2: Carbon emissions cable harvesting crews

The average values for both equivalent annual carbon footprint (based on fuel/oil usage alone) and per m^3 emissions are presented in Table 4 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 4: Statistics for each crew configuration

	Mean Tonnes CO_2e/annum	Mean (kg CO_2e/m^3)	STD (kg CO_2e/m^3)	Coefficient of Variation
Ground Based	855	13.1	8.1	62%
Swing Yarder	964	15.5	5.9	38%
Tower Yarder	1153	18.1	8.3	46%
Production Thin	455*	23.3*	-	-

**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 four crew types identified. For total carbon footprint per annum, Table 4 indicates that hauler crews have the largest, followed by swing yarder and ground based. Outlier values are seen in both figures depicting extreme results.

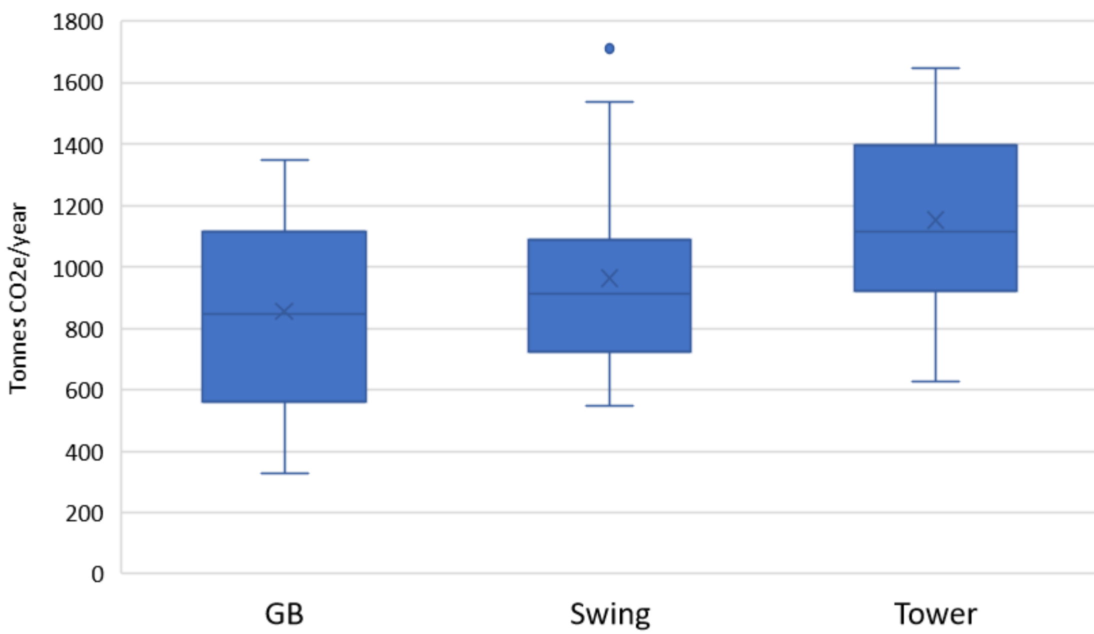

Figure 3: Equivalent footprint per annum by crew type

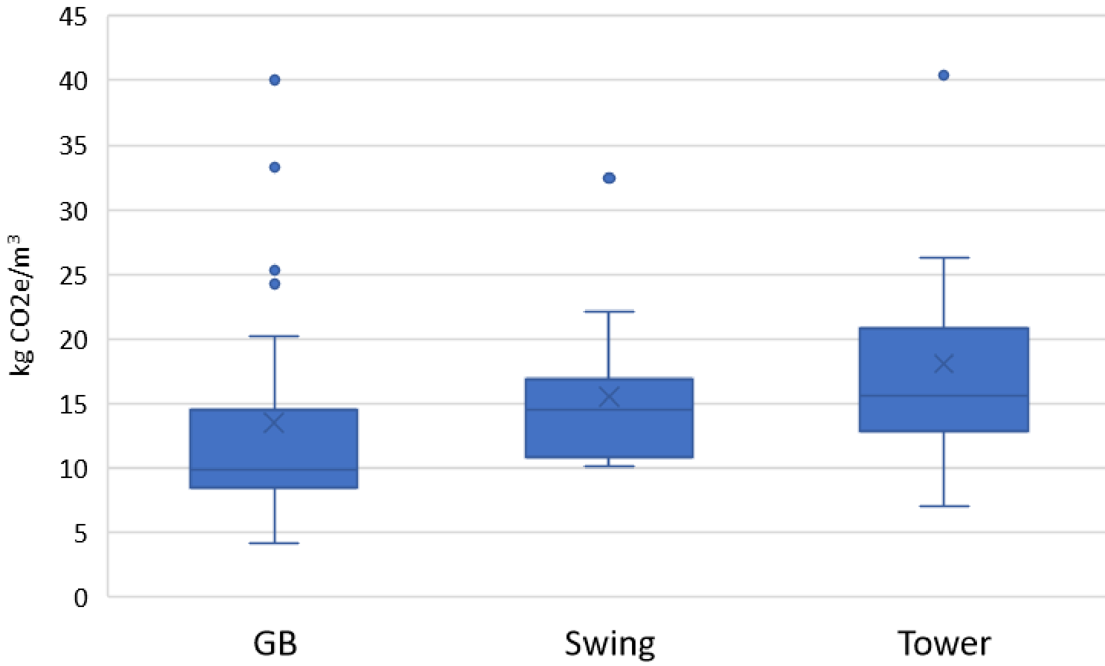

Figure 4: Carbon emissions per m^3 logged by crew type

4.1.4 Comparison with past literature

Oyier (2015) considers a similar investigation wherein the fuel consumption of timber harvesting systems (cable yarder and ground based) is 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 (including WTT factors) to provide results for comparison. The oil usage and crew vehicle usage were estimated as well. Figures 5 and 6 below indicate the total equivalent carbon footprint in tonnes (fuel, oil) as well as this equivalent metric in kg per meter cubed of logs harvested. An average of 11.3kg CO_2e/m^3 for ground based and 11.4 kgCO_2e/m^3 for cable-harvesting systems is observed (note that this is from the 2013 - 2014 calendar years).

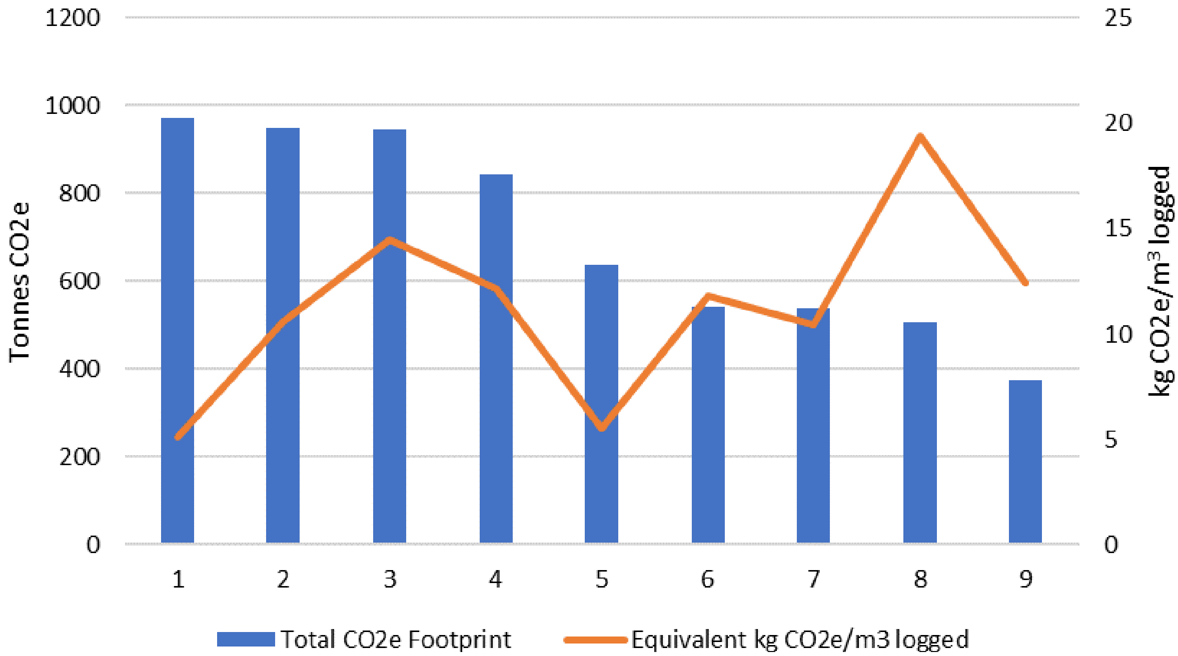

Figure 5: 2015 Ground based harvesting carbon emissions NZ – Fuel data from Oyier (2015)

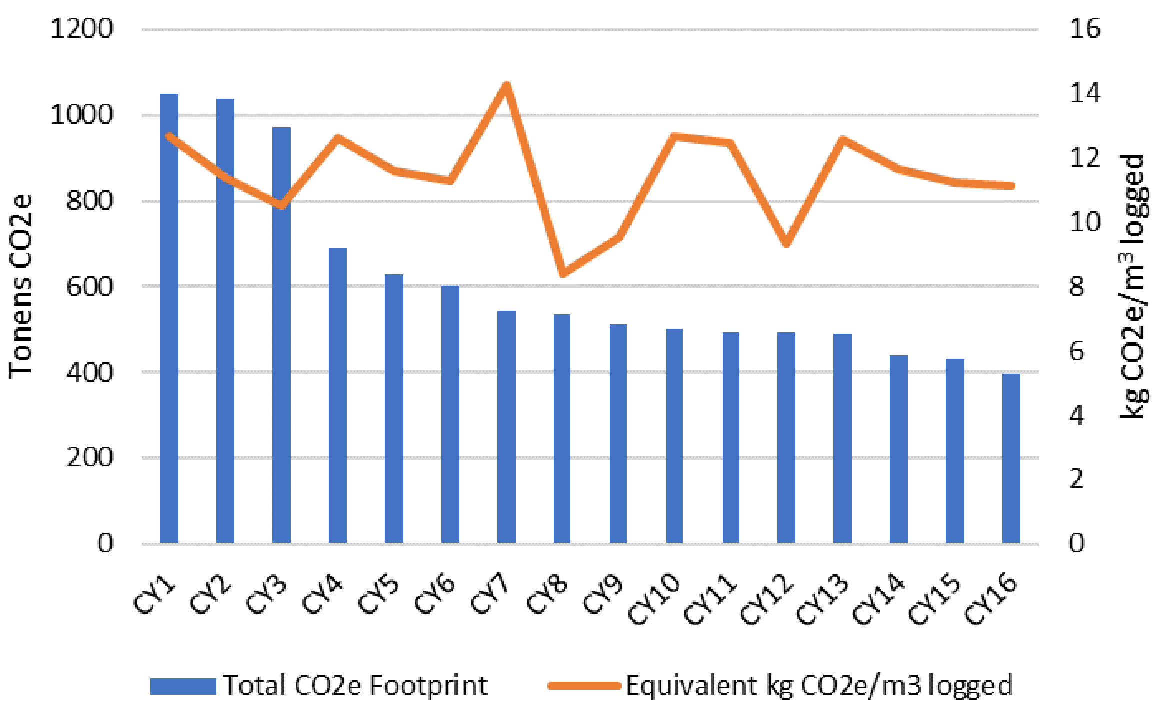

Figure 6: 2015 Cable yarder harvesting carbon emissions NZ - Fuel data from Oyier (2015)

Comparing these results from 2015 to findings from this study, some differences are observed. Findings from Oyier (2015) indicate the overall difference in fuel burn (and thus CO_2e footprint) between ground based and swing yarder systems are minimal. Whilst Oyier (2015) groups both tower and swing yarders as one class, findings in this study help to identify a potential differentiation between the two cable yarding systems in terms of fuel burn and carbon emissions. Alternatively, this study identifies a 24.3% difference in per m^3 carbon emissions between ground based and swing yarder systems, and a 31.9% difference between ground based and tower yarder crews. Oyier (2015) found just a 1.2% difference between ground based and cable/swing yarder crews combined.

Another observation is the large increase in fuel usage/carbon emissions since 2015. This study suggests that both ground-based and cable yarding crews are burning significantly more fuel (resulting in greater carbon emissions) per m^3 of logs harvested (15.1% increase in GB systems and up to a 37.4% increase in cable yarding systems). This is consistent with the idea that mechanisation rates across the industry have continued to grow, 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 well above those of the 2009 study from McCallum, which found ground based and hauler mechanical crew emissions of 8.5 $kgCO_2e/m^3$ and 9.7 $kgCO_2e/m^3$ respectively. McCallum (2009) didn't separate hauler and swing yarders however. Three international studies, Engel, Wegener & Lange (2011), Athanassiadis (2000) and Klvac & Skoupy (2009), all reported significantly lower values for fully mechanised ground-based crews with 7.41 $kgCO_2e/m^3$, 7.79 $kgCO_2e/m^3$ and 9.00 $kgCO_2e/m^3$ respectively.

4.2 Survey results & discussion

4.2.1 Forest manager's responses

As a result of the survey of forest managers, data was collected on several questions about their company's current reporting status and what they see in the future of GHG reporting in the forest industry. 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 on their emissions. Four of the six forest management company responses to the survey reported they currently measure their company carbon footprint and the same amount currently report on the harvest crews. Most companies were in the quantifying and goal setting stages, so didn't currently have initiatives in place to use this information. Using both electric and hydrogen trucking and harvesting machines were mentioned as part of these goals. All companies stated they currently put no pressure on the crews to report, however, they think that with machine tracking/recording data available, this will be possible to do accurately in the future. The consensus with regard to the best ways to reduce emissions in the short term was to reduce idle time and have more efficient usage of machinery and carpooling. In the long term (5+ years), they saw the electrification of machines and more local processing 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 can easily calculate their yearly emissions. The only crew with plans and taking action on the plans to reduce emissions was Hurring Logging, with the importation of the Logset 12H GTE in 2021.

4.2.2 How can reporting be done

For companies, 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
  Carbonreduce and Carbonzero programmes 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/
  'Business Calculator' or 'Business Calculator lite' are calculator services provided by Ekos. Your inputted information with assistance from the Ekos team generates your carbon footprint.
- Oxygen Consulting https://www.oxygen-consulting.co.nz/carbon-management
  Consultancy Service operating specifically in the carbon space, offers either 'carbon efficient' or 'carbon neutral' package.
- Morphum Environmental https://www.morphum.com/sustainability-services Another consultancy type service is available to conduct/verify GHG reporting.

For internal measuring, there is guidance from the Ministry for the Environment (Measuring and Reporting Greenhouse Gas Emissions: Guide for Organisations, 2022). There is also the 2022 Measuring Emissions Interactive Workbook. This is a free excel interactive workbook that companies can use to calculate their full carbon footprint. Many of the above companies refer to the values used in this workbook. If chosen to internally measure it is recommended to get this verified by a third-party organisation. For a forestry company choosing to internally measure, following the methodology used in this report is a good starting point to get a grasp on relative annual emissions (Method, 2. Analysing Data).

4.3 GHG reporting benefits and disadvantages

There are several benefits and disadvantages to reporting GHG emissions. Financial, social and environmental implications should be considered when deciding if to report emissions.

4.3.1 Benefits

To help reach the government's national net zero targets, all industries must make changes to help reduce emissions. Measuring and reporting emissions is the first step of this, 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 as reducing emissions. There may be an increase in the eagerness for planting trees if the harvest is seen as less impactful on the environment. By a company making changes, this may also motivate other companies in the industry.

There is also an opportunity to save money as it identifies efficiencies, ways of cost saving and business opportunities. By moving to electric/hybrid machines, fuel usage will also go down. If a feasibility analysis is done, it may be possible to save fuel costs in the longer term by investing in a fuel-efficient machine.

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. Having an understanding of emissions now will be an advantage.

Factoring in the shorter period of forestry machines and the capital cost, 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. From these loans, the bank would offer a higher loan amount and/or a lower interest rate.

4.3.2 Disadvantages

If the reporting is decided to be 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. This may take significantly longer than an external provider and may not end up costing less.

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 put on delay.

4.4 Improvement and innovative emission reduction options

4.4.1 Hydrogen

Manulife confirmed that a hydrogen truck has been purchased and will be arriving early next year. This confirms that companies are willing to commit to this technology early and are not opposed to the implementation of such vehicles within New Zealand forests.

Within New Zealand hydrogen is beginning to gain more attention as a future renewable fuel to help the country meet its 2030 and 2050 climate targets. One company, Hiringa Energy is taking this opportunity very seriously, with 4 production and refuelling sites under construction in the North Island, and a further 20 planned by 2026. Hiringa Energy produces 'green hydrogen' through a carbon neutral process that utilises renewable electricity, aiming to provide the necessary infrastructure and capability to support a future of hydrogen transport. Beginning with targeting the heavy industry sector of trucking (perhaps first applicable for log trucks), they are branching into other areas and working in conjunction with equipment manufacturers such as JCB. Although still primarily in development, hydrogen specific excavators and similar heavy machinery (thus suitable for forest harvesting systems) are closer than first thought. Other companies are also showing interest in this area, with Meridian and Contact Energy eyeing Southland as a potential location for the world's largest green hydrogen plant (Pelletier, 2021).

Hydrogen engines currently operate as either a full hydrogen intake 'fuel cell' engine or as a hydrogen internal combustion system (usually one that utilises a partial diesel blend). Hydrogen fuel cell engines generate energy through a chemical reaction, resulting in no carbon emissions. The current efficiency (modelling a 50-tonne line haul truck) of a hydrogen fuel cell engine is around 10 km/kg of hydrogen used (with equivalent ~5.5L diesel/kg hydrogen). Capital expenditure for one of these trucks is currently around twice that of its diesel counterpart. Whilst fuel cells may be the best option for trucking, hydrogen injection (internal combustion) engines pose more of a practical solution when considering onsite harvesting equipment. Retrofitting existing engines with the aid of the original equipment manufacturer (OEM) is preferred, however, is currently quite difficult and time consuming/expensive. Therefore, retrofitting without OEM integration is the only feasible solution for hydrogen onsite forestry equipment currently (without the introduction of external new fuel cell lines such as those in development from JCB). Even still, this process takes both considerable time and money, for limited reduction in diesel use (max blend of 30 - 40% hydrogen). Other obstacles such as storage onsite and safety put this technology in the category of 'one to keep an eye on'.

4.4.2 Electric/Hybrid Machines

Logset is a Finnish company producing harvesters, forwarders and harvester heads. In 2016, they released their first electric hybrid harvesting machine, the 12H GTE, weighing 24.5t. This was followed up in 2019 by a smaller 23t model, the 8H GTE. Discussions with the sales vice president at Logset stated there is one machine currently in New Zealand, a 12H GTE owned by Hurring Logging, which can deliver 510 hp and 2,000 Nm of torque. These machines use no batteries, instead using a diesel engine, electric motor and supercapacitors. The harvester uses the electric motor to get more power and when the diesel engine does not require more power, the motor becomes a generator for the super capacitors. Supercapacitors store energy through electric charge accumulated on the plates. This can then be released, so acts similar to a battery. This system works well for harvesters as the engine runs at a static 1100-1500 rpm and the electric motor only becomes of use for the peaks. Logset is currently working on solutions for a forwarder, and it was noted that hydrogen has huge potential in forestry machines.

Furthermore, Logset was able to provide a translated study on the Logset 8H GTE (Poikela & Ovaskainen, 2022), which was completed independently in Finland comparing the Logset 8H GTE and similar diesel machines currently on the market. It shows a preliminary result of 7-30% fuel reduction depending on several variables.

4.4.3 Biofuels

One of New Zealand's largest fuel companies, Z Energy, stated whilst biofuels can directly reduce the carbon emissions of a forestry operation, they have been described as a 'transitionary' step towards longer term energy solutions and it is 'unlikely' that the forest industry will directly deal with a prolonged period of biofuel use. This is due to an expected increase in hydrogen and electric vehicles and systems for use being set up. It was stated that there is currently a high life cycle cost for Z Energy's production of biofuels and economics and efficiency aren't as high as they hoped. This is a combination of many factors, which include high transportation costs and high global feedstock demand. Wood has been explored but doesn't yield satisfactory results for them economically.

Unfortunately, bioethanol and biodiesel are currently around 1.5 to 2.5 times more expensive than fossil fuels, making it not a financially feasible option to reduce emissions for any forest company. Furthermore, complications with both the production process and availability of organic material can result in adoption reluctance (Tabatabaei et al., 2015).

4.4.4 Biodegradable oils

Total Oil NZ stated that the biodegradable oil range in New Zealand can be broken into 2 groups, the triglycerides and the synthetic diesters. Triglycerides are derived from plant material and with the addition of specific additives, they can be used in a range of mechanical applications. However, they are limited in their exposure to higher temperatures and are not compatible with normal mineral type oils. Synthetic diesters are a manufactured oil formed from the combination of naturally forming alcohols and organic acids. The diesters are excellent lubricants with an extremely high viscosity index, excellent high and low temperature properties, fire resistance, and are quite compatible with mineral oil products so small levels of cross contamination are acceptable.

The most likely cause of a significant increase in biodegradable oil uptake is the introduction of mandates by councils or larger companies/funds to have contractors using biodegradables, especially when equipment is operating in environmentally sensitive areas where standard mineral oil pollution could be problematical. Tkáč et al (2014) agreed with this, stating 'To extend the usage of biodegradable oils, it is required legislative intervention by the state respectively taxes or subsidy policy.' A move towards greater use of biodegradable lubricants in other areas of operation will improve their environmental profile and give greater protection to the environment.

4.4.5 Voluntary Mitigation

An option within the carbon space that companies can choose to adopt is the voluntary mitigation of greenhouse gas emissions. Through the voluntary carbon market (VCM), a company can reduce their GHG emissions by purchasing and cancelling voluntary carbon credits. Fundamentally, the VCM brings together organisations with emissions reduction opportunities with organisations that can finance these efforts to reduce their GHG impact (Motu, 2021). The VCM operates outside of the regulated NZ ETS so questions have been raised as to its longevity and transparency.

5. Discussion

5.1 Fuel Consumption

The fuel consumption of forest operations (and by correspondence the CO_2e emissions) has been a hot topic not only in New Zealand, but in countries around the world. One very recent study out of the North of Italy from Spinelli et al. (2022) closely examines the fuel burn across 12 tower cable yarding operations, each with a corresponding processing machine and truck/trailer system (crew size of 3-4). Data to compare with this investigation includes mean fuel consumed for 'yarding and processing' as well as 'commuting' (the movement of logs fuel data is not included). Thus, the average diesel fuel consumption across all sites for these select processes is 3.52 L/m^3. This equates to 13.49 kgCO_2e/m^3 logged (using the same emissions factors outlined in the method and estimating 7% oil consumption per unit of fuel). This is comparable to the results of this study, wherein the cable yarding systems of swing and tower resulted in emissions of 15.55 and 25.08 kgCO_2e/m^3 respectively. It is important to consider the very different parameters of this study in the context of New Zealand forestry operations. Firstly, the new Valentina ~127kW yarders used in this study are significantly smaller scale than the larger (and generally older) tower yarders used in New Zealand (~300kW). Secondly, the stocking volume of ~139m^3/ha and the nature of the harvest operations (primarily salvage cuts following storm events) are considerably different to those assessed in this study (primarily plantation forestry clearcut with expected stocking volumes of 500m^3/ha plus). Nonetheless, key points include the processing unit being the biggest contributor to fuel burn (50% contribution compared to the yarders 39%) and the surprising inclusion of commuting fuel burn (9%) on overall usage.

5.2 Innovation options

The results of the survey showed that some forest management companies in New Zealand are currently reporting emissions for harvesting operations and putting no pressure on crews. The reason for doing so was due to increasing demand for reporting from international investment funds and to get a baseline understanding before making progress in addressing ways to improve. New Zealand is currently in the initial stages of making substantial changes to reducing emissions, with just one import of a hybrid harvesting machine and one hydrogen truck on the way. Most forest management companies stated they are currently trying to set up goals and plans to reduce emissions, however, there is currently little incentive for them or the crews to reduce emissions, thus a lack of urgency.

With domestic companies such as Hiringa Energy actively researching and exploring hydrogen as a fuel source, it is only a matter of time before a scalable forestry suited hydrogen engine (whether internal combustion or fuel cell) is in development. In the context of a New Zealand logging crew, whilst this technology is still being fine-tuned the recommendation is to essentially wait and observe the progress in the sector. In this regard research and results from talking to industry experts are in sync; it is clear that there needs to be a large paradigm shift in the industry away from fossil fuels sometime in the coming years/decades - hydrogen poses a realistic opportunity to do so. While harvesting equipment may take longer to transition to hydrogen as a feasible fuel source; trucking poses the most obvious first step.

Hybrid machines are currently already available. The Logset 12H GTE has been imported into New Zealand and is owned and operated in Southland by Hurring Logging. Poikela & Ovaskainen (2022) was a study completed independently in Finland and shows a 7-30% fuel reduction compared to similar non-electric machines on the market, depending on several variables. This was similar to other studies on fuel savings from hybrid equipment (Johnsen, 2021 & Eniola, 2013). The study was completed with the smaller 8H GTE, with an average piece size of 0.8 - 1.1m^3. Therefore, the 12H GTE may be more suitable for New Zealand conditions. With Hurring Logging's recent purchase of the 12H GTE, further research in New Zealand would be beneficial to determine the effect on fuel efficiency and productivity. With reportedly no reduction in machine power or productivity for this machine, a potential 7-30% fuel saving is very appealing. As old diesel machines are phased out of us in New Zealand, there may be an uptake in machines. A rush to buy new electric hybrid machines is not necessarily a bad thing environmentally, as the manufacturing and transport of new machines and discarding of old will have a huge amount of emissions associated with it. Therefore, a natural cycle of replacing old diesel machines with new hybrid machines may be preferred.

While a switch to hybrid and/or electric machine fleets occurs, transition fuels have the potential to be of use. Both the use of biofuel and hydrogen have the opportunity to be used in existing or retrofit machines. Wood biomass converted to biofuel has been reported in literature to be a viable option for New Zealand (Suckling, 2015; Hall 2013; Pang, 2019). With the government agreeing on a biofuels mandate to help reduce emissions, blends are stated to be implemented on April 1st, 2023 (Ngā Kora Koiora - Biofuels, 2022).

Literature has shown that biodegradable oils have not reduced enough in cost to be a competitive option yet. With a lack of incentives, the higher labelled cost per L, limited access, efficacy and the risk of damage to equipment, there is no reason that it will change drastically in New Zealand. Government mandates are the only likely solution to increase uptake. There is also an issue with equipment manufacturers making it essential under the warranty programme to use approved products, thus many manufacturing companies are not accepting bio lubricants.

5.3 Limitations

There were several limitations to this study. Several broad assumptions were made, especially around the contribution to the carbon footprint. Some of these included the usage of oil by crews to equal 7% of total fuel burn (based on industry assumptions and findings from Klvac et al., (2003)), all fuel recorded to be burnt/utilised on site (or commuting to and from site), and that emissions factors for this calendar year were used in the methodology for data up to 3 years old. It is also important to note that the carbon footprints found in this report are based on fuel data only (with an oil approximation), thus should not be taken as a final figure for the harvesting impact (the real figure is likely to be slightly higher when accounting for factors such as electricity, waste etc). Overall, these approximations do not discredit the validity of the carbon footprint findings however they are aspects to consider.

The study doesn't consider utilisation rates. Using data from forest managers and crews, the number of machines for each configuration were able to be averaged. However, this study did not consider if these machines were all being used, or if they were idle. It also doesn't consider the terrain and other factors affecting per m^3 values such as stocking, forest age or tree species which would impact fuel usage. Studies such as Visser & Oyier (2016) suggest that some of these factors including terrain can have a significant effect on per m^3 values, thus further study in this area may be appropriate. In general, the results for emissions per m^3 in this study were higher than that of previous research. This is not a surprise as many of the studies are 10 or more years old. Over the last decade, mechanisation has increased, which has resulted in more fuel being used, thus more emissions.

It was assumed that for any crew configuration, each machine operator will have their own personnel ute, when not defined otherwise. For the yarder crews, one or more machines are generally utilized as a tail hold vehicle (thus having a lesser contribution to overall fuel burn). Motorized grapple carriages, chainsaws and other harvest small scale equipment are included in the total fuel/carbon analysis.

5.4 Further research

With regard to GHG emission measuring and estimating, further study could be done considering other factors affecting emissions, not just mechanisation. Variables such as tree species, stocking and forest age would impact the amount of fuel usage. The data analysed in this report is still very broad and could be broken into a machine level quite easily. This could then be applied into a calculator type spreadsheet for crews to input their machines used.
For improvement/innovation options, analysing the feasibility and potential applications of hydrogen fuel technology in the forestry industry could be further researched. Companies, such as Hiringa Energy, have shown interest in forest operations, so potential collaborative work could be done. There is also the opportunity to conduct research to get a better understanding of expected fuel savings of the Logset 12H GTE hybrid machine in New Zealand conditions.

6. Conclusion

The analysis of data 55 crews showed tower yarder crews producing the largest quantity of emissions with 1153 tCO_2e/annum, normalised by production data to give 18.1 $kgCO_2e/m^3$. Swing yarder and ground based were significantly lower with 964 and 855t, normalised to 15.5 and 13.1 $kgCO_2e/m^3$ respectively. These results were significantly higher than those reported in other studies. However, this coincides with the increase in mechanisation.

It was found that measuring and reporting of carbon emissions were 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 action on reducing emissions. Key GHG reporting advantages were to aid the governments 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.

Hydrogen energy poses as a long-term alternative to fossil fuels and has the ability to 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. Logset is leading the way with the 12H GTE and 8H GTE models as well as Elforest with the hybrid forwarder. Discussions with Logset determined that the application in New Zealand conditions is still relatively unknown, with just one machine here. Biofuel has been described both in literature and by the industry as a 'transitionary fuel' before hydrogen and/or electric has established themselves. It is still very expensive compared to fossil fuels and the demand for quality feedstock is very high. Forestry being in an uncontained environment is an industry that should be using biodegradable oils. With research showing the cost is very similar and the environmental impact being significantly reduced, there is no disadvantage for crews to try out bio-oils. However, a mandate seems the most likely reason for uptake.

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Appendix

Appendix A. Initial Email Contact Format

Good afternoon *'Insert name'*,

Simon Smith and I are students at the University of Canterbury and are doing a final year dissertation project on the carbon emissions of harvest crews. The purpose of this is to get a better understanding of expected emissions for crews based on mechanization and to provide some improvement/innovation options to reduce emissions. The outcome of the research will be some emissions values that crews can use (per t of logs) to estimate their emissions, which will be of use as reporting to forest managers and stakeholders increases.

We interested to know if you keep data from harvest crews, most importantly the **fuel usage** , **production volumes** (preferably for the 2021 year, however, can extrapolate other data as well) and the machines used by the crew on a typical day. **Oil** usage and **electricity** are other components we would be interested in if crews have any records.

Should you choose to take part in this and feel as though you have some of the above data available, we will send you a follow up questionnaire for you to fill out with specific values.

Please note that any data will be kept anonymous, and the calculated values and report will be made available to you. Feel free to call me on 0220450866 or email me if you have any questions or suggestions on improvement options etc.

We look forward to hearing from you,

Best Regards,

Dougal Shepherd
University of Canterbury

Appendix B. Google form surveys

[Forest Managers]

- What is the name of your company and what is your title/role?
- 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]

- What is the name of your crew and what is your position within the company/crew?
- 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?