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Fuel consumption of timber harvesting systems in New Zealand

Paul Oyier and Rien Visser*
University of Canterbury, New Zealand school of Forestry, 8140 Christchurch, New Zealand

Abstract

Fuel is a major cost in timber harvesting operations. Changes in fuel cost are also typically used by forestry companies in New Zealand to adjust unit harvesting rates. There is however no benchmark on fuel consumption rates for the different harvesting systems to assist optimizing the design of operations. Seventeen ground-based and 28 cable logging crews in New Zealand were surveyed on annual fuel consumption, production, stand and terrain attributes, type and number of machines used and their kW rating. The average rate of fuel consumption was 3.04 lt/m3 and 0.15 lt/kWh for ground-based systems, and 3.18 lt/m3 and 0.09 lt/kWh for cable yarder systems. There was no significant difference between the two groups for the average rates of fuel consumption in lt/m3, but ground-based system were significantly less energy efficient (more lt/kWh) than cable yarder systems. The average rate of fuel used per unit volume harvested decreased with total annual system production. Rates of fuel consumption in lt/kWh are influenced by the type of harvesting system used, total production, number of machines used, average machine power, slope, directions of pulling during extraction and surface moisture conditions during harvesting. Using standard published machine costing spreadsheets, fuel costs per unit volume of wood harvested was approximately 15% of the total harvest system cost.

Keywords: Fuel consumption rates, Ground-based, Cable yarding, Harvesting machines, Fuel costs

1. Introduction

Fuel is a major cost component of timber harvesting. With an expected increase in the level of timber harvesting in New Zealand, coupled with greater levels of mechanization, we can expect higher levels of total fuel used in future harvesting operations. Delivered fuel prices are influenced by market forces beyond the control of logging contractors and stakeholders in the industry. This variability makes it difficult to forecast the impact of change to the logging industry.

For larger scale timber harvesting operations, previous studies indicate that on average fuel contributes 12.8% (Baker et al., 2014), 14% (Baker et al., 2013) and 18.5% (Baker and Greene, 2012) of total harvesting costs in the south-eastern USA; and constitute 10% and 20% of total harvesting cost in Canada and Sweden respectively (Nordfjell et al., 2003).

On-site delivery systems make it possible to keep exact records of fuel consumption by entire crews (Kenny et al., 2014). Despite the prevalence of accurate fuel consumption gauges in modern harvesting equipment, accurate information about actual fuel consumption during harvesting is difficult to find (Athanassiadis et al., 1999). Other fuel monitoring and measurement techniques for harvesting operations have been suggested but these techniques are yet to be embraced by logging contractors (Acuna et al., 2012). Most logging contractors use common rules of thumb or existing spreadsheets in determining the rates of fuel consumption by machines and harvesting systems during operations (Smidt and Gallagher, 2013; Greene et al., 2014; Kenny et al., 2014). In New Zealand such a spreadsheet can be found in the Logging Management Handbook (Alastair, 1994). Accuracy is dependent on the availability of data by single machine or group of machines (Athanassiadis et al., 1999), and dependent on whether the available data is manually or automatically recorded (Spinelli and Magagnotti, 2011).

Logging operations are carried out under constantly changing terrain and stand characteristics that effect rates of fuel consumption by machines and harvesting systems (Nordfjell et al., 2003). Comparing published

*Corresponding author: Tel: +64 3 364 2127 E-mail: rien.visser@canterbury.ac.nz
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fuel consumption rates is difficult because machines, systems, modes of operation, stand and terrain are different, and also because data is often published in different units: liters per productive machine hours (lt/PMH) or scheduled machine hours (lt/SMH); liters per unit of power (lt/kWh); liters per unit weight of the machine (lt/ton). In recent years most published studies do refer to fuel consumption per unit volume of production (lt/m^3) as a relative measure for the purposes of economic comparison (Gordon and Foran, 1980; Athanassiadis et al., 1999; Athanassiadis 2000; Sambo, 2002; Klvac and Skoupy, 2009; Holzleitner et al., 2011a; Holzleitner et al., 2011b; Greene et al., 2014; Kenny et al., 2014).

The opportunity exists to benchmark fuel consumption rates for both ground-based and cable yarding harvesting systems. A benchmarking system has been successfully established for tracking harvest system logging cost and productivity (Visser, 2011, 2015). This helps explore cost minimization options for the harvesting operations (Hackman, 2008) and aids the understanding of variability, but also planning and cost monitoring. For example, mechanization is a means of attaining logging efficiency (Visser et al., 2014), and a reduced number of machines in a harvest system translates to reduced fuel consumption by a single harvesting system (Lindholm and Berg, 2005). While logging fuel consumption surveys involving contractors have been used successfully (Smidt and Gallagher, 2013; Greene et al., 2014; Kenny et al., 2014), capturing quality data remains difficult. Therefore, this study aims at contributing much needed knowledge about fuel consumption in logging operations and it was designed to establish and compare typical rates of fuel consumption in lt/m^3 and lt/kWh for commercial ground-based and cable yarding harvesting systems in New Zealand.

2. Materials and Methods

A survey on logging fuel consumption and production was conducted between June 2014 and July 2015. Data was collected from logging contractors identified using industry contacts. Data collection sheets were sent to participants through email requesting annual fuel consumption and production, systems description (including kW rating of machinery), as well as typical stand and terrain parameters. The survey was conducted across the North and the South Islands of New Zealand (latitudes 29^{0}S to 53^{0}S and longitudes 165^{0}E to 176^{0}E). The operating locations of the participants provided a reasonable geographical spread (Figure 1).

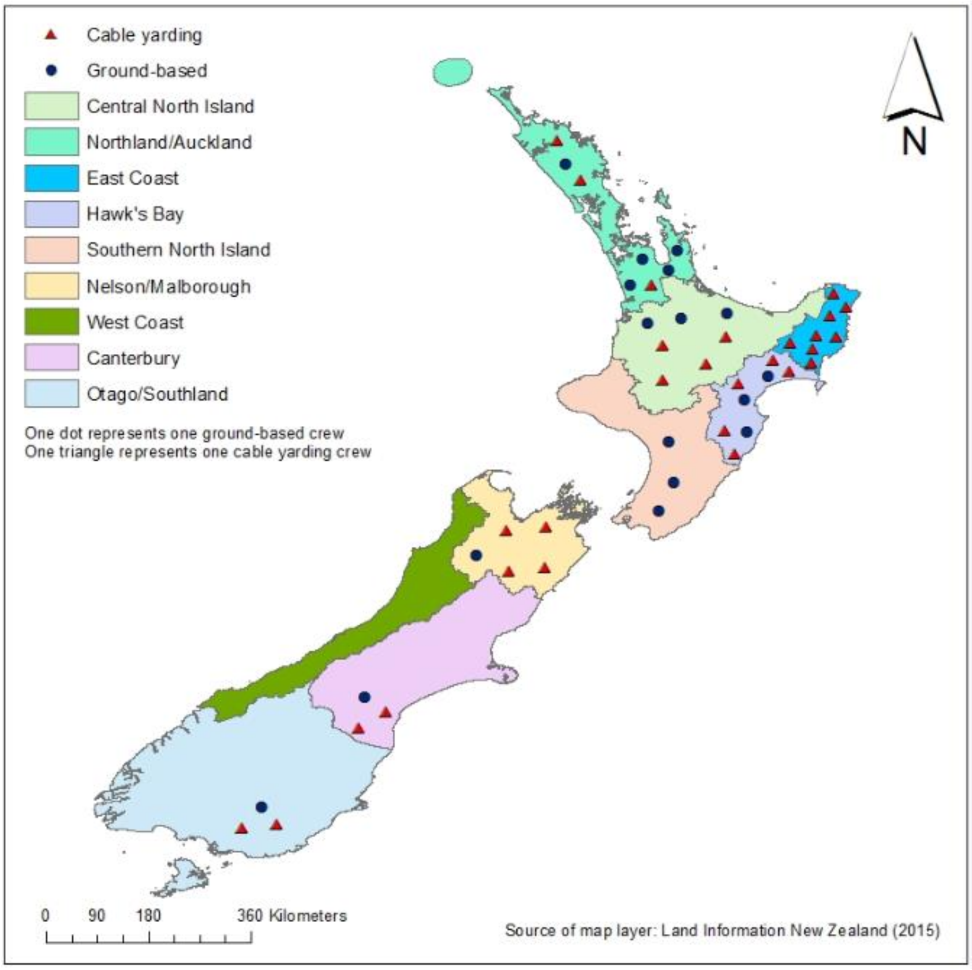

Figure 1. Regional distribution of crews surveyed. Map developed to NZFOA Forest Regions (NZFOA, 2012)

2.1. Description and categories of harvesting site factors

The New Zealand forest industry is based on larger scale pine plantation forests that are clear-cut at the end of the 25 year growing cycle. At time of harvest the average tree size is approximately 2.2 m^3 and volume per hectare is 650 m^3 (Visser, 2015). The harvesting systems are correspondingly larger operations with 5 or 6 machines on site, 6 to 10 workers and machine operators. There is a wide range of terrain conditions across New Zealand. Ground-based (GB) operations are usually conducted on flat and rolling slopes, while cable yarding (CY) operations are done on both steep and very steep slopes (Visser et al., 2011; Visser et al., 2014). All cable yarding operations in the study had motor-manual felling while most ground-based used mechanized felling machines. All of the operation in the study extracted the felled trees to landings for processing. In the survey, operations were categorized as flat (0-15% slope), rolling (16-30% slope) or steep (>35% slope). Directions of pulling during extraction were categorized into flat, uphill and downhill; while surface moisture conditions were categorized into dry, dry/moist, moist, moist/wet, and wet.

2.2. Data collection and analyses

The participants provided monthly (when available) or annual data on fuel consumption, production, average piece size handled, average extraction distances, slope gradient, direction of pulling and soil conditions during harvesting, based on availability. System information included the number of machines and their basic description by type, make and power rating. Participants were encouraged to provide additional operational information such as major system modifications (a change to two-staging, or changing rigging configuration from slack pulling to shot-gunning) during the reported harvesting period.

Rates of fuel consumption were determined both in liters per unit volume of production (lt/m^3) and in litres per unit of power (lt/kWh) by type of harvesting system, for the entire operation. Fuel consumption was calculated by dividing total annual fuel used by total annual production (lt/m^3), or by total system power (lt/kWh). Total system power was the sum of the kW rating for all machines on site multiplied through by the estimated number of system hours worked.

The data was organized in Microsoft excel worksheets and then analyzed using the statistical software package R. Paired t-test were used to check for the differences in means of rates of fuel consumption (lt/m^3 and lt/kWh) between GB and CY harvesting systems. Simple linear and power functions were used to examine relationships between the continuous response variables and each predictor variables. Analysis of variance (ANOVA) at 95% level of confidence was used to test for significant variation in rates of fuel consumption and stepwise regression was used to establish suitable prediction models.

3. Results

Data was received form 45 logging contractors; 17 GB and 28 CY crews. For GB, eleven crews supplied monthly totals, and six crews annual totals. All the study data represents a combined total annual production of about 2.6 million cubic meters of radiata pine (*Pinus radiata* D. Don), harvested using 7.6 million liters of fuel. On average, GB crews harvested 64,930 m^3/year, worked for 217 days while using 3.04 lt/m^3 (Table 1). Total annual production by GB systems was more variable than for CY, whereas GB systems worked slightly longer on a daily basis, with fewer machines on average. CY crews produced 52,420 m^3/year, worked for 226 days while using 3.18 lt/m^3 (Table 2).

Table 1. All study data for all the GB harvesting systems combined (n=17)

Study variable	Average	Minimum	Maximum	SD
Fuel (lt/year)	172,770	104,670	271,150	53,700
Production (m^3/year)	64,930	26,060	190,240	39,210
Days/year	217.00	180.00	247.00	17.00
SMH	8.70	8.00	10.00	0.70
Piece size (m^3)	1.90	1.10	2.90	0.40
Extraction distance (m)	249.00	150.00	400.00	75.00
Number of machines	4.50	3.00	6.00	1.20
Average power (kW)	137.70	111.70	173.60	18.10
Fuel consumption (lt/m^3)	3.04	1.43	5.41	0.95
Fuel consumption (lt/kWh)	0.15	0.10	0.23	0.04

Note: SD = Standard deviation; Average power = per individual machine;
SMH = Scheduled machine hours, inclusive of delays

Table 2. All study data for all the CY harvesting systems combined (n=28)

Study variable	Average	Minimum	Maximum	SD
Fuel (lt/year)	165,470	95,800	292,460	49,420
Production (m^3/year)	52,420	32,400	92,530	15,420
Days/year	228.00	200.00	263.00	16.00
SMH	8.60	8.00	9.50	0.50
Piece size (m^3)	2.20	1.10	3.50	0.40
Extraction distance (m)	264.00	180.00	400.00	69.00
Number of machines	5.10	3.00	8.00	1.30
Machine power (kW)	183.20	161.10	229.70	20.00
Fuel consumption (lt/m^3)	3.18	2.35	3.98	0.39
Fuel consumption (lt/kWh)	0.09	0.05	0.13	0.03

Note: SD = Standard deviation; Average power = per individual machine;
SMH = Scheduled machine hours, inclusive of delays

There were significant differences in average power ($p<0.01$) and piece sizes handled ($p=0.08$) between the harvesting systems. Rates of fuel consumption for GB crews tended to be more variable (ranging from 1.43 to 5.41 lt/m^3) than for the CY harvesting systems (2.35 to 3.98 lt/m^3), but the means were not significantly different between them. On average, GB harvesting systems used 0.15 lt/kWh (range 0.10 to 0.23 lt/kWh) while CY harvesting systems used 0.09 lt/kWh (0.05 lt/kWh to 0.13 lt/kWh). Average rates of fuel consumption in lt/kWh between GB and CY harvesting systems were significantly different ($p<0.01$).

The average rate of fuel consumption (and range) for harvesting operations on flat slope harvest sites was 2.22 lt/m^3 (range 1.43 to 2.91 lt/m^3). On rolling slopes, fuel consumption was higher and more variable at 3.39 lt/m^3 (2.34 to 5.41 lt/m^3). On steep slopes the average fuel consumption was higher (3.18 lt/m^3) than on flat slopes, and less variable (2.35 to 3.98 lt/m^3) than on rolling slopes (Figure 2).

In general, the rates of fuel consumption varies significantly with slope ($p=0.002$), although there was no significant difference between rolling and steep. This result is confounded by the fact that all cable yarding operations were categorized as steep, but the low number of ground-based operations identified as working on variable or steep slope means the result was not statistically significant.

Fuel efficiency was 0.15 lt/kWh on flat slopes, 0.16 lt/kWh on rolling slopes and 0.09 lt/kWh on steep slopes. The ANOVA test showed that fuel efficiency rates were highly dependent on slope ($p<0.01$). Fuel consumption varied with the direction of pulling during extraction (p-value=0.03), with average rates of fuel consumption for pulling on flat site at 2.53 lt/m^3 (ranging from 1.43 to 4.04 lt/m^3) (Figure 3). The average rate of fuel consumption when pulling uphill was 3.19 lt/m^3 (range 2.34 to 5.41 lt/m^3). These rates are associated with both GB and CY operations.

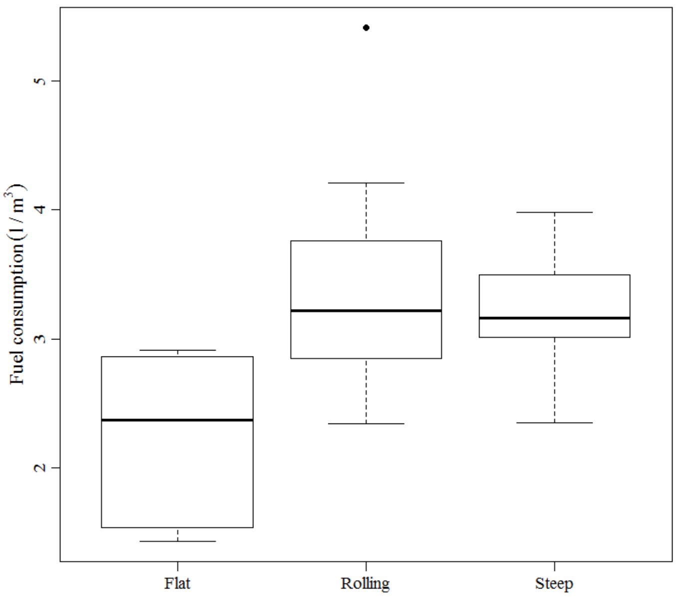

Figure 2. Box and whisker plots showing rates of fuel consumption in lt/m^3 by slope category

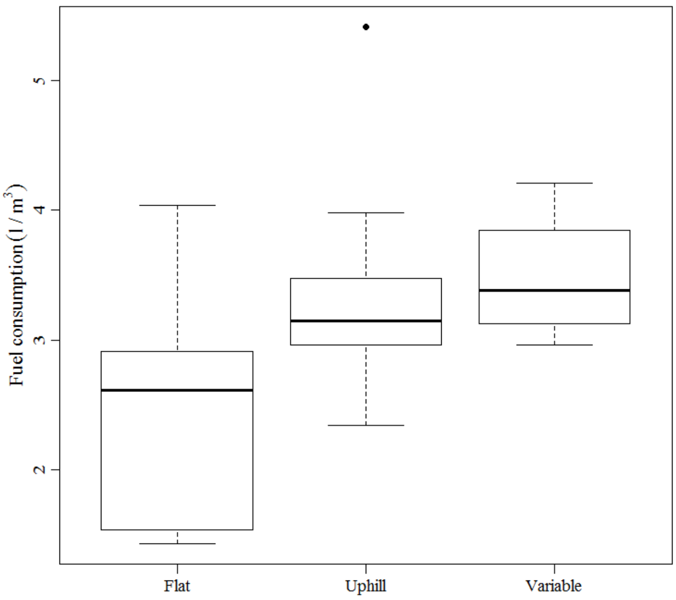

Figure 3. Box and whisker plots showing rates of fuel consumption in lt/m^3 by direction of pulling during extraction

The average rate fuel efficiency was 0.15 lt/kWh for pulling on flat sites, was 0.13 lt/kWh for pulling on non-flat sites (variable direction) and 0.11 lt/kWh for pulling uphill, but the difference not statistically significant.

Fuel consumption per unit volume did not vary significantly with soil conditions, and it was: 3.40 lt/m^3 on wet soil, 3.15 lt/m^3 on moist/wet soil, 3.11 lt/m^3 on moist soil, 2.87 lt/m^3 on moist/dry soil and 2.67 lt/m^3 on dry soil. The overall mean for variable soil moisture conditions was 3.10 lt/m^3.

3.1. Fuel consumption relationships

A power function correlation showed decreasing rates of fuel consumption with increasing total production (R2=0.45). There was no or weak correlation between rates of fuel consumption in lt/m3 and number of machines used, average piece size, average power rating and average extraction distances. Fuel efficiency in lt/kWh showed a correlation with average power (R2=0.50) and a weak correlation with number of machines used (R2=0.22), but no correlation with total annual production, average piece size and average extraction distance.

The average rates of fuel consumption for GB harvesting systems decreased with increase in total annual production (R2=0.68) (Figure 4). However, increase in total annual production showed marginal decrease in average rates of fuel consumption for CY harvesting systems (R2=0.04) (Figure 5). GB operations tended to be more productive than CY operations due to the relatively easy working environment represented by typically flat and rolling slopes, in comparison with the steep terrain and difficult working conditions associated with CY systems.

The following linear regression model was developed to predict rates of fuel consumption in lt/m^3. From all the input variables and factors tested in the regression model, the only significant predictors were: total production, average extraction distance and slope class (R^2=0.47; P<0.01).

$$FR = 3.33 - 1.2*10^{-5}*PDR + 2.8*10^{-3}ETD - 0.69*GBFL - 0.26*CY \qquad (1)$$

where FR is the rate of fuel consumption (lt/m^3), PDR is annual system production (m^3/yr), ETD is average extraction distance (m), GBFL = 1 when ground-based on flat terrain, and CY = 1 when cable yarding.

A linear model was also developed to predict fuel efficiency in lt/kWh (R^2=0.82; P<0.01).

$$FE = 0.25 + 9.5*10^{-7}*PDR - 0.018*MAC - 7.35*10^{-4}*PWR + 0.028*GBRL + 0.036*CY \qquad (2)$$

where *FE* is fuel efficiency (lt/kWh), *PDR* is production in (m^3/yr), MAC is average number of machines in the system, PWR is average power rating of the machines (kW), GBRL = 1 when ground-based on rolling terrain, and CY = 1 when cable yarding.

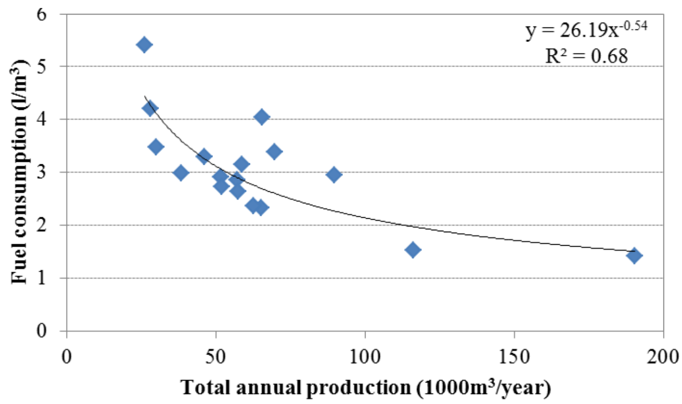

Figure 4. Relationships between fuel consumption and total annual production for GB systems

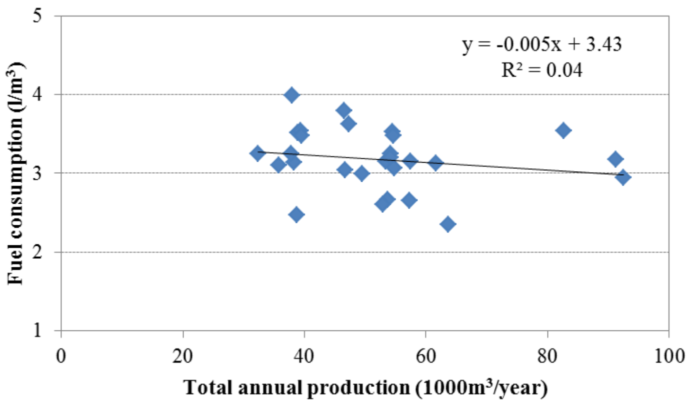

Figure 5. Relationships between fuel consumption and total production for CY systems

3.2. Percentage of fuel costs in unit harvesting costs

Using the rates of fuel consumption estimated from this study and the unit logging rates of \$25.30/m^3 for GB and \$35.13/m^3 for CY operations obtained from previously collected cost benchmarking data (Visser, 2015), the incidence of fuel costs on total harvesting cost was determined for an average diesel price of \$1.51/litre, as current in 2014 (NZ MBIE, 2015). Results showed that fuel consumption represented between 9 and 33% (16% average) of total harvesting cost in GB operations. Similarly, fuel costs constituted between 10 and 17% (average of 14%) of total harvesting cost in CY operations.

4. Discussion

Determining rates of logging fuel consumption by harvesting systems and machines proved to be a difficult task as few contractors have this information readily available, and some consider it commercially sensitive, because it may affect logging rate negotiations. This is consistent with survey observations from other published studies (Sambo, 2002; Smidt and Gallagher, 2013; Kenny et al., 2014; Greene et al., 2014). Data could not have been acquired without the active help of industry and research partners.

Rates of fuel consumption by GB and CY harvesting systems operating in New Zealand harvesting conditions are higher than averages reported in many other countries (Sambo, 2002; Baker and Greene, 2012; Smidt and Gallagher, 2013; Greene et al., 2014). Specifically, the average rates of fuel by GB systems in New Zealand was 32% higher than those of similar GB crews in the southern USA (Kenny et al., 2014). Some of this variation can be explained by crew size, where NZ GB operations on flat to rolling slopes use 4.5 machines on average, the US average only three machines (Smidt and Gallagher, 2013; Kenny et al., 2014). Higher fuel consumption rates may also depend on the extensive log processing that is common to NZ harvesting operations, up to 15 log grades are often produced (Tolan and Visser, 2015). In comparison most GB operations in the USA produce mainly three log grades of pulp, saw-logs and structural logs and occasionally chipping material as reported by (Kenny et al., 2014). The production of so many log sorts makes it necessary to add at least one additional machine for sorting the logs and fleeting them into separate piles. Differences may also be attributed to variability in level of mechanization; only 59% of NZ GB operations were fully mechanized (Visser, 2015).

The use of standardized machine costing spreadsheet (Alastair, 1994) assumes that GB and CY machines use fuel at the same rates irrespective of differences in harvesting site factors and machines used. The spreadsheet relies only on power rating in determining rates of fuel consumption by operational system. Similarly a published schedule of machine costs (FORME, 2012) assumes similar harvesting sites factors and equal number of SMH and days worked annually. This study offers a more detailed picture than obtained by applying standard fuel consumption (Alastair, 1994) or fuel efficiency (Gordon and Foran, 1980) rates, confirming the gains made in New Zealand through the mechanization of steep terrain logging over the last three decades. Results by Gordon and Foran (1980) showed that larger cable haulers commonly in use during the 1980s in New Zealand incurred higher fuel consumption than recorded in this study on current cable yarder operations. This is an indication of increased mechanization and the use of more efficient machines.

5. Conclusion

The study objective of determining rates of fuel consumption and setting a benchmark for harvesting systems for New Zealand ground-based (GB) and cable yarding (CY) systems was achieved. The average rate of fuel consumption for GB systems was 3.04 lt/m^3 and 0.15 lt/kWh, while that of CY systems was 3.18 lt/m^3 and 0.09 lt/kWh. There was no clear difference in average fuel consumption between GB and CY, whereas differences existed for fuel efficiency (lt/kWh). Sensitivity analyses showed that fuel costs represents on average 16 and 14% of total harvesting cost, for GB and CY operations respectively. The average fuel consumption per product unit did not differ significantly between GB and CY harvesting, and was dependent on total production, extraction distance. Fuel efficiency (lt/kWh) is influenced by the type of harvesting system used, total production, number of machines used, average power, slope, directions of pulling during extraction and surface moisture conditions during harvesting.

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