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Diesel Consumption and Carbon Balance in South African Pine Clear-Felling CTL Operations: a Preliminary Case Study

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Abstract

Recent and increasing use of mechanized cut-to-length (CTL) operations in South Africa has been associated with greater diesel and lubricant requirements than was previously the case with motor-manual or semi-mechanized activities, placing a strain on the environmental and economic sustainability of operations. This case study explores diesel and lubricant consumption of a typical CTL pine saw timber operation, taking into account the stand and terrain factors, with the aim of setting baselines for these consumption rates as well as carbon emissions. Data analyzed was provided by Bosbok Ontginning, a contractor based in Mpumulanga, throughout their clear-fell operations over the 49 compartments from May 2014 to June 2015. The mean diesel consumption rate was found to be 0.64 l m^{-3} *and 0.38 l m*$^{-3}$*, while the lubricant consumption was 0.08 l m*$^{-3}$ *and 0.03 l m*$^{-3}$ *for the harvester and the forwarder, respectively. Carbon emissions from diesel were found to account for less than 1% of the carbon stored in the harvested timber. Statistical analysis showed that tree size, stand density and ground condition were not significant predictors of either diesel or lubricant consumption. Prior research suggests that other factors not included in this study (i.e. machine characteristics, operator habits and productivity) may have a more pronounced effect on diesel consumption. Future studies should therefore be conducted to analyze these factors within South African conditions as well as explore stand and terrain conditions more specifically and over more diverse stand and terrain conditions as well as machine types.*

Keywords: diesel, lubricant, emissions, carbon, cut-to-length

1. Introduction

Commercial forestry has seen an increase in the use of mechanized harvesting in the past few decades (Jiroušek et al. 2007). Cut-to-length (CTL) logging, involving a harvester and a forwarder, is one system of harvest that can be fully mechanized (Holtzscher and Lanford 1997, Nurminen et al. 2006). Although it has been used and studied extensively on a global scale, mechanized CTL is a fairly new technology in South Africa. Internationally, mechanized harvesting has contributed to increasing productivity, improving conditions for forest workers and decreasing the demand for manpower in forest operations (Holtzscher and Lanford 1997). However, it has also increased fuel and oil requirements (Athanassiadis 2000, Berg and Karjalainen 2003). Both the fuel consumed by large harvesting machines as well as the oils and lubricants that they require not only present an expense that should ideally be minimized, but also contribute to emissions (Markewitz 2006, Cosola et al. 2016). This is important because carbon emissions, notably CO_2, have been linked to a variety of negative environmental consequences, such as the greenhouse gas effect, acidification, oxidant formation as well as negative health impacts (Athanassiadis 2000). This trend, coupled with global concerns over climate change, makes further investigation into how mechanized harvesting contributes to carbon emissions a priority.

In his analysis of emissions from different fuel and oil types, Athanassiadis (2000) found that harvesters consume 1167 l of diesel per 1000 m^3 of wood processed, while emitting 4.22–4.25 tons of CO_2. He also found forwarders to consume 935 l of diesel per 1000 m^3, emitting 3.52–3.55 tons of CO_2. Studies have predicted fuel consumption rates between 1.4 l m^{-3} (Ghaffariyan and Sessions 2012) and 2.0 l m^{-3} (Sambo 2002). Furthermore, a study by Berg (1997) estimated emissions from harvesting and forwarding combined in a clear cutting system in Sweden to be approximately 3 kg CO_2 m^{-3}, whereas Klvač and Skoupý (2009) reported 8.58 kg CO_2 m^{-3} in their study of a clearfelling operation in Ireland. Past studies have shown that both fuel consumption and emissions are affected by many factors, including operator characteristics, stand and terrain variables, as well as machine specifics (Berg 1997, Athanassiadis 2000, Klvač and Skoupý 2009, Ghaffariyan et al. 2015, Cosola et al. 2016). In fact, in their literature review on the carbon footprints of different management regimes, Cosola et al. (2016) found that operations in plantations tended to produce lower emissions due to easier access and working conditions.

Although mechanized harvesting is a source of carbon emissions, forestry has been shown to have the potential to play a role in stabilizing atmospheric CO_2 as trees sequester carbon into their biomass (Berg and Karjalainen 2003, Tavoni et al. 2007, Cosola et al. 2016). In many countries, carbon sequestration is used to offset greenhouse gas emissions and, if correctly managed, forested land can pool carbon in plant biomass, in organic litter, and sometimes, in soil (Dixon et al. 1994, Jandl et al. 2007). Wood products are an especially stable pool of carbon (Jandl et al. 2007, England et al. 2013, Levasseur et al. 2012). In their life cycle assessment of carbon in wood products harvested from Australian plantations, England et al. (2013) found that the carbon stored in logs that were sustainably harvested nearly offset the amount of carbon released through burning, harvesting and transporting the product. In South Africa, plantations have been found to offset approximately 3.8% of carbon emitted by the country (Christie and Scholes 1995). However, few studies have been conducted on the carbon balances of forest operations in South Africa. Those that have been conducted tend to focus either on machine emissions or on carbon storage in biomass exclusively. As such, this study aims to determine the carbon balance of South African plantations by assessing the emissions associated with mechanized CTL harvesting and comparing these to the carbon stored in the harvested logs. Further, it will determine first (for South African operations) and baseline estimates for mechanized CTL diesel and lubricant consumption with the view of more precise machine and harvesting systems costing. The study will also explore some of the stand and terrain factors that could affect these rates since they present an environmental and economic cost.

Objectives:

⇒ Estimate diesel and lubricant consumption, CO_2 emissions and carbon stored in harvested timber related to the case-study that can form baseline estimates for machine costing and harvest planning

⇒ Determine whether tree size, stand density and/or ground condition are significant predictors of diesel and lubricant consumption rates for the harvester.

2. Materials and methods

2.1 Data collection

Data used in this study was provided by Bosbok Ontgnning operating typical CTL pine saw timber clear-felling operations. The contractor is based in the Mpumulanga region of South Africa, an area characterized by cool, dry winters and hot, wet summers (Louwa and Scholes 2002). Mean annual temperature is approximately 14 ºC to 19 ºC, while mean annual rainfall is between 840 mm and 1670 mm and soils are typically ferralitic or podzolic (Louwa and Scholes 2002).

Bosbok Ontgnning's historical records (outlining data recorded by on-board computer systems and costing archives) were used to obtain values concerning volumes harvested and the hours worked in each compartment over the period from May 2014 to June 2015 (14 months). Further, average monthly data was provided, from which diesel consumption volumes were drawn. The protocol for diesel and lubrication consumption data gathering was as follows. At the end of each shift, a service truck with a fuel bowser dispensed diesel and lubrication. The fuel was administered via a fuel meter from the bowser (the metering system was calibrated weekly) and this volume was recorded via a job card for each machine. Seeing that these are scheduled services (daily or shift), machine hours were read and included to the job-card. Information contained on the job-card was then captured to the machine records, which were in turn made available to the authors. Using the calculated machine utilization figures and the volume produced, fuel consumption per PMH or volume was calculated.

Machine utilization rates were calculated based on a time study conducted in their operations over three 8 hour shifts according to standard procedures for South African forestry, outlined in Ackerman et al.

(2014). This involved timing the machines as they worked, breaking down their activities into productive work time and delays (accounted for if they were over 30 seconds) in order to better understand the efficiency of the operation.

Bosbok Ontginning operates its CTL harvesting activities using two harvesters and two forwarders concurrently (Table 1). For the purposes of this study, it was assumed that the total volume of wood cut by harvester I was extracted by forwarder I and that the wood cut by harvester II was extracted by forwarder II since the harvesters were not always working in the same compartments. In total, 49 compartments were harvested (806.8 ha).

The areas studied were planted with *Pinus patula* and had similar terrain, which was classified using the National Terrain Classification for Forestry (Erasmus 1994). Compartments were characterized by low ground roughness and minimal slopes. The mean stand density was 328 stems ha^{-1} (SD=76), average tree volume was 1.05 m^3 (SD=0.24) and all compartments had received their final thinning. Compartments differed mostly in terms of their ground condition, a measure of the strength of the soil and its trafficability when it is either wet, moist or dry (Table 2). The soil moisture level (i.e. wet, moist or dry) was estimated based on average weather conditions for the time of year in which harvesting occurred. Based on precipitation trends reported in (Louw 1997), harvesting that occurred between May and October was assumed to be dry, moist between March and May, and wet from November to February. From this, the applicable ground condition was derived using the classification provided by the National Terrain Classification for Forestry (Erasmus 1994), with a rating of 1 equating to »very good« and 5 being »very poor«. Operators had similar experience and were deemed adequately trained for the operations. All machines were advanced in operating hours (Table 1).

Based on Erasmus' (1994) national classification standards, ground conditions can range from very good (1) to very poor (5), ground roughness scale extends from smooth (1) to very rough (5), and slope class ranges from level (1) to very steep (7).

2.2 Data analysis

Calculations were modeled based on the average values found for both harvesters and both forwarders, thus representing a CTL system using only one machine of each type. Productivities per productive machine hour (i.e. excluding delays) and per scheduled machine hour (i.e. including delays) were calculated according to Ackerman et al. (2014) based on the volumes and working hours provided by the contractor.

Since diesel consumption was provided, emissions were calculated using equation (1) developed by the Environmental Protection Agency (2008).

Table 1 Machine and operator specifications relating to harvesters and forwarders studied

	Harvester I	Harvester II	Forwarder I	Forwarder II
Make and model	John Deere 759JH	John Deere 759JH	John Deere 1710D	John Deere 1710D Eco III
Engine power, kW	179.7	179.7	160	160
Age (in April 2015), PMH	19,095	11,348	18,723	5196
Average operator experience (years)	2.25	3	2.5	2.5

Table 2 Stand and terrain characteristics of harvested compartments, grouped based on ground condition class (standard deviations are shown in brackets)

Ground condition	Ground roughness	Slope class	Age, years	Stand density, stems ha^{-1}	Tree volume, m^3	Sample size, n
1	1.05 (0.15)	1.53 (0.24)	23.01 (1.49)	287.05 (60.44)	1.15 (0.21)	19
2	1.00 (0.00)	1.54 (0.28)	22.97 (1.28)	402.69 (109.00)	0.87 (0.23)	7
3	1.50 (0.41)	1.75 (0.20)	23.69 (0.49)	284.33 (64.34)	1.12 (0.36)	3
4	1.00 (0.00)	1.55 (0.14)	23.22 (0.94)	343.17 (94.64)	1.07 (0.17)	15
5	1.29 (0.50)	1.57 (0.11)	22.89 (1.91)	327.16 (38.96)	1.16 (0.26)	19

$$\text{Emissions} = \frac{\text{Fuel} \quad FD \quad FO \quad CO_{2(\text{m.w.})}}{C_{(\text{m.w.})}} \qquad (1)$$

Where:

Fuel daily diesel volume consumed, l

FD carbon content of diesel, 0.731757 kg C l^{-1} (EPA 2008)

FO fraction of diesel oxidized, assumed to be 1.00 (EPA 2008)

$\frac{CO_{2(\text{m.w.})}}{C_{(\text{m.w.})}}$ conversion factor for C to CO_2 based on their molecular weights, 3.6667 g CO_2 g C^{-1} (EPA 2008)

In order to focus the results of this analysis on the harvesting operation itself, emissions from other phases of the forestry operation (such as secondary transport and processing) were not included. Further, emissions related to preparation of the site, such as road construction, were excluded. In addition, carbon produced during the production phases of diesel, lubricants and harvesting equipment used were not considered in this study.

Estimates of carbon storage in round wood logs were attained based on a modified version of Christie and Scholes' (1995) equation (2).

$$C_p = V_k \quad p_h \quad F_{\text{carbon}} \qquad (2)$$

Where:

C_p amount of carbon stored in timber products, Mg

V_k volume of harvested wood timber, m^3

p_k density of air dried timber product, Mg m^{-3} (Malan 2012)

F_{carbon} fraction of oven-dry mass that is carbon, assumed to be 0.5 (Christie and Scholes 1995)

Statistical analysis aimed to determine whether tree size, stand density and ground condition are significant predictors of diesel and lubricant consumption. However, the available data from Bosbok Ontiginning's historical records were limiting. Due to unbalanced and incomplete block design, relevant analysis was only possible for the harvester and not for the forwarder. Analysis, including basic statistics, correlation analysis and an analysis of covariance (ANCOVA) using Generalized Linear Modelling (GLM) were conducted using STATISTICA 12.6 software (StatSoft, Tulsa). The generalized linear model approach was used as the desired model has multiple predictors of differing sample sizes and the GLM allows for normality and homoscedasticity assumptions to be validated by using Mallows' cp. Once validated, prediction from the model is the same as that of a simple linear regression.

3. Results

The machines harvested and forwarded a total of 255,594 m^3 and worked 13,767 SMH over the course of the data collection period. The average productivity of harvesters was 54.13 m^3 PMH^{-1}, while forwarders had an average productivity of 45.92 m^3 PMH^{-1} (Table 3). Availability, utilization and productivity figures for the machines can be found in Table 3.

Table 3 The average availability, utilization and productivity of the harvester and forwarder used as well as the entire mechanized CTL system

	Mechanical availability %	Utilization %	Mean productivity m^3 PMH^{-1}
Harvester	74.52	68.84	54.13
Forwarder	91.87	78.52	45.92
Full CTL system	83.19	73.68	50.02

On average, harvester I and II consumed 0.64 l m^{-3} or 23.55 l SMH^{-1} of diesel and 0.08 l m^{-3} or 2.62 l SMH^{-1} of lubricant (Table 4). Forwarders consumed less diesel and lubricant with a rate of 0.38 l m^{-3} or 13.45 l SMH^{-1} and 0.03 l m^{-3} or 1.09 l SMH^{-1}, respectively (Table 4). Further, CO_2 emissions of the harvesters from diesel

Table 4 Diesel and lubricant consumption as well as emission estimates (calculated based on EPA (2008)) for the harvester and forwarder used in the mechanized CTL system

	Diesel consumption l m^{-3}	Diesel consumption l SMH^{-1}	Lubricant consumption l m^{-3}	Lubricant consumption l SMH^{-1}	CO_2 emissions kg SMH^{-1}	CO_2 emissions kg m^{-3}
Harvester	0.64	23.55	0.08	2.62	63.18	1.71
Forwarder	0.38	13.45	0.03	1.09	36.08	1.02
Full CTL system	1.02	37.00	0.11	3.71	99.26	2.73

were calculated to be 1.71 kg m^{-3} and of the forwarders they were calculated to be 1.02 kg m^{-3}. Meanwhile, the carbon stored in the harvested logs was calculated to be 260 kg m^{-3}. As such, throughout the study period, carbon emissions from CTL operation were 342,811 kg, while carbon stored in the harvested wood volume was 48,796,931 kg. This translates to emissions from the CTL operation accounting for less than 1% carbon being stored in the harvested wood.

As mentioned above, data concerning the forwarder was found to be insufficient to conduct any meaningful statistical tests. For the harvester, correlation analysis of the predictor variables showed average tree volume and stand density (Table 2) to be significantly correlated (p<0,01), but their correlation was not high enough for them to be considered collinear (Pearson r=0.55) (Carey 2012). As such, a GLM was conducted on diesel consumption with stand density, tree size and ground condition as potential predictors (Table 2). For statistical analysis, ground conditions ranging from 1 to 3 (classified according to Erasmus (1994)) were grouped as »good« and conditions 4 and 5 were considered »poor«.

Results found that these predictors were not significantly related to diesel consumption. There was actually only a small decrease in the mean diesel consumption rate in good ground conditions versus poor ground conditions (0.71 l m^{-3} and 0.67 l m^{-3}, respectively). Another GLM was conducted between lubricant consumption and stand density, tree size and ground condition. This analysis also showed that there were no statistically significant relationships between the predictor variables and the rate of lubricant consumption by the harvester. In the case of lubricant, the mean rate of consumption (0.07 l m^{-3}) is identical when comparing good and poor ground conditions.

4. Discussion

The emissions from harvesting accounted for less than 1% of the carbon stored in the harvested wood, which is similar to findings in Berg and Karjalainen (2003) and England et al. (2013). The mean diesel consumption values found in this study, which were 0.64 l m^{-3} for the harvester and 0.38 l m^{-3} for the forwarder (Table 4), are within the range of those reported in prior studies, although on the lower end (Athanassiadis et al. 1999, Athanassiadis 2000, Berg and Karjalainen 2003, Klvač et al. 2003, Nordfjell et al. 2003, Ghaffariyan et al. 2015). Emissions followed a similar trend as the results of this study fell on the lower end of the range of estimates reported in earlier literature (Berg 1997, Berg and Karjalainen 2003, Klvač and Skoupý 2009). For instance, Berg (1997) estimated that emissions from mechanized clear-cutting were 3 kg m^{-3} and Dias et al. (2007) estimated 3.12 kg m^{-3} and 2.31 kg m^{-3} for harvesters working on Eucalypt and Maritime pine, respectively, as well as 2.43 kg m^{-3} for forwarders. Meanwhile, this study shows an emission rate of 2.73 kg m^{-3}. This may be due to easier working conditions in the South African plantations studied compared to prior research locations, which mainly took place in natural forests. As noted by Cosola et al. (2016), emissions from harvesting natural stands tend to be higher than from plantations. However, these rates are difficult to directly compare since the studies involved machines with different engines and of various ages, which may affect emissions and efficiency. Few studies have reported lubricant consumption rates, but the ones found in this study (0.08 l m^{-3} for the harvester and 0.03 l m^{-3} for the forwarder) are approximately twice as high as those reported in Athanassiadis (2000). According to Athanassiadis et al. (1999), harvesters tend to consume twice as much lubricant as forwarders due to the complexity of the machine and potential (and in some cases frequent) hydraulic hose breakages.

Since a variety of factors influence both diesel consumption and emissions, it is quite likely that factors specific to each study had sizeable effects on the obtained results. In fact, studies have found that machine and engine characteristics, terrain conditions as well as operator habits can significantly affect diesel consumption and thus, CO_2 emissions (Athanassiadis et al. 1999, Athanassiadis 2000, Makkonen 2004, Klvač and Skoupý 2009, Cosola et al. 2016). However, the results showed that site conditions, notably tree size, stand density and ground condition, had no significant effects on the rate of diesel or lubricant consumption. This contrasts Cosola et al. (2016) review, in which they found that tree volume affected fuel consumption through changes in productivity because harvesting larger trees usually entailed using larger, more powerful machines. Although no studies report the effects of tree size on diesel consumption rates, many have found that diesel consumption is affected by productivity (Nordfjell et al. 2003, Cosola et al. 2016). In comparison to prior time study data (Kellogg and Bettinger 1994, Nurminen et al. 2006, Jiroušek et al. 2007, Eriksson and Lindroos 2014), each machine relatively high productivity within its respective range (54.13 m^3 PMH^{-1} for the harvester and 45.92 m^3 PMH^{-1} for the forwarder) (Table 3) may help to explain their fairly low levels of diesel consumption. Accordingly, it would be expected that both tree size and stand density might only affect diesel and lubricant consumption if the difference in conditions was substantial enough to affect productivity. However, the tree sizes varied minimally in the harvested compartments (Table 2), as can be expected in pine clear-felling age trees, and thus, did not likely affect machine productivity. Although Nordfjell et al. (2003) and Cosola et al. (2016) found that the distance travelled does have an effect on the volume of diesel consumed by a forwarder, this study found that stand density, which could be associated with travelling distance (since the harvester would likely move a greater distance between felling locations to harvest trees that are spaced further apart), did not affect the harvester's diesel consumption. However, not only were the actual distances travelled not measured in this study, but the GLMs were only conducted on the harvester, which may have a different work pattern than the forwarder. Nonetheless, our results suggest that stand density should not necessarily be considered a proxy for distance travelled in future studies of harvester diesel consumption rates. However, it is likely that an efficient work pattern that minimizes unnecessary travel would also reduce fuel consumption, as noted by Cosola et al. (2016). In terms of terrain factors, some studies have reported that the difficulty of the work being performed affects the rate of emissions from the machine (Berg 1997, Berg and Karjalainen 2003, Nordfjell et al. 2003). Results here show a slight decrease in terms of diesel consumption when comparing harvesting in good ground conditions versus poor ground conditions (0.71 l m^{-3} and 0.67 l m^{-3}, respectively), which is the opposite trend to that reported by Nordfjell et al. (2003), who noted that difficult conditions translate to lower productivities and lower efficiencies. The difference here is minimal, however, and thus may be due to another factor that was not studied. Markedly, analysis in this study was limited by the data available (small sample sizes and incomplete blocking). As such, it would be useful to collect more data on this operation to further and more accurately assess the effects of these variables.

Other factors may have more substantial effects on diesel use and allocation to volume produced. In general, past research has shown that it is the machine itself, the operator's habits, the amount of time that the machine is working, its productivity, and the entire management approach used for the stand that are most important when considering diesel consumption rates (Athanassiadis et al. 1999, Berg and Karjalainen 2003, Cosola et al. 2016). Machine characteristics seem to be particularly important. Machine size can affect consumption, with larger machines having lower rates of consumption (Athanassiadis et al. 1999) and fuel type changing emissions by up to 80% (Athanassiadis 2000). This may help to explain why the factors analyzed in this study were not significant in determining the diesel or lubricant consumption rates. It is recommended that further research be conducted to investigate the relationships between machine as well as operator factors and diesel consumptions in South Africa. In addition, data presented here only represents a snapshot of typical mechanized CTL operations in South Africa. Terrain conditions were only represented by averages and, ideally, data concerning fuel consumptions should be collected for a longer period of time. Studies using remote sensing technology, such as LiDAR, could be useful in better assessing the specific relationships between terrain characteristics and lubricants, diesel as well as emissions, as has been done with studies assessing the relationships between productivity and slope (Alam et al. 2012, Alam et al. 2013, Strandgard et al. 2014). It may also be useful to conduct further research to discover which terrain factors (such as slope and ground roughness), if any, do have significant effects on diesel consumption rates for mechanized CTL operations in South Africa.

5. Conclusions

In this study, carbon emissions from mechanized CTL were found to only represent a small fraction of the carbon stored in harvested saw timber, as has been reported in studies on mechanized harvesting in other countries. In fact, emissions from diesel were calculated to be 2.73 kg m^{-3} and carbon stored in logs was approximated at 260 kg m^{-3}, so emissions accounted for less than 1% of the carbon stored. The mean diesel consumption rate, found to be 1.02 l m^{-3} (0.64 l m^{-3} for the harvester and 0.38 l m^{-3} for the forwarder), and the lubricant consumption rate of 0.11 l m^{-3} (0.08 l m^{-3} for the harvester and 0.03 l m^{-3} for the forwarder), were on the lower end of the range of values found in prior studies. However, these can be considered baseline figures for mechanized CTL in South African plantation conditions, potentially useful for future machine costing and harvest planning. Further, the results of the GLMs conducted found that tree size, stand density and ground condition, grouped as either good or poor, were not significant predictors of either diesel consumption or lubricant consumption. This may be due to confounding effects of the machine productivity on the calculated diesel and lubricant consumption rates. When comparing to prior research, it is also evident that other factors, such as the machine itself, its engine specifics, the operator's techniques and work habits, have a more pronounced effect on diesel consumption and thus, carbon emissions, which were not explored in this study due to the lack of specific data. Markedly, the data used in this study only represents average values over a relatively short period of time. It would be useful to conduct longer term studies with more specific data to further analyze the work condition factors that affect diesel consumption and emissions, both important in terms of making mechanized CTL environmentally and economically sustainable.

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