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Mechanisation of Different Logging Operations: Environmental Impact Assessment using Life Cycle Assessment (LCA) Approach

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Different logging systems (or harvesting systems) can be used for wood extraction. Cable logging system is typically carried out on steep slopes and other rough terrain. In these contexts, also cable yarding can be an efficient and effective harvesting system. Ninety-five per cent of timber production in southern Italy comes from terrain classified as very steep slope, limiting the use of machines for ground-based extraction. Cable extraction is a desirable alternative to either a skidder or forwarder on a sensitive site.
To each harvesting system a different environmental load is associated depending on machine productivity and site characteristics. In this study, three different logging systems were analysed and compared using the Life Cycle Assessment approach. The compared logging systems are characterised by felling with chainsaw and three different extraction methods: by farm tractors equipped with a winch; by a skidder; and by a cable crane. The Full Tree harvesting method was adopted for both felling sites; trees were felled and transported to roadside with branches and top intact. The functional unit is 1 m^3 of wood; the system boundary involves all the operations carried out in the forestry (felling, bunching and extraction) and all the related inputs (diesel fuel, lubricating oil, capital goods such as chainsaw, tractors, skidder, cable yarder) and related emissions. Inventory data were collected in three different test sites located in southern Italy and concern working times, productivity, wood yield, fuel consumption. The cable yarder shows the worst performances for 7 of the 8 evaluated impact categories. The use of skidder shows a lower impact for 5 of the 8 evaluated impact categories while, for the remaining 3, the best performances are achieved by the logging system in which tractor is used. For climate change, the impact is equal to 8.57, 8.04 and 10.46 kg CO_2eq/m^3 for the harvesting system with extraction carried out using tractor, skidder and cable yarder, respectively.

1. Introduction

In Europe, energy policies are increasingly promoting the generation of energy from renewable sources (i.e. the European Union [EU] target of 27% renewable energy by 2030 and 40% of greenhouse gas [GHG] emission reduction) (European commission, 2014; Moneti et al., 2015). Among the different renewable sources, woody biomass is an interesting solution for energy generation in rural areas for both electricity and heat production (Caserini et al. 2010; Facciotto et al., 2014; Colantoni et al., 2016). Woody biomass can be produced from forestry management but also from dedicated plantations in which woody species are grown for energy purposes (Pierobon et al., 2015; Negri et al., 2016; Zambon et al., 2016).
Wood extraction on steep slopes and other rough terrain has typically been associated with cable logging systems. Cable yarding proves to be an efficient and effective harvesting system for the extraction of timber on steep terrain, and their use in the mountainous regions of Europe is becoming more widespread. Nevertheless, in Italy, above all in southern regions, the use of this machinery is still limited (Zimbalatti and

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Proto, 2009). In forests where firewood is produced, cable cranes are not used at all. About 95% of timber production in southern Italy comes from very steep slope terrains where the use of machines for ground-based extraction is limited (Proto et al., 2016a). In this situation, cable extraction is a desirable alternative to either a skidder or forwarder (Macrì et al., 2016). Several studies previously carried out evaluated the economic performances of the different logging systems (Han et al., 2004; Putz et al., 2008; Proto et al., 2016b). For example, Proto and Zimbalatti (2016) highlighted that also for these machines requiring higher investment costs, sufficient margins of value for the producer emerged. Nevertheless, only limited researches have considered the environmental impact related to logging systems (Gonzalez-Garcia et al., 2009; Valente et al., 2011). Depending on machine productivity and site characteristics, each logging system shows its own environmental impact.
Using the Life Cycle Assessment (LCA) approach, this study aims to analyse from an environmental point of view three different logging systems (or harvesting systems) composed by different logging operations and able to operate in forestry with medium and high sloped soils.

2. Materials and methods

2.1 Description of the logging systems

Three different sites were monitored, each characterised by a harvesting system composed by a different sequence of logging operations. Globally the three sites cover an area of 35 ha. In all felling sites, “The Full Tree harvesting method” was adopted; therefore, the trees were felled and transported to roadside with branches and top intact.
To each harvesting system, a different environmental performance is associated depending on machine productivity and site characteristics. In this study, the compared logging systems are characterised by felling with chainsaw and three different extraction methods (Figure 1). After felling (always carried out by 2 workers equipped with chainsaw):

- in Site A (30% and 45% as average and maximum slope, respectively), bunching and extraction are carried out using a farm tractor equipped with a winch (in the following this harvesting system is referred to as "Harvesting system TRACTOR or HS-TR");
- in Site B (43% and 65% as average and maximum slope, respectively), bunching and extraction are performed by a skidder. Respect to the use of a farm trailer, this solution requires a higher initial investment, but achieves higher productivity above all rough terrains (in the following this harvesting system is referred to as "Harvesting system SKIDDER or HS-SK");
- in Site C (60% and 80% as average and maximum slope, respectively), the trees are directly extracted and brought till the roadside using a cable crane. This solution requires the highest investment, but can operate also with very steep sloped soils (in the following this harvesting system is referred to as "Harvesting systems CABLE CRANE or HS-CR").

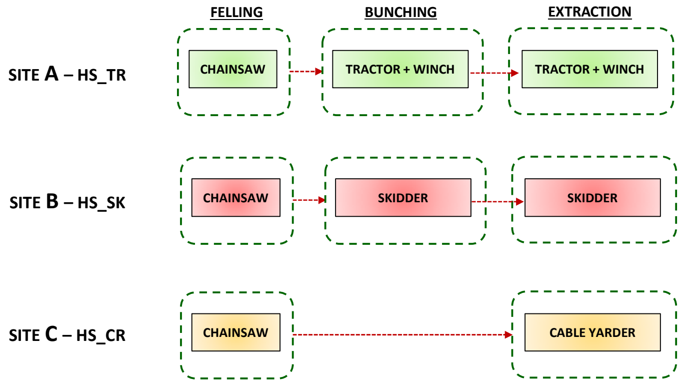

Figure 1: Schematisation of the three compared harvesting systems.

2.2 Life Cycle Assessment

LCA is a useful tool to determine the environmental impact of a product and service and has been widely used also for agricultural systems. The LCA approach foresees 4 steps: 1) goal and scope, functional unit and system boundary definition, 2) inventory data collection, 3) impact assessment and 4) results interpretation (ISO, 2006a, ISO, 2006b). In this study, the selected functional unit (the measurable unit reference to which all the results are referred) is 1 m^3 of roundwood at the roadside. Concerning the system boundary, the analysis considers all the operations carried out in the forestry (felling, bunching and extraction) and all the related inputs (diesel fuel, lubricating oil, capital goods such as chainsaw, tractors, skidder, cable yarder) and related emissions into the environment. Emissions depend mainly on exhaust gases due to the combustion of fossil fuels into internal combustion engines. The inventory data concerning the flow of materials and energy along the different logging operations and between the analysed system and the environment were collected in three different test sites located in Calabria. For each logging operation, the collected data are:

- working times,
- productivity,
- wood yield,
- fuels and lubricant consumption.

Table 1 and Table 2 report the inventory data measured during the trials in the three sites. Secondary data concerning the production of diesel, petrol-two stroke, lubricant as well as the manufacturing and disposal of machines (tractor, skidder, cable crane, chainsaw) and the emissions related to the combustion of the different fuels in the internal combustion engines were retrieved from the Ecoinvent database (Ecoinvent, 2012).

Table 1: Productivity recorded for the different logging operations

Parameter	Felling			Bunching			Extraction		
	Site A HS_TR	Site B HS_SK	Site C HS_CR	Site A HS_TR	Site B HS_SK	Site C HS_CR	Site A HS_TR	Site B HS_SK	Site C HS_CR
Productivity (m^3/day)	72	88	62.3	112.8	172.8	-	124.8	204.0	55.2
Workers (number)	2	2	2	3	3	-	3	3	3

Table 2: Main inventory data for the different logging operations

Parameter	Felling			Bunching			Extraction		
	Site A HS_TR	Site B HS_SK	Site C HS_CR	Site A HS_TR	Site B HS_SK	Site C HS_CR	Site A HS_TR	Site B HS_SK	Site C HS_CR
Machine	Chainsaw	Chainsaw	Chainsaw	Tractor with winch	Skidder with winch	-	Tractor with winch	Skidder with winch	Cable crane
Power (kW)	4.8	4.8	4.8	75	110	-	75	110	85
Mass (kg)	7.1	7.1	7.1	4160	12160	-	4160	12160	6185
Life span (year)	3	3	3	15	15	-	15	15	15
Economic lifespan	3000	3000	3000	12000	10000	-	12000	10000	10000
Annual use (h)	1440	1440	1440	1600	1280	-	1600	1280	1080
Diesel fuel consumption (kg/h)	-	-	-	12.6	18.7	-	14.3	21.3	16.2
Petrol blend consumption (kg/h)	1.0	1.2	0.8	-	-	-	-	-	-

During the 3rd step the environmental impacts are selected and, after classification and characterisation, the inventory data are converted in few numeric indexes. Each index represents an environmental impact (or effect) also called impact category. In this study, the Recipe (Goedkoop et al., 2008) characterisation method~~s~~ was used and the following impact categories were evaluated: climate change (CC), ozone depletion (OD), particulate matter formation (PM), terrestrial acidification (TA), freshwater eutrophication (FE), marine eutrophication (ME), mineral depletion (MD) and fossil depletion (FD).

3. Results and discussion

Table 3 shows the comparison among the three different harvesting systems. More in details, the absolute values for the three harvesting systems and the impact variation respect to HS-TR (the harvesting system in which the extraction is carried out with tractor) are reported.
For impact categories such as marine eutrophication the variation among the logging systems is limited, while for others (e.g., metal depletion) the differences are wider.

Table 3: Environmental impact assessment: Absolute values and comparison.

Impact category	Unit	HS-TR (Site A)	HS-SK (Site B)		HS-CR (Site C)	
		Value	Value	Δ	Value	Δ
Climate change	kg CO_2 eq	8.57	8.04	-6%	10.46	22%
Ozone depletion	mg CFC-11 eq	1.42	1.27	-11%	1.66	17%
Terrestrial acidification	kg SO_2 eq	0.026	0.025	-3%	0.032	26%
Freshwater eutrophication	g P eq	0.352	0.496	41%	0.563	60%
Marine eutrophication	kg N eq	0.0044	0.0047	8%	0.0047	8%
Particulate matter formation	kg PM10 eq	0.011	0.011	1%	0.015	31%
Metal depletion	kg Fe eq	0.207	0.439	112%	0.499	141%
Fossil depletion	kg oil eq	2.662	2.440	-8%	3.174	19%

The harvesting system carried out in the Site C (HS-CR) and characterised by extraction with cable crane shows the highest environmental impact for all the evaluated impact categories except for ME, where the higher impact is related to harvesting system 2 characterised by the skidder use. This latter shows the best performance for CC, OD, TE and FD with an impact reduction respect to harvesting system 1 ranging from -3% to -11%.

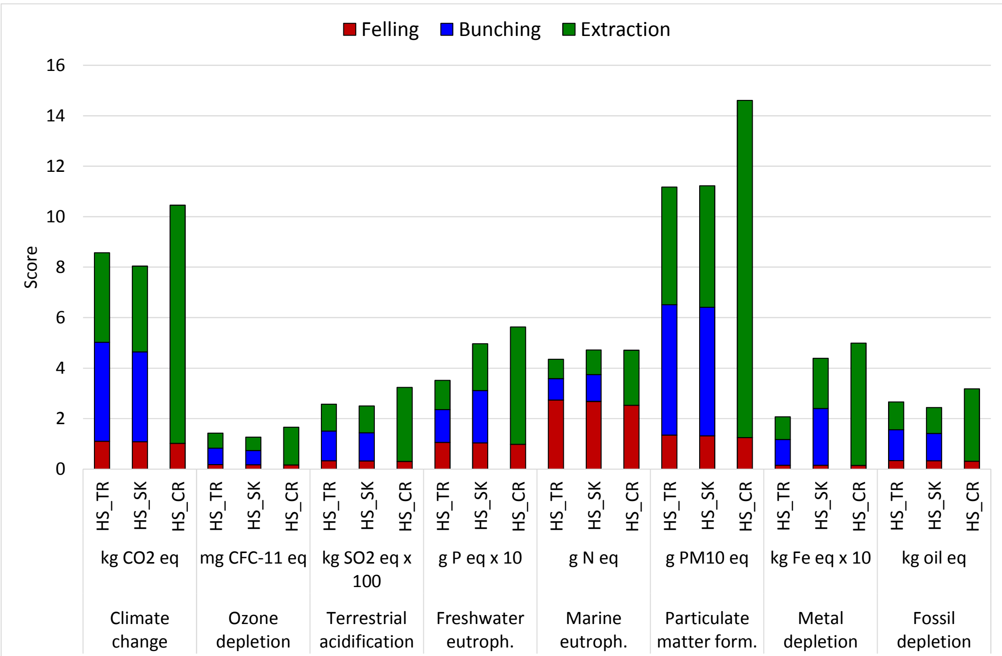

Figure 2: Comparison among the different harvesting systems (for the different impact categories the unit of measure of the score are reported in the X- axe.

Among felling, bunching and extraction, this latter represents the logging operation responsible for the highest proportion of the impact, except for ME where the most impacting operation is felling. For HS_CR, the higher impact arises mainly from the extraction carried out by means of cable crane; this operation involves an impact higher than the sum of bunching and extraction in the other two harvesting systems. Although with variable relevance for the different operations, the main environmental hotspots are:

- Fuel consumption, above all for OD and FD (>95% of the total impact) but also for PM, TA and TE (from 25-30% of the total impact),
- Lubricant consumption is relevant for felling (e.g., from 33% to 52% for CC, PM, TA and TE) when vegetable oil is consumed, while is negligible (<1% in all the evaluated impact categories) in bunching and extraction where fossil lubricant is consumed,
- Machinery manufacturing, maintenance and disposal for mineral depletion (MD) impact category,
- The emissions related to fuel combustion in the engine of chainsaw, tractor, skidder and cable yarder show a different role between felling, where petrol and vegetable oil are used, and bunching and extraction, in which there is the consumption of diesel and fossil lubricant. For felling, these emissions are relevant for FE and CC (about 40%). For the operation carried out by machines equipped with a diesel engine, combustion emissions are the main hotspot for CC, TE and ME (about 75-85%).

Figure 3 shows the environmental hotspots for the extraction operation carried out in HS-CR with cable crane; for this logging operation, the production of cable for forestry operation (substituted every 2 years) is responsible for 53% of Metal Depletion and 30% of Freshwater Eutrophication (due to mine operations). Nevertheless, considering the three whole logging systems (HS_TR; HS_SK; HS_CR) cable production involves a negligible environmental impact for all evaluated impact categories.

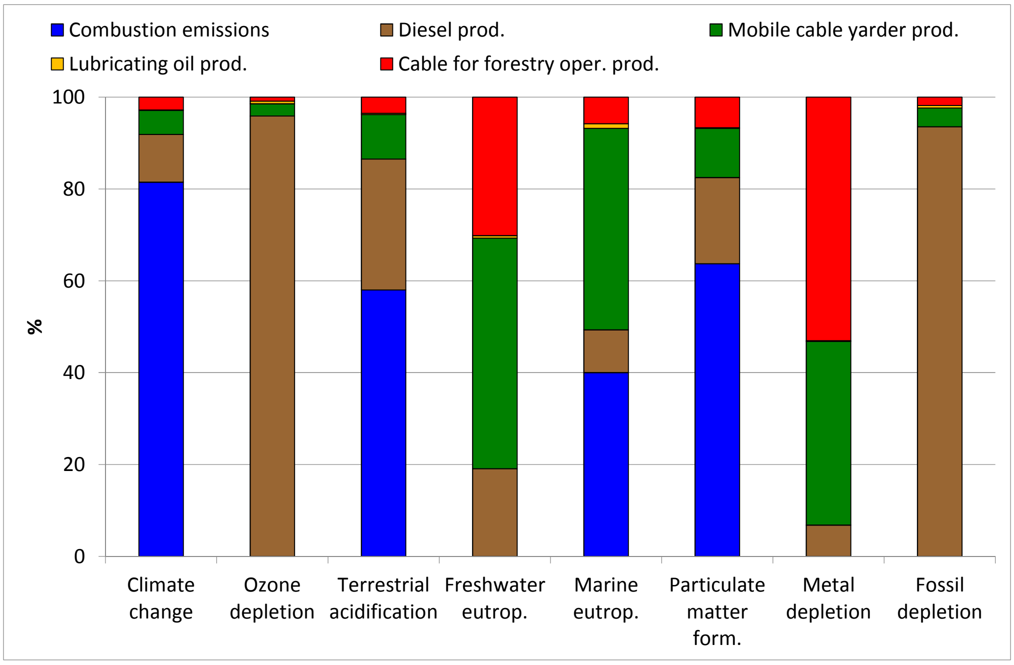

Figure 3: Environmental hotspots for the extraction with cable crane.

4. Conclusions

This study evaluated, using the LCA approach, the environmental impact of three different logging systems (or harvesting systems) for wood extraction in Southern Italy (Calabria Region). The compared harvesting systems were monitored over an area of about 35 ha and primary data were collected. The cable logging system, typically carried out on steep slopes and other rough terrain, shows the highest environmental impact, while the use of tractor and skidder achieve better environmental performances. Nevertheless, despite its higher environmental impact, cable extraction is a desirable alternative on sensitive sites with high slope where tractors and skidder cannot be used. In conclusion, this results bring a new and important perspective to classic agricultural and forestry engineering and allows placing forest operations within a wider context.

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