Forest operations for implementing silvicultural treatments for multiple purposes

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Introduction

In silvicultural treatments, the methodologies of felling, processing and extraction have to be planned on a larger scale; they cannot be sporadic events, not connected to the social, environmental and economic contexts. The forest operations have to be planned during implementation and execution of the working phases.

Three harvesting methods are commonly used in forest operation: cut-to-length systems (CTL), tree length system (TLS) and whole-tree harvesting (WTH). In CTL, trees are felled and processed at the stump before extracted to landing (Maesano *et al.*, 2013; Spinelli *et al.*, 2010a). In TLS, trees are felled, delimbed and topped at the stump before extracted to landing (Rushton *et al.*, 2003). In WTH, trees are felled and removed to a landing area where they are processed, thereby reducing potential fire severity more than other methods, which left slash within the stands (Marchi *et al.*, 2014; Picchio *et al.*, 2012a, 2012c). The main forest operations are felling and processing, bunching and extraction. Felling and processing can be efficiently carried out by chainsaw. The introduction of harvester and feller increased productivity and reduced costs of forest operation, especially in comparison with motor-manual (chainsaw) felling and processing on wide forest surfaces to cut (Wang *et al.*, 1998). The ground slope and roughness are the main limiting conditions for the introduction of these modern machineries.

Wood bunching and extraction could be performed mainly by skidding, forwarding or cable yarding, with different performances in terms of productivity. Extraction by skidder with winch is the most affordable in thinnings or similar silvicultural treatments due to the low effective costs and its flexibility. Traditionally, the cable of the winch is used in bunching logs or trees to skid trail (winching). In such way, only the limited part of the topsoil layer is damaged by skidder compression, while the rest remains unharmed (Ampoorter *et al.*, 2012). Today, skidder with grapple could be used on terrains with moderate slopes. To maximize the performances of skidding systems, a network of strategically planned forest trails is necessary to ensure a good productivity and minimize the impact on forest soil (Picchio *et al.*, 2011, 2012a, 2012b). The extraction by forwarder or by tractor and trailer is usually not recommended in the first thinning and in the selective thinning due to the considerable size and weight of these machines. In cable yarding, trees are removed by skyline cable system and can be processed at the stump or at the landing. Cable yarding is generally reserved for steep slopes, where the use of ground-based forest equipment is restricted.

The impacts on the environment, especially on soil and residual trees, is an important aspect to be considered in forest operation planning. The area affected by soil disturbance (compaction, rutting, soil mixing and displacement) may range between 10 and 70% of the total logged stand and the impact on the ecosystem can be substantial (Grigal, 2000; Frey *et al.*, 2009; Picchio *et al.*, 2012b). The damaged trees due to forest operations may range between 4-21% of the total post harvest stand (Picchio *et al.*, 2011; Spinelli *et al.*, 2010b; Vasiliauskas, 2001). Other impacts, directly linked to the logging operation should be assessed, because they contribute to the ecological footprint of a product or a production cycle. For example the energy input may range between 56 to 900 MJ m^{-3} (Picchio *et al.*, 2009; Balimunsi *et al.*, 2012; Maesano *et al.*, 2013; Vusic *et al.*, 2013), or CO_2 emissions may range between 1.3 to 7.2 kg m^{-3} (Valente *et al.*, 2011; Vusic *et al.*, 2013).

Planning, design and execution of forest operation in silvicultural treatments have to take into consideration also the potential impacts.

In four ManFor sites (Pian Cansiglio, Tarvisio, Chiarano e Mongiana) forest treatments were applied and studied. The planning of logging methodologies were not done on a large spatial and temporal scale. The single forest operation was planned only during implementation and execution of the work phases. To assess the impact on the environment on the basis of recent scientific publications (Parisi *et al.*, 2005; Marchi *et al.*, 2014; Visuc *et al.*, 2013), were analysed soil, top soil and air modification due to forest operations.

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Materials and methods

To assess the impact on the environment for the silvicultural treatments applied on some ManFor sites, pollutant emissions, some soil characteristics and post harvest stand situation were analysed.

The study of working time and productivities are the preliminary approach to the pollutant emissions evaluation. Working times were recorded for every single phase to evaluate efficiency of workers, by a chronometric table Minerva equipped with three centesimal chronometers. To calculate outputs on different plots, effective time and delays in the work routine up to 15 min (UT, unavoidable time and AT, avoidable time) were taken into consideration (Picchio *et al.*, 2009). Based on working times for volume, the productivity per worker for the different operations was calculated as an average gross productivity (PHS_{15} productivity) and average net productivity (PHS_0 productivity) (Savelli *et al.*, 2010).

Pollutant emissions due to the extraction operations at both sites were determined as described by Vusic *et al.* (2013). Emissions generated from the fuel were calculated as the sum of emissions produced by fuel combustion (Efc) and emissions produced during the fuel production, transport, and distribution (Efp). The emissions related to lubricant consumption were calculated as the sum of the emissions produced by both the production processes (Eop) and the reprocessing of used oils for the purposes of combustion (Eor). For the logging wound analysis (Picchio *et al.*, 2012a), measurements were performed on four plots per method, adjacent to the forest road and projected 90 m into the forest, (the average distance). Each plot was 40 m wide, for a unitary surface of 3600 m^2. Aboveground damage was determined by visual inspection on all standing trees. Once the wound was detected, the following data were recorded: tree diameter at breast height (DBH); hierarchical and geographical positions of the tree within the stand; location, size, and depth of the wound. These parameters were translated into numerical classes. Wound size and depth classes were multiplied to obtain a synthetic damage severity index. Wounds with an index larger than 6 were considered severe, and capable of affecting tree growth, quality and survival (Picchio *et al.*, 2011, 2012a; Tavankar *et al.*, 2015).

Impact on forest soil was studied as described by Marchi *et al.* (2014). For the study three transects for each harvested forest have been identified. Each transect was rectangular (width 2 m, length 50 m) and located parallel to the contour lines. In these transects we have measured and recorded the portions of damaged and undamaged soils by logging operations.

The impact on soil was assessed on twenty (20) randomly selected sampling plots (SP). On every plot, we measured bulk density, pH, organic matter content, penetration resistance, and shear strength. Each SP consisted of a circular area 12 m in diameter, where two different points (PO) were selected based on visual assessment *(e.g.* presence or absence of bent understory, crushed litter, ruts or soil mixing) to represent disturbed and undisturbed soil conditions, respectively. As a control, for the effect due to the silvicultural treatment, it was considered a forest area neighbouring, managed, but not impacted for more than 10 years, in this area 20 randomly selected SP have been identified. One measurement each PO for bulk density, pH, organic matter, and three measurements for penetration resistance and shear strength were performed. For the microarthropods extraction and QBS-ar index application, three soil cores 100 cm^2 and 10 cm deep were sampled in each soil typology. Microarthropods were extracted using a Berlese-Tüllgren funnel; the specimens were collected in a preserving solution and identified to different taxonomic levels (class for Myriapoda and order for Insecta, Chelicerata and Crustacea) using a stereo microscope. Soil quality was estimated with the QBS-ar index (Parisi *et al.*, 2005; Blasi *et al.*, 2013; Venanzi *et al.*, 2016).

Statistical analyses were carried out with the Statistica 7.1 (2007) Software. As a first step, data distribution was plotted and checked for normality (Lilliefors) and homogeneity of variance (Levene test). All the data points then underwent to t-test, ANOVA or MANOVA test, to test the effect of different treatments or were processed using the non parametric ANOVA the Kruskal-Wallis test.

Results

Tarvisio site

On the study area harvesting has been performed with high level of mechanization on the basis of Hippoliti classification (1997). The felling and processing operations were done by harvester, while bunching, extraction and transport operations by forwarder. Three silvicultural treatments were applied, one traditional and two innovative, working productivity analysis are shown in Table 1.

The pollutant emissions (Table 2) caused by fuel production process (Efp) were negligible in comparison with those caused by fuel combustion (Efc), with the exception of HC. The combustion process was responsible, on average, for 93.8% of CO_2, 97.8% of CO, 32.2% of HC, 97% of NOx, and 95.1% of PM emissions.

The smaller pollutant emission values were calculated for treatment ‘Innovative 1’, which allowed a reduction in GHG emissions than other two treatments, ranging from 3 to 5%. From the analysis of the damage to the trees released after the treatment we can observe that the traditional treatment had highest amount of damages (6%), followed by the ‘innovative 1’ (2%); no damage was found in the treatment ‘innovative 2’.

Table 1. Logging operation productivities for the three applied treatments.

Operation	Parameter	Traditional treatment	Innovative treatment 1	Innovative treatment 2
Felling and processing	PHS_{15} (m^3/h)	20.6	21.5	19.0
	PHS_0 (m^3/h)	21.1	22.1	19.2
Bunching-extraction	PHS_{15} (m^3/h)	10.0	10.0	10.0
	PHS_0 (m^3/h)	10.9	10.5	10.9

Table 2. Logging operation GHG emissions, for the three applied treatments.

Treatment	CO_2 (g m^{-3})	CO (g m^{-3})	HC (g m^{-3})	NO_x (g m^{-3})	PM (g m^{-3})	CO_{2eq} (g m^{-3})
Traditional	13983	141	17	235	24	98100
Innovative 1	13464	135	15	228	21	94800
Innovative 2	13992	143	19	239	26	99100

On average, damaged trees by logging operations were classified as dominant in both traditional and innovative 1 treatment. Regarding the average location of the damage, two main situations have been observed: in case of the traditional treatment, the wound position on the ground level was on the collar, while in the treatment 'innovative 1', wound position on the ground level were on roots. Assessing the size of the wounds on trees, the middle classes appeared similar in both treatments and amounted to an average value found ranging between 50 - 200 cm^2. Depth of the wound on the released trees in both treatments (traditional and innovative 1) were profound, both affecting tree fibres.

Logging operations affected over 17±4% of the stand surface for the three treatments, with highest rate found for the 'innovative 1' (21%) and a minimal rate for the traditional (14%) treatment.

Soil bulk density, organic matter content and QBS-ar index were significantly affected by extractions in all three treatments (Figure 1). Resistance to penetration and shear strength, due to soil typology, were not possible to be sampled due to specific soil typology.

Cansiglio site

On the study area harvesting has been performed by an average level of mechanization (Hippoliti, 1997). The felling and processing operations were done by chainsaw, while bunching and extraction operations were done by wheeled tractor equipped by forest winch. The silvicultural treatments applied were two: traditional and innovative 1, working productivity analyses are shown in Table 3.

The pollutant emissions (Table 4) caused by the fuel production process (Efp) were negligible in comparison to those caused by fuel combustion (Efc), with the exception of HC. The combustion process was responsible, on average, for 93.8% of CO_2, 99.4% of CO, 33.6% of HC, 97.9% of NOx, and 100% of PM emissions.

The lower pollutant emission values were calculated for treatment 'Innovative 1', which allowed a reduction in GHG emissions of 6% compared to traditional one.

Traditional treatment had highest negative effect (67%), followed by the 'innovative 1' (64%).

On average, damaged trees by logging operations were dominant in the traditional treatment, and codominant in the 'Innovative 1' treatment. For both treatments wound position on the ground level were on the collar. Size of the wounds on trees in the middle classes was similar for both treatments, on average value between 10 to 50 cm^2. Depth of the wounds in both treatments (traditional and innovative 1) was light, affecting only the bark of the trees.

Logging operations affected over 39±4% of the stand surface in both treatments, with 42% in the 'innovative 1' and 35% in the traditional approach.

Soil bulk density, organic matter content, pH, QBS-ar index, penetrometric and shear resistance (Figure 2) were significantly affected by extraction in both treatments.

Mongiana site

On the study area harvesting has been performed by an average level of mechanization (Hippoliti, 1997). The felling and processing operations were done by chainsaw, while bunching and extraction operations were done by wheeled tractor. Two silvicultural treatments were applied, working productivity analysis are shown in Table 5.

Table 3. Logging operation productivities for the applied treatments.

Operation	Parameter	Traditional treatment	Innovative treatment 1
Felling and processing	PHS_{15} (m^3/h)	13.6	14.5
	PHS_0 (m^3/h)	17.4	18.7
Bunching-extraction	PHS_{15} (m^3/h)	3.1	4.8
	PHS_0 (m^3/h)	3.4	5.6

Table 4. Logging operation GHG emissions, for the applied treatments.

Treatment	CO_2 (g m^{-3})	CO (g m^{-3})	HC (g m^{-3})	NO_x (g m^{-3})	PM (g m^{-3})	CO_{2eq} (g m^{-3})
Traditional	8897	101	10	151	21	54000
Innovative 1	8545	95	10	142	19	51000

Table 5. Logging operation productivities.

Operation	Parameter	Traditional treatment	Innovative treatment 1
Felling and processing	PHS_{15} (m^3/h)	7.4	7.1
	PHS_0 (m^3/h)	8.6	8.2
Bunching-extraction	PHS_{15} (m^3/h)	3.7	5.4
	PHS_0 (m^3/h)	4.0	6.1

Table 6. Logging operation GHG emissions, for the two treatments applied.

Treatment	CO_2 (g m^{-3})	CO (g m^{-3})	HC (g m^{-3})	NO_x (g m^{-3})	PM (g m^{-3})	CO_{2eq} (g m^{-3})
Traditional	6857.2	150.8	15.1	225.7	31.0	75000
Innovative 1	7108.6	160.7	16.5	238.5	32.0	78000

The pollutant emissions (Table 6) from the fuel production (Efp) were negligible in comparison with those due to fuel combustion (Efc), with the exception of HC. The combustion process was responsible, on average, for 93.9% of CO_2, 99.3% of CO, 33.5% of HC, 97.7% of NOx, and 99.9% of PM emissions. The lower pollutant emission values were calculated for traditional treatment. This treatment has allowed a reduction in GHG emissions than the other treatment (4%).

Again, traditional treatment caused more damages (38%), than 'innovative 1' (20%). In traditional treatment average damaged trees were co-dominant and dominant in the 'Innovative 1' treatment. In both treatments wound position on the ground level was on the collar, while the size of the wounds on trees were of middle class, similar for both treatments and amounted in average between 10 to 50 cm^2. In both treatments damages found were light, affecting only the bark.

Logging operations affected over 34±11% of the stand surface, mostly the 'innovative 1' (45%) and least the traditional way (23%). Soil bulk density, organic matter content, pH, QBS-ar index, penetrometric and shear resistance (Figure 3) were significantly affected by extraction in both treatments.

Chiarano site

On the study area harvesting has been performed by a low level of mechanization (Hippoliti, 1997). The felling and processing operations were done by chainsaw, while bunching and extraction operations were done by animals (mules). Three silvicultural treatments were applied, one traditional and two innovative ones, working productivity analysis are shown in Table 7.

The pollutant emissions (Table 8) from the fuel production process (Efp) were negligible in comparison with those due to fuel combustion (Efc), with the exception of HC. The combustion process was responsible, on average, for 62% of CO_2, 99% of CO, 7% of HC, 96% of NOx, and 99.9% of PM emissions.

The lower pollutant emission values were in 'Innovative 1' treatment. This treatment has allowed a reduction in GHG emissions

Table 7. Logging operation productivities for applied treatments.

Operation	Parameter	Traditional treatment	Innovative treatment 1	Innovative treatment 2
Felling and processing	PHS_{15} (m^3/h)	2.2	2.3	2.3
	PHS_0 (m^3/h)	3.6	3.7	3.7
Bunching-extraction	PHS_{15} (m^3/h)	1.2	1.2	1.2
	PHS_0 (m^3/h)	1.3	1.5	1.5

Table 8. Logging operation GHG emissions, for the applied treatments.

Treatment	CO_2 (g m^{-3})	CO (g m^{-3})	HC (g m^{-3})	NO_x (g m^{-3})	PM (g m^{-3})	CO_{2eq} (g m^{-3})
Traditional	3172.3	18.3	9.5	33.3	4.2	13500
Innovative 1	3113.1	18.3	8.9	32.7	4.1	12900
Innovative 2	3122.2	18.4	8.9	32.8	4.1	13100

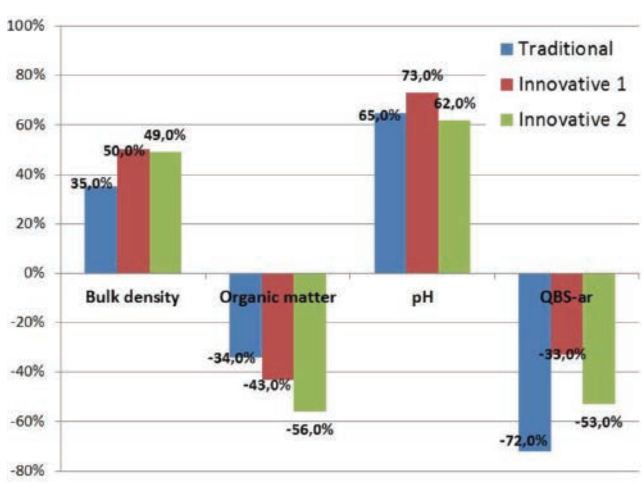

Figure 1. Tarvisio. Studied main soil characteristics, their percentage changes compared to the undisturbed soil, for the three treatments applied.

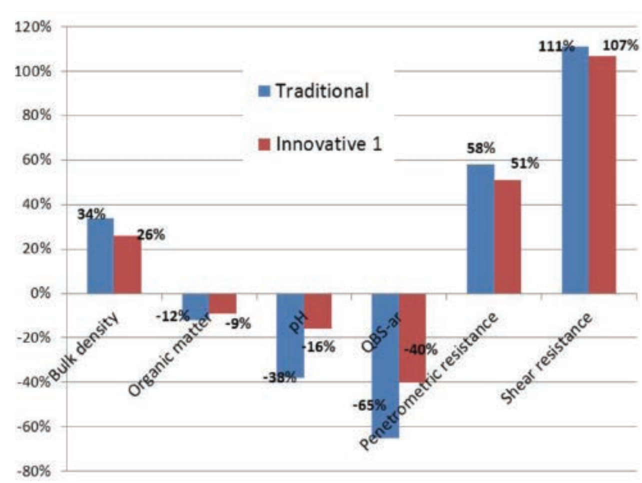

Figure 2. Cansiglio. Main values of soil studied characteristics, presented as the percentage changes compared to the undisturbed soil.

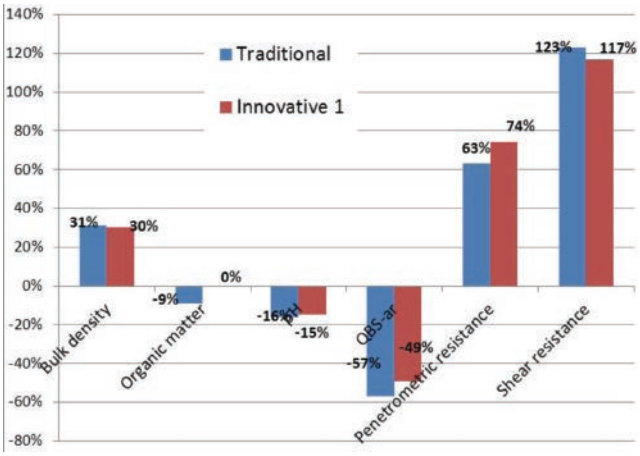

Figure 3. Mongiana. Main studied soil characteristics studied and percentage changes compared to the undisturbed soil.

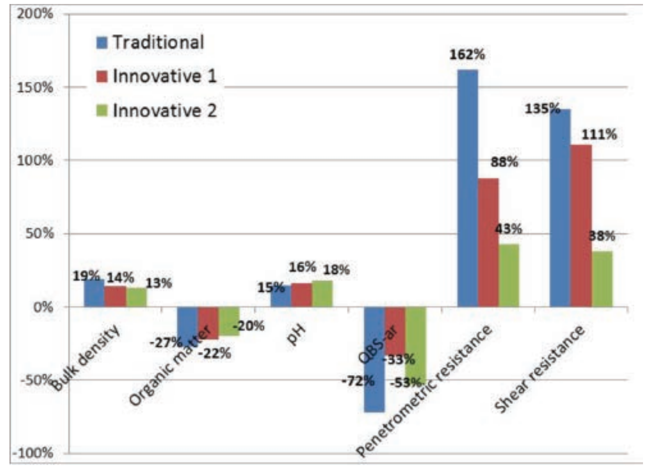

Figure 4. Chiarano. Main studied soil characteristics studied, percentage changes compared to the undisturbed soil.

Table 9. General qualitative assessment of the treatments applied on the four ManFor sites.

Treatment	Tarvisio			Cansiglio		Mongiana		Chiarano		
	T	I1	I2	T	I1	T	I1	T	I1	I2
Productivity	N	S	U	N	S	U	N	U	N	N
GHG emissions	U	N	U	N	S	U	U	N	S	N
Trees wound	U	U	S	U	U	U	S	U	U	U
% of disturbed soil	S	N	S	N	U	N	U	S	N	U
Bulk density variation	N	U	U	N	S	N	N	N	S	S
Organic matter variation	S	N	U	N	S	N	S	N	N	N
pH variation	N	U	S	U	N	N	N	N	N	N
QBS-ar variation	U	S	N	U	N	U	N	U	S	N
Penetrometric resistance	-	-	-	N	N	N	N	U	U	N
Shear resistance	-	-	-	U	U	U	U	U	U	N

S, suitable; U, unsuitable; N, neutral.

than the other treatment ranging between 1-2%.

Highest negative damage impact was evidenced in 'Innovative 2' treatment (56%), followed by the 'Innovative 1' (50%) and then the traditional one (44%).

Damaged trees by logging operations were classified as codominant in the traditional and 'Innovative 2' treatments, and dominant in the 'Innovative 1' treatment. In traditional and 'Innovative 2' treatments, the wound position on the ground was on the collar, while in case of the 'innovative 1' treatment it was on roots. For traditional and 'Innovative 1' treatments wounds were in size of middle class between 50 to 200 cm^2 and for the 'Innovative 2' treatment amounted between 10 to 50 cm^2. The depth of the wounds in all treatments was middle, affecting the phloem of the trees. Logging operations affected over 18±4% of the stand surface in all three treatments, mostly in the 'Innovative 2' (22%) and least in the traditional (14%) treatment.

Soil bulk density, organic matter content, pH, QBS-ar index, penetrometric and shear resistance (Figure 4) were significantly affected by extraction in all the treatments.

Conclusions

To comprehensively assess the potential and the sustainability of different systems, equal weight was given to the studied variables and presented in a table. For every variable were reported in Table 9 the main results, expressed as suitable, unsuitable and neutral referred to a sustainable system of reduced impact logging. From the data analysis it is possible to note as the different silvicultural treatments applied had impacted differently on the 4 sites studied, although at least one of the innovative treatments had provided the best result. Considering the different mechanization levels employed, on average, the less impactful results are by average and low levels of mechanization. However the high mechanization level employed in Tarvisio site has not led to significant differences. Overall it is evident that the combination of planning and technical management of interventions leading to fit the reduced impact logging purpose.

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