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The Effects of Soil Moisture on Harvesting Operations in *Populus* spp. Plantations: Specific Focus on Costs, Energy Balance and GHG Emissions

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Abstract: Background: Poplar tree plantations for wood production are part of a worldwide growing trend, especially in moist soil sites. Harvesting operations in moist sites such as poplar plantations require more study for detailed and increased knowledge on environmental and economic aspects and issues. Methods: In this study, the effects of soil moisture content (dry vs. moist) on productivity, cost, and emissions of greenhouse gases (GHG) caused by operations of different harvesting systems (chainsaw-skidder and harvester-forwarder) were evaluated in three poplar plantations (two in Italy and one in Iran). Results: The productivity (m^3 h^{-1}) of both systems in the dry sites were significantly higher (20% to 30%) than those in the moist sites. Production costs (€ m^{-3}) and GHG emissions (g m^{-3}) of both systems in the dry sites were also significantly lower than those in the moist sites. The productivity of the harvester-forwarder system was about four times higher, and its production cost was 25% to 30% lower than that of the chainsaw-skidder system, but the calculated GHG emissions by harvester-forwarder system was 50–60% higher than by the chainsaw-skidder system. Conclusions: Logging operations are to be avoided where there are conditions of high soil moisture content (>20%). The result will be higher cost-effectiveness and a reduction in the emission of pollutants.

Keywords: skidding productivity; logging cost analysis; harvesting site conditions; sustainable forest operations

1. Introduction

Poplar planting has occurred around the world for a very long time. The plantations in Iran and Italy provide an important source of wood supply. At present, in both countries there are over 100,000 ha of these monospecific plantations (50,000 ha in Iran and 66,000 ha in Italy) and they mainly consist of *Populus deltoides* and *P. euramericana* [1–3]. Although poplar plantations cannot be currently considered among the main sources of wood in both countries, their importance is rapidly increasing [4,5]. Poplar wood shows interesting features, such as uniform mechanical properties and a high percentage of juvenile wood. These make it possible to obtain several products from plantations, i.e., building and veneering material, paper pulp and wood chips for bioenergy [2,6,7]. Moreover, the poplars in both the Italian and Iranian conditions can reach a growth rate of approximately 10–30 m^3 ha^{-1} $year^{-1}$, which is substantially higher than local tree species [8–10].

Considering the growing importance of poplar plantations as a source of wood material, it is necessary to assess the technical and environmental characteristics of the harvesting operations in these plantations. Wood production from artificial stands is indeed a simplified multistage process as compared to forestry production, but proper planning of the logging operations is crucial when viewing the overall sustainability of the intervention [11]. The concept of sustainability in the forestry sector is strictly related to the paradigm of sustainable forest operations (SFO) [12]. SFO refers to the implementation of logging operations which are able to meet the requirements of all three pillars of sustainability (economy, environment and society) [13,14]. Machine productivity and operation costs are the two main factors in evaluating harvesting operations regarding the economic aspect of plantation management [15–18]. Having accurate information on the productivity of logging machines is therefore a key issue for the economic assessment of production. Work productivity evaluation is a complex issue, considering that the working performance of a given harvesting system is related to several factors, for instance, machine type, tree size, logging intensity, number of trees per hectare, terrain conditions, operator skills and planned treatment [19–23]. However, always considering the concept of SFO, assessing and optimizing work performance is not enough to obtain sustainable logging. The environmental aspect is also fundamental [24–27]. Along with soil impact and stand damage, greenhouse gases (GHG) emission related to mechanical operations is a major aspect to be evaluated so as to assess the environmental performance of a given harvesting system [28,29].

Considering the points listed above, it is a major challenge for forest managers to evaluate the manifold consequences of decisions and to estimate the economic and environmental performance of different alternatives before carrying out action.

These statements are valid for all forestry and agro-forestry interventions, but are even more important when dealing with poplar plantations, which show particular features. Poplar plantations are often located in plain or floodplain lands, which means that very often harvesting operations take place in soil conditions with high moisture content. Among all the variables, the soil moisture content during logging can significantly influence the degree of soil disturbance, with greater potential for higher soil compaction on wet/saturated soils than on dry ones [30]. Several studies have focused on the effects of different levels of soil moisture content during harvesting on soil disturbance and the physical properties of the soil [31,32]. On the other hand, the effects of different soil moisture content at the time of felling and skidding on the harvesting operations' performance has not yet been studied.

Considering these peculiarities of poplar plantations and their growing importance in both the Italian and Iranian forestry systems, the main aims of the present study were: (i) to provide a comparative analysis of different harvesting technologies for poplar plantations; (ii) to determine the influence of soil moisture on harvesting operations' performance both from an economic and an environmental point of view.

This study will make a detailed statement of what can be verified and a general statement of what cannot. More precisely, one can state that operations in specific soil conditions could produce the performance reported here under the specific conditions of this study. This knowledge is worth having, although poorly suited to any generalization, and can be used to estimate an expected forest operation's performance that may occur under different conditions with some level of approximation.

2. Materials and Methods

2.1. Study Areas

This study was carried out in three different geographical areas, two in Italy and one in Iran, investigating three different harvesting operations in poplar plantations.

The Iranian poplar plantation (IR) is located in the coastal area of the Caspian Sea in the Guilan province in northern Iran. The total area of the plantation is 60 ha, situated in flat terrain at an altitude range from 0 m to 20 m a.s.l. The average annual rainfall is from 1260 to 1340 mm and most of the precipitation occurs between the months of September and December. The average annual temperature is +15 °C, with the minimum during the winter at a few degrees below 0 °C, and the maximum at +25° during the summer. The soil type is clay loam with poor drainage. This plantation was divided into two areas of 30 ha each. The harvesting operation in 30 ha for the dry site was performed in the first half of September 2019 before the rainfall. Harvesting operations were carried out in the second half of September 2019 after rainfall in the 30 ha moist site. The soil moisture content was 14.4% in the dry site and 34.6% in the moist site. Trees were felled by chainsaw, and whole trees were extracted to roadside landings by wheeled skidder Timberjack 450C. Finally, processing operations were motor-manually performed at the landing site.

The first Italian poplar plantation (IT1) was located in the Lazio region in central Italy. The total area of the plantation is 20 ha and it is situated in flat terrain and with an altitude range from 90 m to 110 m a.s.l. The average annual rainfall is from 830 to 900 mm and most of the precipitation occurs from October to December. The average annual temperature is +14.9 °C with a minimum during the winter at 2.5 °C, and a maximum at +30.7 °C during the summer. The soil type is clay loam with a low level of organic matter, nitrogen and phosphorus and with poor drainage. This plantation was divided into two areas of 10 ha each. The harvesting operations in 10 ha on the dry site were performed in the second half of June 2018. Harvesting operations were carried out in the first half of April 2018 after rainfall in the 10 ha moist site. The soil moisture content was 12.1% in the dry site and 36.8% in the moist site. As in the Iranian site, trees were motor-manually felled by chainsaw, and whole tree extraction was carried out by a wheeled skidder Timberjack 450C. In this case too, motor-manual processing with a chainsaw was carried out at the landing site.

The second Italian poplar plantation (IT2) was located in the Veneto region in North Italy. The total area of the plantation is 20 ha and situated in flat terrain with an altitude range from 10 m to 30 m a.s.l. The average annual rainfall is from 730 to 850 mm and most of the precipitation occurs from September to November. The average annual temperature is +13.6 °C with a minimum during winter of 0.1°C, and a maximum of +29.2 °C during the summer. The soil type is clay loam texture with a low level of organic matter and with poor drainage. This plantation is divided into two areas of 10 ha each. The harvesting operations in the 10 ha dry site were performed in the first half of July 2018. Harvesting operations were carried out in the second half of September 2018 after rainfall in the 10 ha moist site. The soil moisture content was 15.0% in the dry site and 35.7% in the moist site. Trees were mechanically felled and processed by a harvester and cut to length through an extraction system by a forwarder. Technical characteristics of the machinery used in the various harvesting sites are given in Table 1. Average dendrometric characteristics of the three plantations are shown in Table 2. A preliminary analysis for dendrometric characteristics of the three different stands was done by one-way ANOVA to check for differences among the average values of the three plantations. There were no significant differences of dendrometric characteristics between the Italian sites (IT1 and IT2). However, density, basal area and standing volume of trees in the Iranian site were higher than in the Italian sites.

2.2. Data Collection and Analysis

Dendrometric data were obtained through systematic plot sampling. Grid dimension was 150 m × 150 m, the area of each circular plot was 1256 m^2 (20 m radius), and in total 20 plots in each area were established. Diameter at breast height (dbh) and height of tree species were measured by caliper and clinometer, respectively, in each plot. The volume of winched logs was calculated by Huber's formula ($V = A_m \times L$), where V is log volume (m^3), A_m is the middle point cross-sectional area of log (m^2), and L is the length of log (m).

Soil samples were collected with a steel ring (inside diameter 5 cm, length 10 cm) and immediately put in hermetic plastic bags and labeled. The wet weight of all samples was measured before transfer to the laboratory (on the same sampling day). In the laboratory, soil samples were dried in an oven at 105 °C for 24 h until reaching a constant mass to determine the soil moisture content.

Table 1. Specification of the mechanization used in the three harvesting sites.

Characteristics	Chainsaw Stihl ms880	Harvester John Deere 1470 D	Skidder Timberjack 450C	Forwarder John Deere JD1110 D
Displacement (cm^3)	122	9000	6800	4140
Power (kW)	6.4	179.7	120.0	121.0
Weight (kg)	10	19,700	10,270	17,500
Bar length (cm)	90	75	-	-
Oil tank volume (l)	0.7	290.0	150.0	300.0
Fuel tank volume (l)	1.3	470.7	159.0	150.0
Number of cylinders	1	6	6	6
Maximum traction or load (kg)	-	-	11,000	8500
Maximum operative distance (m)	-	8.6	75.0	10.5

Table 2. Average dendrometric stand and main wood characteristics before harvesting in the three poplar plantations. The wood density values (±SD) showed refer to fresh matter and recorded during the harvesting operation.

Description	IR	IT1	IT2
Plantation area (ha)	60	20	20
Tree density ($stem \cdot ha^{-1}$)	400	278	279
Mean DBH (cm)	38.3	42.8	40.4
Mean basal area ($m^2 \cdot ha^{-1}$)	46.1	39.9	35.8
Mean tree height (m)	25.3	24.8	27.2
Standing volume ($m^3 \cdot ha^{-1}$)	876.4	702.6	749.8
Wood density ($kg \cdot m^{-3}$)	795.8 (±11.5)	702.9 (±15.6)	721.7 (±9.4)
Wood moisture (%)	98.2 (±19.2)	95.4 (±18.5)	99.1 (±21.7)

A time-motion study was carried out to evaluate working productivity. Each working cycle was stop watched individually, separating productive time from delay time [33]. Calculated delay factor represents the quotient of delay time over net cycle time. Productivity was evaluated both on delay-free time and on actual total time, inclusive of all delays. Inclusion of delays was not capped on the basis of a maximum event duration. Scheduled Machine Hours (SMH) include all the time the machine is scheduled to work, whereas Productive Machine Hours (PMH) represent the time during which the machine actually performs work, excluding the time lost to both mechanical and non-mechanical delays.

The working group had 10 to 15 years of work experience with the machines and they were able to service and repair them.

The working cycles are reported, for the three areas, in Tables 3 and 4. Continuous time was recorded to the nearest second with a chronometer. The cycle times of the machines were divided into time elements (process steps) that were considered characteristic of this work.

Table 3. Description of felling and processing cycle elements of harvesting in the three yards.

Time Elements	IR & IT1 by Chainsaw (2 Operators)	IT2 by Harvester (1 Operator)
Moving (M)	starts when the chainsaw operator moves from the last felled tree to the next to be felled and ends when the team cleans the tree stump before the felling	starts when the harvester wheels start moving from one standing point and ends when they stop at the next standing point
Felling (F)	starts when the chainsaw operator turns on the chainsaw and performs the cut and ends with the fall of the tree	starts when the harvester head grips the stem and ends when the tree falls onto the ground
Processing (P)	starts when the chainsaw operator cuts the first branch and ends when he finishes the cross cutting of the tree	starts when the tree stem starts moving through the harvester head and ends when the harvester wheels start moving

Table 4. Description of extraction cycle elements of harvesting in the three yards.

Time Elements	IR & IT1 by Skidder (2 operators)	IT2 by Forwarder (1 Operators)
Travel unloaded (TUL)	begins when the skidder leaves the roadside landing area and ends when the skidder arrives at a suitable position (nearest distance from the logs) on the skid trail	begins when the forwarder leaves the roadside landing area and ends when the forwarder arrives at the first suitable position (nearest distance from the first logs)
Bunching—Loading (B)	begins when the skidder driver releases the cable and ends when the winching phase is finished	begins when the forwarder driver loads the first log and ends when the forwarder is fully loaded
Travel loaded (TL)	begins when the skidder starts to move and ends when the skidder arrives on roadside landing	begins when the fully loaded forwarder starts to move and ends when the forwarder arrives at the roadside landing
Landing operations (LO)	begins when the choker setter opens the load and ends when load is piled up in final position and the skidder is preparing for the next cycle	begins when the forwarder driver starts to unload the logs and ends when load is piled up in final position and the forwarder is preparing for the next cycle

Details of the harvested trees and volume in each treatment are given in Table 5.

Table 5. Harvested trees, volume and working cycles for work productivity analysis in each treatment (data reported to FU of 1 t of fresh mass showed in Table A1).

Parameter	IR Dry	IR Moist	IT1 Dry	IT1 Moist	IT2 Dry	IT2 Moist
Felled-processed trees (N)	601	625	556	528	2790	2762
Felled processed-volume (m^3)	1314.600	1367.184	1405.200	1334.940	7498.000	7423.020
Extraction cycles (N)	100	100	100	100	100	100
Extracted volume (m^3)	672.000	690.000	791.000	602.000	1350.000	1180.000

The system boundaries for the study area were set to those of the harvesting operations, from the felling to the landing site. The Functional Unit (FU) for the analyses was the cubic meter of round wood (m^3); in Appendix A the data referring to another Functional Unit (FU) are shown (1 t of fresh mass, following the data shown in Table 2). This is important in order to compare these results more readily with other studies.

Operational costs were estimated according to the Miyata method [34] as previously explained in Spinelli et al. [35]. Economic evaluation of the different machines was carried out taking into consideration different periods of use. The skidder, harvester and forwarder depreciated by 1200 SMH per year [35,36] in a depreciation period of 10 years [37]. The chainsaw for the felling depreciated by 800 SMH per year in a depreciation period of 2 years [36]. Labor cost was set at € 15 SMH^{-1} inclusive of indirect salary costs [38]. Lubricant consumption was calculated as reported by Picchio et al. [39].

Costs for insurance, repair and service were obtained by literature analysis [35], while the fuel and lubricant prices were taken by a market survey (second semester 2019) conducted upon three company products. The calculated operational cost, as reported in similar studies [35], was increased by 10% to account for overhead costs [40].

Focusing instead on the environmental aspects, an energy consumption analysis was performed, applying the Gross Energy Requirement (GER) method [41]. Indirect input (MJ kg^{-1}) of harvesting machinery was evaluated taking into consideration the average energy value of the raw materials. This is related to several parameters, i.e., quantitative presence (%), total mass of the machine (kg), overall service life of the machine (h m^{-3}) and use of the machine during harvesting. Energy consumption related to human manpower was evaluated according to what was reported in previous works [42–44], through the application of a standard value equal to 0.030 MJ min^{-1} $worker^{-1}$.

To calculate the energy balance, the energy value of poplar wood was determined as Higher Heating Value (HHV) (CEN/TS 14918), on 30 random samples, through Parr calorimeter, model 6200 [45].

Regarding pollutant emissions during logging operations, emissions related to fuel were evaluated as the sum of the emissions during combustion (Efc) and the emissions produced within the production and logistic process (Efp). For Efc assessment of fuel energy content, the emission factor of the engine and the thermal efficiency of the combustion were taken into consideration, as reported in Klvac et al. [46] and Athanassiadis [47].

Dealing with Efp assessment, fuel energy content and emission factors were obtained by [46], but HC emission factor was taken from [47].

2.3. Statistical Analysis

The first step in statistical analysis was checking for normality using the Kolmogorov-Smirnov test and for homogeneity of variance using the Levene test. Averages of dendrometric characteristics, skid trail network, and average extraction cycle time elements in each area between the two site conditions (moist and dry soil) were compared by independent t test. A regression analysis of time study data was used to check the model's capability of predicting productivity as a function of statistically significant independent variables such as distance and load size. If the data were not normally distributed, a non-parametric Spearman's rank coefficient was applied to analyze the correlation between the variables.

A major focus was placed on extraction operations investigating the relationships between time elements and dendrometric characteristics of extracted timber, and between time elements and bunching-extraction distance. This investigation was performed by non-linear regression analysis, performed by SPSS 19.0 software (New York, NY, United States).

3. Results

Results of the *t*-test showed no statistically significant differences regarding both extraction distance and mean volume per working cycle between moist and dry sites in all the three plantations. Bunching distance was statistically lower in the IT1 dry site than in the moist one, while in IR and IT2 no statistically significant difference was found for this parameter (Table 6).

Table 6. Extraction trail and corridors' average features for the three areas in the two soil moisture conditions (mean ± SD), From the *t*-test for independent samples applied, statistically significant differences ($p < 0.05$) between the average values are highlighted (underlined text) (data reported to FU of 1 t of fresh mass showed in Table A2).

	IR		IT1		IT2	
	Dry	**Moist**	**Dry**	**Moist**	**Dry**	**Moist**
Mean bunching distance (m)	38.6 ± 10.1	49.8 ± 9.5	17.5 ± 5.2	56.1 ± 8.2	22.7 ± 4.2	18.4 ± 2.1
Mean extraction distance (m)	146.0 ± 20.1	144.5 ± 12.2	118.2 ± 14.3	138.1 ± 10.3	152.4 ± 12.5	158.7 ± 11.2
Mean volume per working cycle (m^3)	6.72 ± 0.15	6.90 ± 0.14	7.91 ± 0.22	6.02 ± 0.18	13.5 ± 0.31	11.8 ± 0.42

Data regarding working time analysis of felling and processing operations are given in Table 7 and Figure 1. In all three plantations felling operation time (motor-manual in IR and IT1 and mechanized in IT2) did not show any statistically significant differences between dry and moist sites. There were some differences found in processing and moving time. In every study area the most time-consuming operation was processing.

The soil moisture in IT2 did not affect working productivity, with no statistically significant difference among different soil moisture conditions for every phase, and consequently also for the overall working time. In IR1 and IT1, instead, both TET (Total Effective Time) and TGT (Total Gross Time) were significantly higher in moist conditions than in dry ones, with higher DT (Delay Time) also in the moist soil. However, as previously reported, such differences are related not to the felling operations, but only to moving (both IR and IT1) and processing (only IR).

Working time analysis data in bunching and extraction are reported in Table 8 and Figure 2. The only phase which did not show an effect of soil moisture on productivity was the landing operation (LO), while all the other phases were influenced by the moisture content of the soil. This led to a significant difference in overall working times (both TET and TGT), related to the different site conditions, in all the three yards. In particular, higher soil moisture negatively affected working productivity.

Table 7. Description statistics of felling-processing operations for the harvesting sites studied referring to a single tree. From the *t*-test for independent samples applied, statistically significant differences ($p < 0.05$) between the average values are highlighted (underlined text). Statistical comparisons are between columns.

Sites	IR-Dry	IR-Moist	IT1-Dry	IT1-Moist	IT2-Dry	IT2-Moist
Time Elements			**Average Value ± SD (minutes)**			
M	0.36 ± 0.05	0.48 ± 0.06	0.31 ± 0.04	0.42 ± 0.03	0.53 ± 0.05	0.55 ± 0.06
F	2.85 ± 0.22	2.75 ± 0.15	3.15 ± 0.22	3.08 ± 0.31	0.56 ± 0.04	0.59 ± 0.05
P	13.91 ± 0.38	14.85 ± 0.45	14.58 ± 0.87	15.29 ± 0.65	3.05 ± 0.25	3.15 ± 0.15
DT	0.29 ± 0.04	0.41 ± 0.11	0.38 ± 0.12	0.45 ± 0.08	0.11 ± 0.03	0.13 ± 0.03
TET	17.12 ± 0.45	18.08 ± 0.81	18.04 ± 0.88	18.79 ± 0.50	4.14 ± 0.72	4.29 ± 0.44
TGT	17.41 ± 0.52	18.49 ± 0.73	18.42 ± 0.91	19.24 ± 0.71	4.25 ± 0.65	4.42 ± 0.61

M: moving, F: felling, P: processing, DT: delay time, TET: total effective time, TGT: total gross time.

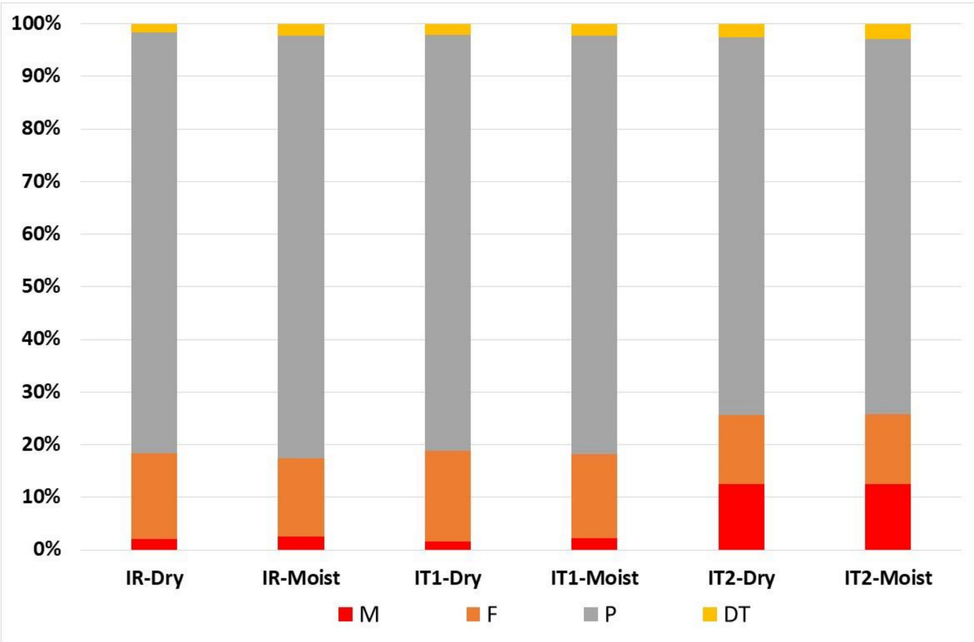

Figure 1. Working time distribution for felling-processing operations in the harvesting sites studied.

Table 8. Description statistics of bunching-extraction operations for the harvesting sites studied referring to single cycle. From the *t*-test for independent samples applied, statistically significant differences ($p < 0.05$) between the average values are highlighted (underlined text). Statistical comparisons are between columns.

Sites	IR-Dry	IR-Moist	IT1-Dry	IT1-Moist	IT2-Dry	IT2-Moist
Time Elements			**Average Value ± SD (minutes)**			
TUL	4.53 ± 0.44	6.86 ± 0.50	3.88 ± 0.64	5.48 ± 0.98	1.35 ± 0.50	1.89 ± 0.44
B	2.10 ± 0.80	3.40 ± 1.00	1.38 ± 0.21	3.52 ± 0.61	2.15 ± 0.44	2.39 ± 0.40
TL	4.30 ± 1.50	7.20 ± 0.50	4.11 ± 1.07	6.92 ± 1.16	3.02 ± 0.28	5.12 ± 0.31
LO	5.70 ± 2.10	6.50 ± 1.90	5.90 ± 0.92	5.80 ± 0.89	5.20 ± 1.10	5.39 ± 0.81
DT	1.00 ± 0.45	1.20 ± 0.50	1.24 ± 0.22	1.85 ± 0.18	1.02 ± 0.10	1.39 ± 0.13
TET	16.63 ± 1.80	23.96 ± 1.90	15.27 ± 1.78	21.72 ± 1.55	11.72 ± 0.97	14.79 ± 0.84
TGT	17.63 ± 1.80	25.16 ± 1.90	16.51 ± 1.89	23.57 ± 2.01	12.74 ± 1.16	16.18±1.01

TUL, travel unloaded; B, bunching; TL, travel loaded; LO, landing operations; DT, delay times; TET, total effective time; TGT, total gross time.

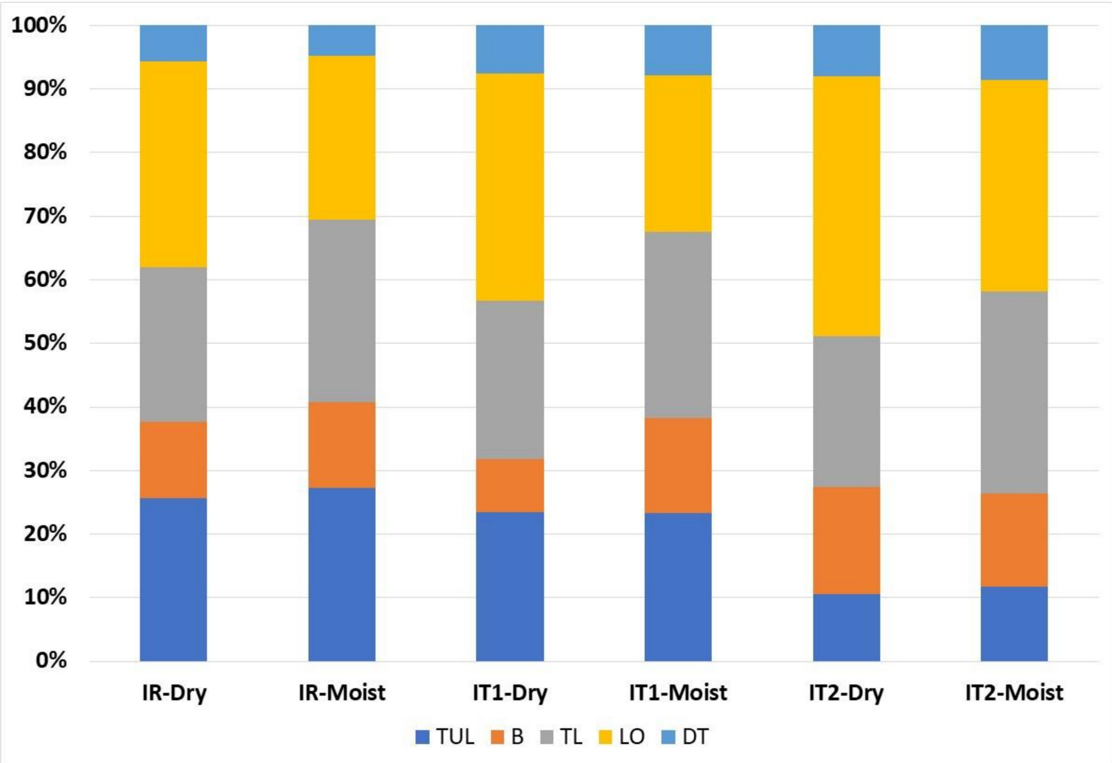

Figure 2. Working time distribution for bunching-extraction operations in the harvesting sites studied.

The analysis of the various factors influencing extraction time (Table 9) revealed that the parameter with the highest impact on time consumption was bunching–extraction distance, with R^2 values ranging from 0.6 to 0.8 for both dry and moist sites in all the three yards.

Table 9. Cycle time (Y) equations of bunching–extraction in studied sites. D: distance of bunching-extraction; and LV: load volume.

Site (Machine)	Variable	Model	Equation	R2 Adj.	p-Value
IR-Dry (Skidder)	D	Polynomial	$Y = -4 \times 10^{-5}(D)^2 + 0.0592(D) + 8.0769$	0.633	<0.001
	LV	Polynomial	$Y = 0.9524(LV)^2 + 8.2375(LV) + 28.361$	0.380	<0.001
	D and LV	Linear	$Y = 0.059(D) + 1.546(LV) - 1.523$	0.679	<0.001
IR-Moist (Skidder)	D	Polynomial	$Y = -2 \times 10^{-5}(D)^2 + 0.1343(D) + 6.2007$	0.764	<0.001
	LV	Exponential	$Y = 3.1537e^{0.2875(LV)}$	0.363	<0.001
	D and LV	Linear	$Y = 0.116(D) + 2.089(LV) - 6.076$	0.812	<0.001
IT1-Dry (Skidder)	D	Linear	$Y = 0.088(D) + 6.3003$	0.821	<0.05
	LV	Polynomial	$Y = 0.7512(LV)^2 + 4.2725(LV) + 8.030$	0.231	>0.05
	D and LV	Linear	$Y = 0.085(D) + 2.156(LV) + 0.125$	0.401	>0.05
IT1-Moist (Skidder)	D	Exponential	$Y = 9.312e^{0.0064(D)}$	0.724	<0.01
	LV	Polynomial	$Y = 0.95210(LV)^2 + 2.1225\ (LV) + 5.103$	0.412	>0.05
	D and LV	Linear	$Y = 0.109(D) + 1.816(LV) + 0.231$	0.502	> 0.05
IT2-Dry (Forwarder)	D	Polynomial	$Y = -0.0001(D)^2 + 0.078(D) + 5.103$	0.811	<0.05
	LV	Polynomial	$Y = -0.0021(LV)^2 + 0.807(LV) + 2.210$	0.452	>0.05
	D and LV	Linear	$Y = 0.080(D) + 2.086(LV) - 0.957$	0.568	> 0.05
IT2-Moist (Forwarder)	D	Polynomial	$Y = 0.0003(D)^2 + 0.004(D) + 7.7868$	0.765	<0.01
	LV	Polynomial	$Y = -0.052(LV)^2 + 1.105(LV) + 1.574$	0.431	>0.05
	D and LV	Linear	$Y = 0.128(D) + 1.974(LV) - 0.358$	0.631	>0.05

Increased bunching–extraction distance obviously led to increased bunching–extraction time; however, it is interesting to notice (Figure 3) how this effect is less evident in forwarding operations (IT2) than it is in winching operations (IR and IT1).

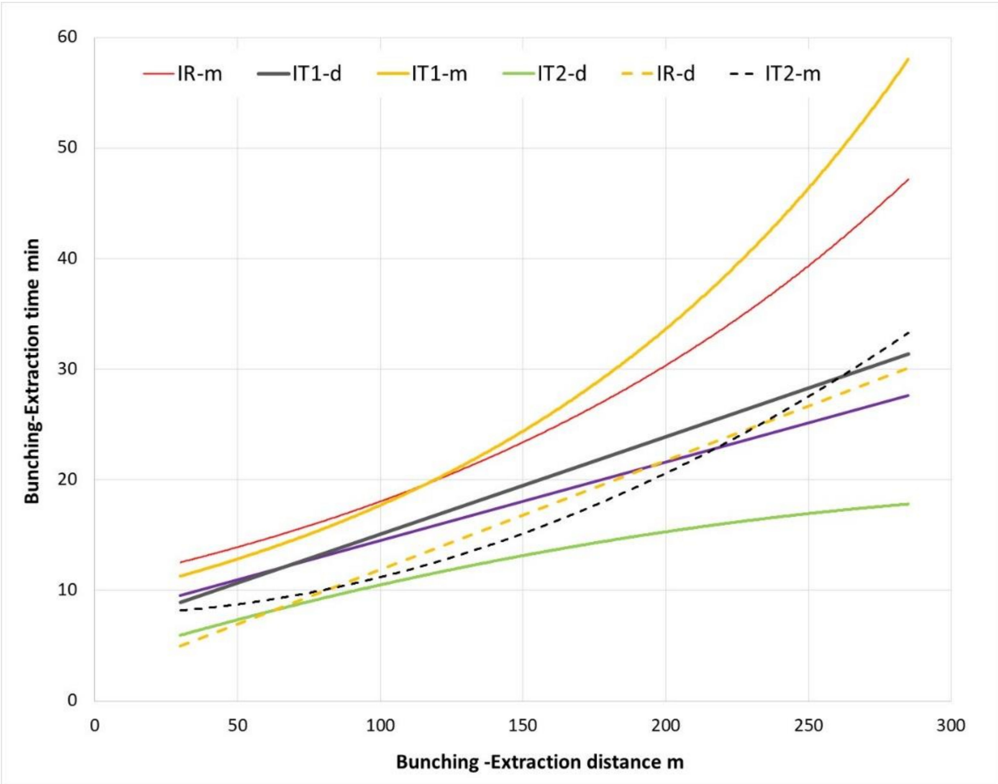

Figure 3. Graphical regression analysis referring to bunching–extraction time in relation to bunching–extraction distance in the studied areas (IR-d: Iranian dry site; IR-m: Iranian moist site; IT1-d: skidding Italian site with dry soil; IT1-m: skidding Italian site with moist soil; IT2-d: forwarding Italian site with dry soil; IT2-m: forwarding Italian site with moist soil).

Focusing on the overall harvesting system productivity (Figure 4), moist soil showed negative effects in all three plantations. In detail, SMH in dry soil conditions was 5.671 $m^3 h^{-1}$ in IR, 6.403 $m^3 h^{-1}$ in IT1 and 23.761 $m^3 h^{-1}$ in IT2; while, respectively, were 12.53%, 18.68% and 16.27% lower in the moist soil. Moreover, the higher moisture content of soil also resulted in a higher percentage difference between PMH and SMH, i.e., 2.73% vs. 3.08% in IR; 3.39% vs. 4.40% in IT1; and 4.4% vs. 5.83% in IT2. Referring to the single operations, SMH in felling-processing was 7.541 vs. 7.101 $m^3 h^{-1}$ in IR; 8.238 vs. 7.887 $m^3 h^{-1}$ in IT1; and 37.941 vs. 36.481 $m^3 h^{-1}$ in IT2. Bunching-extraction productivity was also negatively affected by higher soil moisture; specifically, SMH was 22.870 vs. 16.455 $m^3 h^{-1}$ in IR; 28.746 vs. 15.325 $m^3 h^{-1}$ in IT1 and 63.580 vs. 43.758 $m^3 h^{-1}$ in IT2.

Focusing on harvesting costs, the results of the economic evaluation carried out within the present study are given in Tables 10 and 11.

The details of hourly costs reported in Table 10 show how the harvesting machinery applied in IT2 (harvester and forwarder) presents higher hourly costs, mostly related to the higher purchase price. However, the higher productivity of this fully mechanized harvesting system allowed IT2 to have a lower cost per m^3 of timber produced (Table 11).

Regarding the influence of soil moisture conditions on harvesting costs, it is evident that the negative influence on working performance correlated to higher moisture also led to higher harvesting costs. In detail, this was about 16%, 26% and 16% higher in the moist site than in the dry one for IR, IT1 and IT2, respectively.

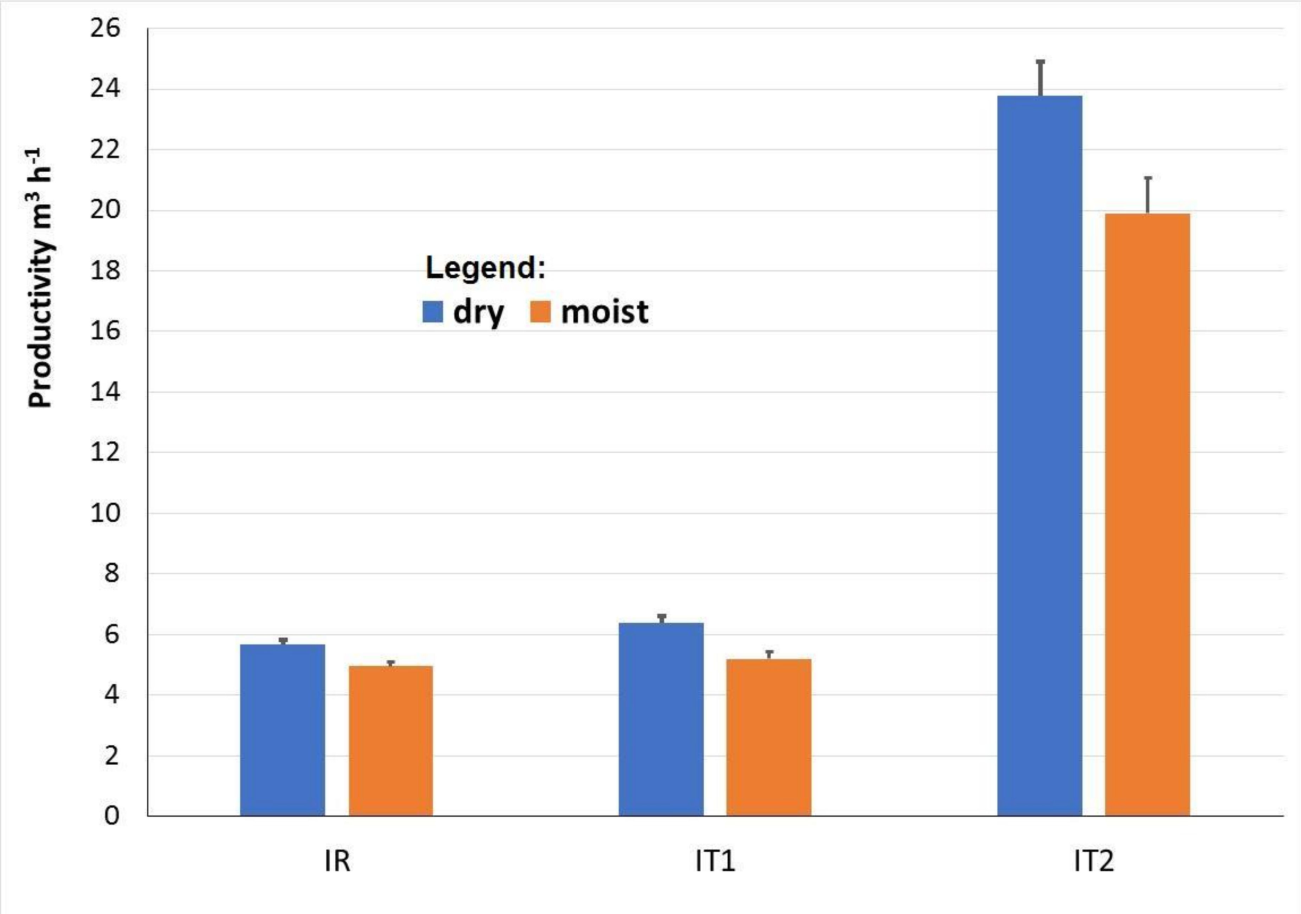

Figure 4. Average yard productivity (bars) and possible increase of performance (lines) from SMH to PMH for the six harvested sites (data reported to FU of 1 t of fresh mass showed in Figure A1).

Table 10. Summary cost assessment of mechanization used in the logging activities studied.

Description	MU	Chainsaw	Skidder	Harvester	Forwarder
Investment cost	€	1674.00	155,000.00	390,000.00	365,000.00
Service life	Years	2	10	10	10
Annual use	H	800	1000	800	800
Recovery value	€	167.40	15,500.00	39,000.00	36,500.00
Interest on capital	%	3	3	3	3
Fuel consumption	$l\ h^{-1}$	1.0	4.2	15.0	17.0
Fuel price	$€\ l^{-1}$	2.00	0.80	0.80	0.80
Lubricant cost	% of fuel cost	20	35	35	35
Labor cost	$€\ h^{-1}$	16.40	16.90	17.50	17.50
Crew	n°	2	2	1	1
		Fixed costs			
Depreciation	$€\ year^{-1}$	753.30	13,950.00	35,100.00	32,850.00
Interest	$€\ year^{-1}$	38.92	2766.75	6961.50	6515.25
Insurance and tax	$€\ year^{-1}$	64.87	4611.25	11,602.50	10,858.75
Yearly fixed costs	$€\ year^{-1}$	857.09	21,328.00	53,664.00	50,224.00
Hourly fixed costs	$€\ h^{-1}$	1.07	21.33	67.08	62.78

Table 10. *Cont.*

Description	MU	Chainsaw	Skidder	Harvester	Forwarder
		Variable costs			
Fuel	€ h^{-1}	2.02	3.36	12.00	13.60
Lubricant	€ h^{-1}	0.40	1.18	4.20	4.76
Repair and maintenance	€ h^{-1}	0.94	13.95	43.88	41.06
Workers	€ h^{-1}	32.80	33.80	17.50	17.50
Hourly variable cost	€ h^{-1}	36.17	52.29	77.58	76.92
Operating cost	€ h^{-1}	37.24	73.61	144.66	139.70
Profit and overhead	%	10	10	11	12
Profit and overhead	€ h^{-1}	3.72	7.36	15.91	16.76
Total operating cost	**€ h^{-1}**	**40.96**	**80.98**	**160.57**	**156.47**

Table 11. Harvesting costs for one cubic meter of wood and percentage of costs at two main operations (felling–processing and bunching–extraction to landing) in the studied sites (data reported to FU of 1 t of fresh mass showed in Table A3).

Description	MU	IR Dry	IR Moist	IT1 Dry	IT1 Moist	IT2 Dry	IT2 Moist
Real unit cost (SMH)	€ m^{-3}	8.97	10.69	7.79	10.48	6.69	7.98
Felling-Processing percentage	%	60.5	54.0	63.8	49.6	63.2	55.2
Bunching-Extraction percentage	%	39.5	46.0	36.2	50.4	36.8	44.8
Hypothetical unit cost (PMH)	€ m^{-3}	8.68	10.33	7.47	9.94	6.39	7.54
Felling-Processing percentage	%	61.5	54.6	65.1	51.0	64.6	56.7
Bunching-Extraction percentage	%	38.5	45.4	34.9	49.0	35.4	43.3

Regarding environmental aspects, the results of the analysis of energy efficiency are given in Table 12. The highest energy input was reported for IT2, due to the complete mechanization of the overall harvesting operations. The effects of moisture on environmental performance can be observed in all of the three plantations where higher soil moisture led to lower energy efficiency, more exactly, 97.7% vs. 97.0% in IR; 98.1% vs. 96.9% in IT1 and 97.0% vs. 96.6% in IT2.

Table 12. Total energy inputs and balance in the studied harvesting yards (data reported to FU of 1 t of fresh mass showed in Table A4).

Description	M.U.	Energetic Output	Direct Input	Indirect Input	Human Labor Input	Total Inputs	Output/Inputs Ratio	System Efficiency
IR-d	MJ m^{-3}	11,658	257.62	4.22	0.70	262.54	44.4	97.7%
	GJ ha^{-1}	10,217	225.78	3.70	0.61	230.09		
IR-m	MJ m^{-3}	11,658	338.67	5.83	0.80	345.30	33.8	97.0%
	GJ ha^{-1}	10,217	296.81	5.11	0.70	302.72		
IT1-d	MJ m^{-3}	11,658	212.05	3.37	0.62	216.04	54.0	98.1%
	GJ ha^{-1}	8191	148.99	2.37	0.44	151.79		
IT1-m	MJ m^{-3}	11,658	352.75	6.24	0.76	359.76	32.4	96.9%
	GJ ha^{-1}	8191	247.84	4.39	0.53	252.76		
IT2-d	MJ m^{-3}	11,658	337.20	7.80	0.06	345.06	33.8	97.0%
	GJ ha^{-1}	8741	252.83	5.85	0.05	258.73		
IT2-m	MJ m^{-3}	11,658	386.36	9.18	0.08	395.62	29.5	96.6%
	GJ ha^{-1}	8741	289.69	6.89	0.06	296.63		

In IR and IT1 a major part of the energy input is related to bunching–extraction operations in both moist and dry soil conditions. Instead, in IT2, felling operations via harvester were the reason for the highest portion of energy input in this yard, in both soil conditions (Figure 5). Interestingly, moist soil led to an increased portion of energy input related to bunching–extraction in all three yards (77.2% vs. 81.6% in IR; 74.6% vs. 84.0% in IT1 and 25.8% vs. 32.7% in IT2), showing how this operation was most influenced by soil moisture when regarding environmental issues.

As shown in Table 13 and Figures 6 and 7, soil moisture also showed negative effects regarding pollutant emissions in the three different yards, with increasing emissions for all the investigated parameters in moist soil conditions. What is more, mechanized felling via harvester (IT2) led to higher emissions in comparison to motor-manual felling (IR and IT1).

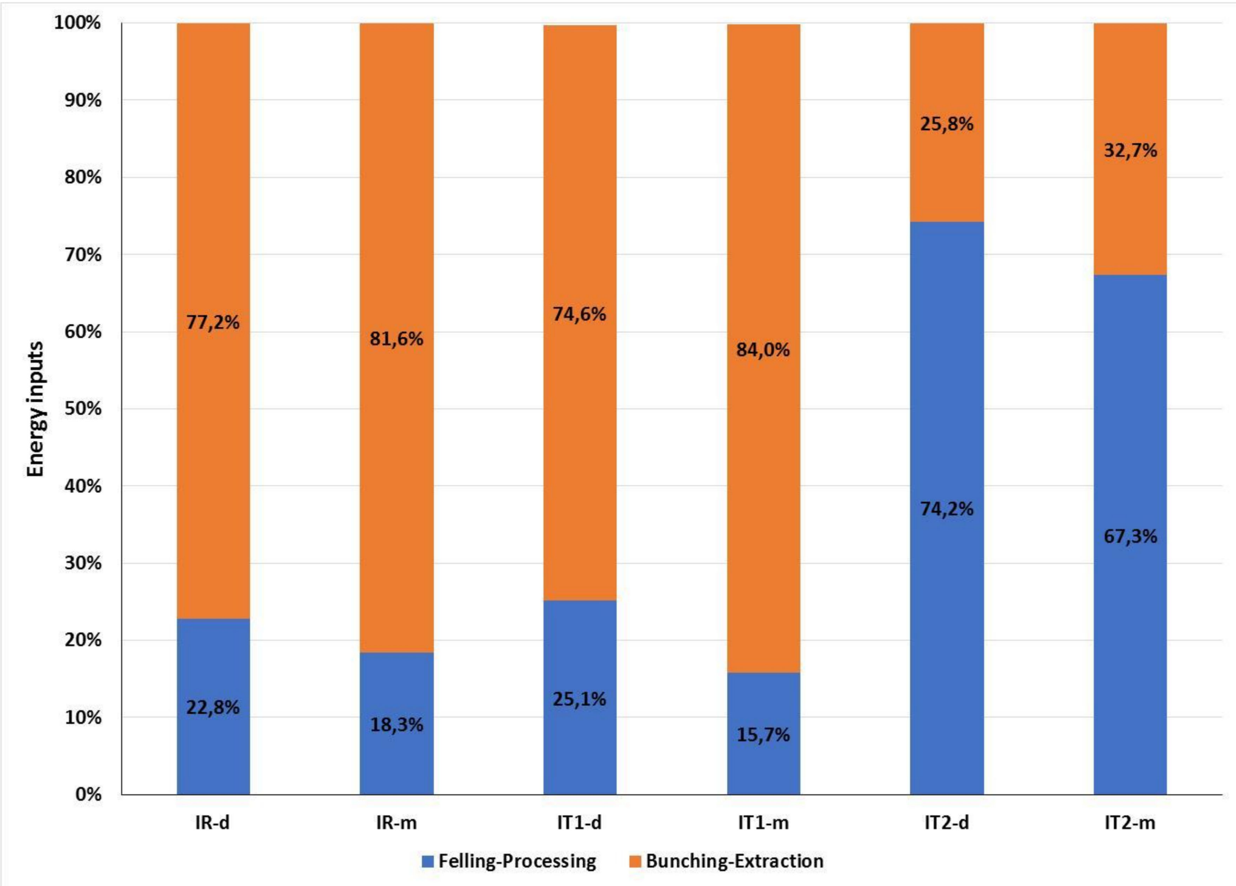

Figure 5. Energy inputs percentage for each harvesting operation assessed in the studied sites.

Table 13. Total emission assessed in the studied harvesting yards (data reported to FU of 1 t of fresh mass showed in Table A5).

Harvesting Sites	CO_2	CO	HC	N_{ox}	PM_{10}
			$g\ m^{-3}$		
IR-d	1650.72	26.20	0.42	25.16	3.77
IR-m	1699.04	27.31	0.46	26.60	4.08
IT1-d	1602.18	24.08	0.35	24.20	3.35
IT1-m	1627.43	25.19	0.41	25.04	3.65
IT2-d	2651.56	48.35	0.74	41.85	6.51
IT2-m	2789.36	55.08	0.78	47.91	7.73

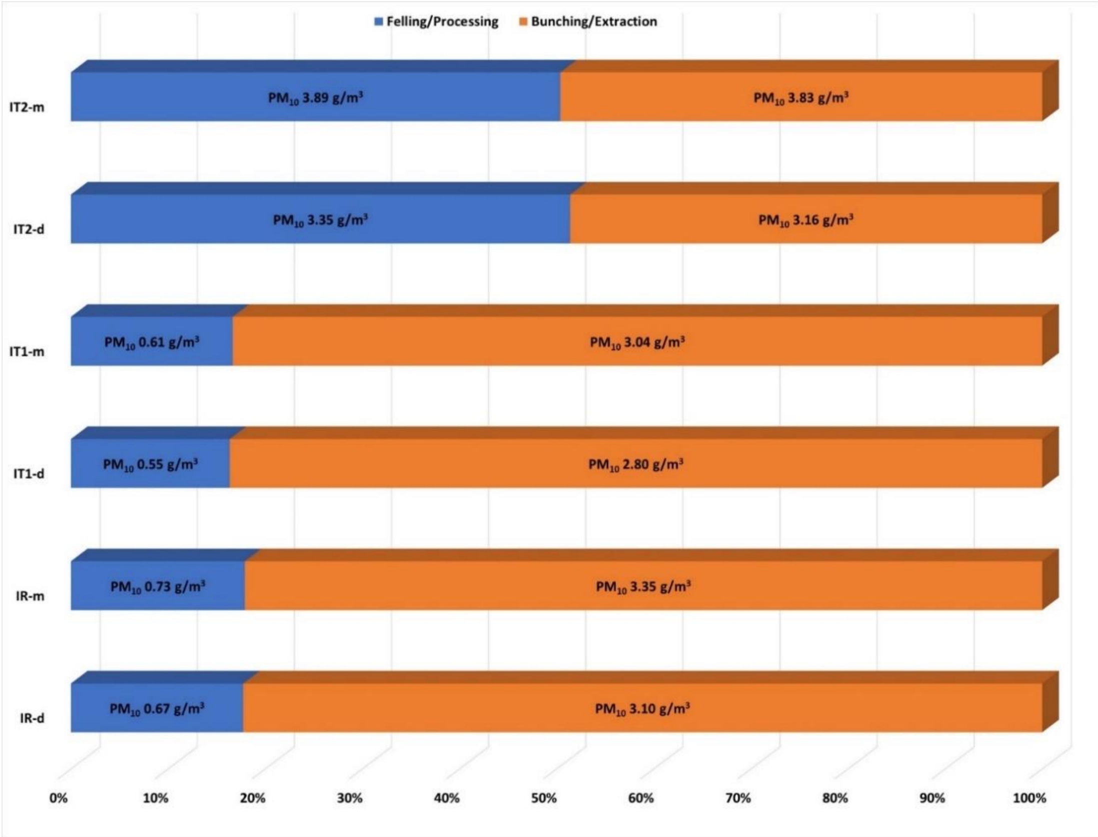

Figure 6. Percentage distribution of total PM10 emission in the harvesting sites studied, data shown for single operation (data reported to FU of 1 t of fresh mass showed in Figure A2).

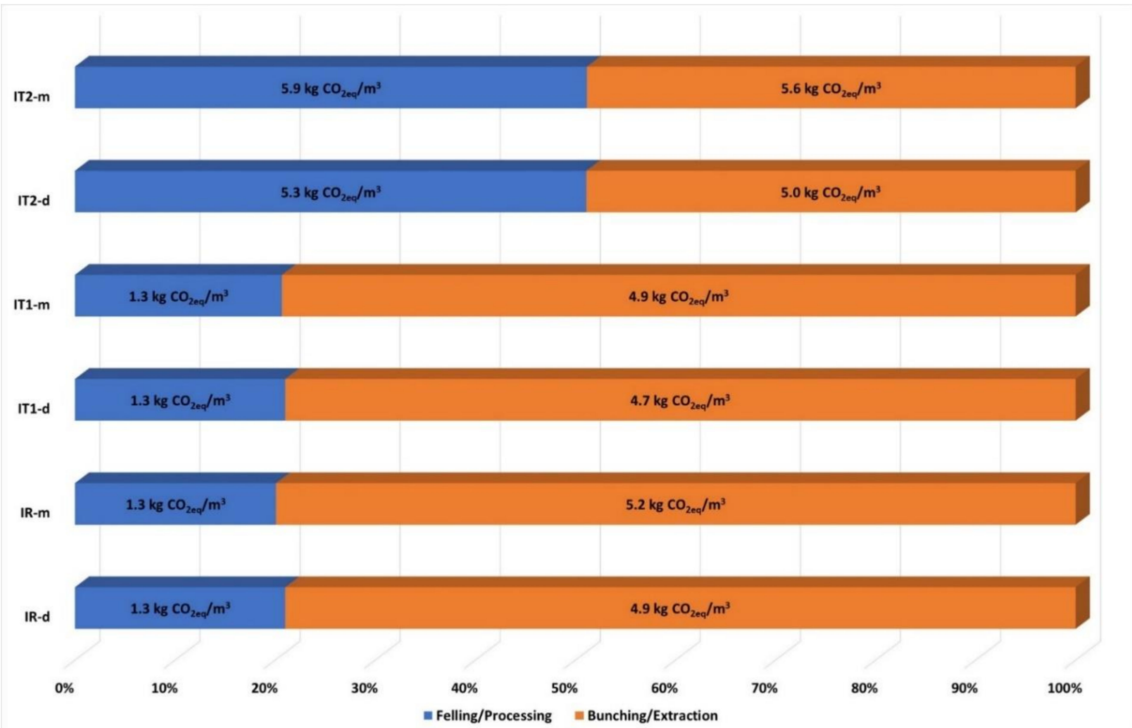

Figure 7. Percentage distribution of GHG emission in the harvesting sites studied, data shown for single operation and reported in CO_2 equivalent (data reported to FU of 1 t of fresh mass showed in Table A3).

4. Discussion

4.1. Comparison of Harvesting Systems Performance

Several studies on work productivity and cost analysis in poplar plantations are available in the literature, even if most of these deal with Short Rotation Coppice (SRC) plants for bioenergy production [48]. Indeed, few studies have focused on productivity analysis in poplar plantations for timber production. In a poplar plantation located in Serbia, Danilovic et al. [49] reported a productivity for mechanized felling–processing via harvester of 30.3 to 34.7 m^3 h^{-1}, depending on working method and stem dimension. In the same year, Spinelli et al. [50] carried out an extensive productivity and cost analysis in a 25 year old poplar plantation in Italy, reporting an average work productivity (SMH) for motor-manual felling and processing via chainsaw of 6.3 m^3 h^{-1} and a value of 21.1 m^3 h^{-1} for the same operation performed via harvester.

The productivity values found in the present study are higher than reported in the above cited studies, both for motor-manual and mechanized felling processing. This difference is more pronounced in comparison to Spinelli et al. [50]. Such a gap concerning mechanized felling–processing can be partially related to the lower average dbh of the stems in the previous study (around 30 cm vs. 40.4 cm). However, the major difference between the present studies and the literature, which can explain the higher productivity found in the present analysis, is the lower percentage of delay times. In particular, delay percentage ranges from 1.7% in IR to 2.9% in IT2, while the average delay for motor-manual felling-processing in Spinelli et al. [50] was 29.6%, decreasing to 13.0% in mechanized operations, while in Danilovic et al. [49] delay accounted for 28.5 of the working time.

Concerning bunching–extraction operations, no study on winching and forwarding in poplar plantations for timber production were found in the literature. However, there are several studies on bunching and extraction via TimberJack 450 cable skidder, which analyzed work productivity in different forest stands. Lotfalian et al. [51] found a winching productivity of 20.2 m^3 h^{-1} in beech high stand thinning with an average extraction distance of 289 m, while Mousavi [52] reported a bunching–extraction productivity of about 11 m^3 h^{-1} in beech selection cutting with an average skidding distance of 439 m. Nikooy et al. [18] reported instead a lower value of 5.2 m^3 h^{-1} productivity of Timberjack 450C in timber extraction of path cutting in a pine plantation. Such lower productivity is probably related to the lower dimension of trees considering that skidding distance was comparable to those in both IR and IT1 [18]. Therefore, as a general trend, bunching-extraction productivity in the present study showed higher values than previous works reported in the literature for the same machinery in different stands and silvicultural interventions. This difference is related to both the type of forest intervention (clear cut) and to the flat terrain of IR and IT1, which facilitated logging operations.

Regarding forwarding operations, also in this case it is possible to make a comparison regarding work productivity only between different stands, considering the lack of studies on poplar plantations for timber production. The forwarder is the most commonly applied machinery in CTL (Cut to Length) harvesting operations, and it has been widely applied in artificial plantations, mostly of softwood species [53]. This machinery can reach a very high working productivity [54,55], even if a proper planning of the intervention is needed to reduce the impact which can occur considering the average dimension of a forwarder [13]. Comparing the findings of the present study with other forestry interventions in artificial plantations, it is evident that the substantial average dimension of stems, the short extraction distance and the flat terrain features in IT2 led to higher work productivity. In detail, Puttock et al. [56] reported a SMH productivity of 11.2 m^3 h^{-1} in a poplar-dominated mixed-wood stand in Southern Ontario during thinning interventions; Eriksson and Lindroos [57] showed PMH productivity for forwarding in clear cutting in pine and spruce stands of 21.4 m^3 h^{-1}. Another study performed in Romania reported a SMH productivity of 15.35 m^3 h^{-1} in a clear cut of spruce stand, with an average slope of 10% and an average extraction distance of 479 m [58]. In another study recently carried out in Poland, Magagnotti et al. [11] reported a forwarding productivity of 24.4 m^3 h^{-1} SMH for a poplar plantation.

Focusing on harvesting costs, it is possible to notice how felling and processing operations accounted for the major part of these in all the yards in both soil moisture conditions, as reported by previous literature [38,59]. Felling and processing costs, with values ranging from 4.22 € m^{-3} (IT2 dry) to 5.77 € m^{-3} (IR moist), were in line with the literature findings for several Italian poplar plantations for high value timber production, notwithstanding higher work productivity. Spinelli et al. [50] reported a unit cost of about € 5 m^{-3} for both motor-manual and mechanized felling–processing. This can be explained by the higher purchase costs of the machinery applied in the studied plantations. Skidding and forwarding costs are also in line with the literature, for similar harvesting systems but in different kinds of stands. In the present study the lowest cost for extraction was shown by IT2 dry at € 2.46 m^{-3}, while the highest cost was related to winching in IT1 moist (€ 5.28 m^{-3}). Regarding winching operations through cable skidder, Jourgholami and Majnounian [33] reported 6.15 € m^{-3} as the cost of Timberjack 450C in timber extraction on a pine plantation, while the findings of Lotfalian et al. [51] showed 5.15 USD m^{-3}. Focusing on forwarding, extraction costs were assessed by Cabral et al. [60] at about 1.95 € m^{-3}, while about 7.5 € m^{-3} were reported by Kaleja et al. [61], and about 9.2 € m^{-3} by Magagnotti et al. [11].

Concerning environmental impact, a comparison was carried out between the findings of the present study and other similar studies, regarding both high and medium level of mechanization. In both cases, energy inputs and energy balance in the investigated poplar plantations were substantially higher [37,62].

System efficiency values were high in all three yards in both the soil conditions (ranging from 96.6% to 98.1%), and thus were in line with previous literature findings in other forest interventions [16,62,63].

GHG emissions, mostly regarding CO_2, were lower than in previous literature findings, which reported a range between 3 and 33 kg CO_2eq, while the values of the present work ranged from 1.6 to 2.8 kg CO_2eq [5,16,24,46,64].

4.2. Influence of Soil Moisture on Harvesting Performance

There is a considerable amount of literature regarding working productivity evaluation, but a major part of the studies focused on the influence on working performance of parameters such as terrain features, working distance, age, species composition, labor skills, etc. However, not much attention has been directed towards soil moisture conditions and productivity. Studies were, however, conducted on soil impact related to logging activities [65–68].

In all of the three yards, higher soil moisture led to lower work productivity, thus to higher harvesting costs, in accordance to what was reported in the few studies dealing with this topic [69,70]. High soil moisture negatively affected both motor-manual and mechanized operations, resulting in higher working times, except for felling (both with chainsaw and harvester) and processing (only with harvester). Longer working time in higher soil moisture conditions for mechanized operations (bunching –extraction) is related to the lower driving speed which the machinery was able to achieve with moist soil. The high level of moisture of the terrain caused reduced tire grip and the operators had to reduce the working speed for safety reasons. Interestingly, this did not happen for felling–processing operations by harvester, which were not affected by soil moisture regarding working time. Soil moisture also negatively affected motor-manual operations, specifically, moving (IR and IT1) and processing (only IR). This is equally related to worker safety issues, with operators that had to be more cautious during the logging activities, due to the fact that high moisture in the soil made the trail slippery, and therefore prone to accidents.

High soil moisture showed negative effects on the environmental performance of logging activities in the studied poplar plantations. There were two reasons for these negative effects: the longer working time, which required more time in which motors were running, and the higher torque needed to move the machinery in moist soil, considering the lower grip and higher attrition. Thus, there were higher emissions of pollutants.

5. Conclusions

Although poplar plantations are important sources of timber in both Iran and Italy, few studies have focused on work productivity evaluation under different aspects related to sustainability in such kinds of stand. Moreover, these plantations are often located in plain or floodplain lands, therefore harvesting operations can occur in soil conditions with a high moisture content.

The aims of this study were: (i) to evaluate different harvesting systems in poplar plantations and (ii) to evaluate the influence of soil moisture on economic and environmental performance of logging operations.

In order to assess different harvesting systems in poplar plantations, from what was analyzed it is possible to state that a fully mechanized harvesting system (harvesting forwarder) is the most productive and economically sustainable with respect to semi-mechanical harvesting/processing and skidding extraction. However, in terms of energy balance and emissions, it is possible to state exactly the opposite, that the best harvesting system was semi-mechanical harvesting/processing and skidding extraction. These are aspects to be carefully considered during operations planning, but they must also be analyzed in terms of greater efficiency of the mechanization used, seeking to bring mechanical technologies that are increasingly efficient also in environmental terms to the forestry sector.

In order to assess the influence of soil moisture on economic and environmental performance of the logging operations, the findings revealed that high moisture content led to lower work productivity in all of the three investigated plantations, with detrimental effects on harvesting costs, which were found to be higher in moist soil conditions in all three yards. Moreover, environmental features related to pollutant emissions were higher in moist soil conditions, as a consequence of the longer time and the major torque required for the machinery to perform the logging activities.

It can be concluded from these findings that it is advisable to avoid logging operations in conditions of high soil moisture (>20%), to decrease the impact on the soil, to create higher cost-effectiveness, and to reduce the emissions of pollutants.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

The data assessed in the Appendix A are referred to another Functional Unit (FU) respect to how reported in the main text. The FU in this case was 1 t of fresh mass (following the data showed in Table 2). This was important in order to give more possibility to compare these results with other studies.

Table A1. Harvested trees, fresh mass and working cycles for work productivity analysis in each treatment.

Parameter	IR Dry	IR Moist	IT1 Dry	IT1 Moist	IT2 Dry	IT2 Moist
Felled-processed trees (N)	601	625	556	528	2790	2762
Felled processed-wood (t)	1046.159	1088.005	987.715	938.329	5411.307	5357.194
Extraction cycles (N)	100	100	100	100	100	100
Extracted wood (t)	534.778	549.102	555.994	423.146	974.295	851.606

Table A2. Extraction trail and corridors' average features for the three areas in the two soil moisture conditions (mean ± SD). From the *t*-test for independent samples applied, statistically significant differences ($p < 0.05$) between the average values are highlighted (underlined text).

	IR		IT1		IT2	
	Dry	Moist	Dry	Moist	Dry	Moist
Mean bunching distance (m)	38.6 ± 10.1	49.8 ± 9.5	<u>17.5 ± 5.2</u>	<u>56.1 ± 8.2</u>	22.7 ± 4.2	18.4 ± 2.1
Mean extraction distance (m)	146.0 ± 20.1	144.5 ± 12.2	118.2 ± 14.3	138.1 ± 10.3	152.4 ± 12.5	158.7 ± 11.2
Mean mass per working cycle (t)	5.35 ± 0.12	5.49 ± 0.11	5.56 ± 0.15	4.23 ± 0.13	9.74 ± 0.22	8.52 ± 0.30

Table A3. Harvesting costs for one wood, fresh tons and percentage of costs at two main operations (felling–processing and bunching–extraction to landing) in the studied sites.

Description	MU	IR Dry	IR Moist	IT1 Dry	IT1 Moist	IT2 Dry	IT2 Moist
Real unit cost (SMH)	€ t^{-1}	11.27	13.43	9.79	13.17	8.41	10.03
Felling–Processing percentage	%	60.5	54.0	63.8	49.6	63.2	55.2
Bunching–Extraction percentage	%	39.5	46.0	36.2	50.4	36.8	44.8
Hypothetical unit cost (PMH)	€ t^{-1}	10.91	12.98	9.39	12.49	8.03	9.47
Felling–Processing percentage	%	61.5	54.6	65.1	51.0	64.6	56.7
Bunching–Extraction percentage	%	38.5	45.4	34.9	49.0	35.4	43.3

Table A4. Total energy inputs and balance in the studied harvesting yards, referring to surface unit and to fresh mass.

Description	M.U.	Energetic Output	Direct Input	Indirect Input	Human Labor Input	Total Inputs	Output/Inputs Ratio	System Efficiency
IR-d	MJ t^{-1}	14,649	323.72	5.30	0.88	329.91	44.4	97.7%
	GJ ha^{-1}	10,217	225.78	3.70	0.61	230.09		
IR-m	MJ t^{-1}	14,649	425.57	7.33	1.01	433.90	33.8	97.0%
	GJ ha^{-1}	10,217	296.81	5.11	0.70	302.72		
IT1-d	MJ t^{-1}	16,585	301.68	4.79	0.88	307.36	54.0	98.1%
	GJ ha^{-1}	8191	148.99	2.37	0.44	151.79		
IT1-m	MJ t^{-1}	16,585	501.85	8.88	1.08	511.82	32.4	96.9%
	GJ ha^{-1}	8191	247.84	4.39	0.53	252.76		
IT2-d	MJ t^{-1}	16,153	467.23	10.81	0.08	478.12	33.8	97.0%
	GJ ha^{-1}	8741	252.83	5.85	0.05	258.73		
IT2-m	MJ t^{-1}	16,153	535.35	12.72	0.11	548.18	29.5	96.6%
	GJ ha^{-1}	8741	289.69	6.89	0.06	296.63		

Table A5. Total emission assessed in the studied harvesting yards, referring to fresh mass.

Harvesting Sites	CO_2	CO	HC	N_{ox}	PM_{10}
			$g\ t^{-1}$		
IR-d	2074.29	32.92	0.53	31.62	4.74
IR-m	2135.01	34.32	0.58	33.43	4.77
IT1-d	2279.39	34.26	0.50	34.43	4.77
IT1-m	2315.31	35.84	0.58	35.62	5.19
IT2-d	3674.05	66.99	1.03	57.99	9.02
IT2-m	3864.99	76.32	1.08	66.38	10.71

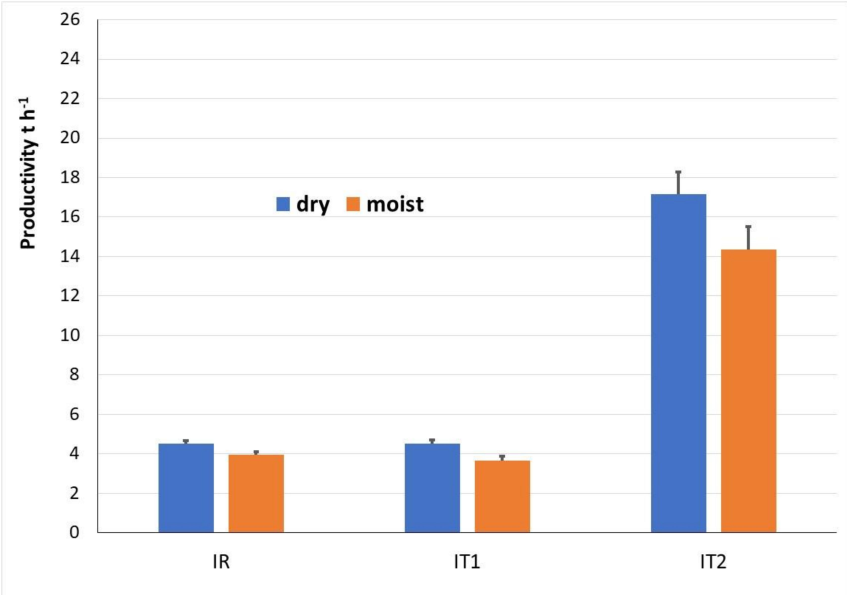

Figure A1. Average yard productivity (bars) and possible increase of performance (lines) from SMH to PMH for the six harvested sites.

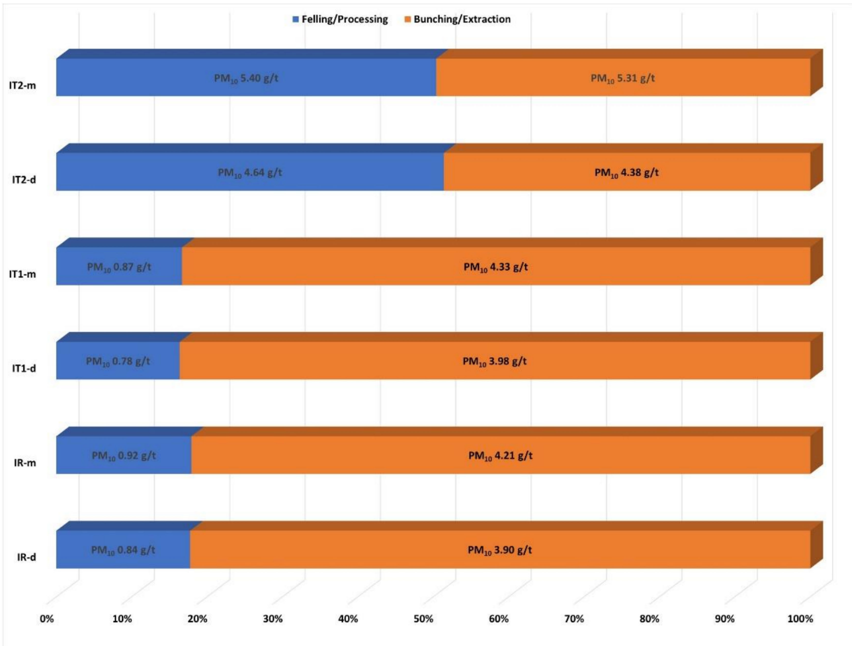

Figure A2. Percentage distribution of total PM10 emission in the harvesting sites studied, data shown for single operation, referring to fresh mass.

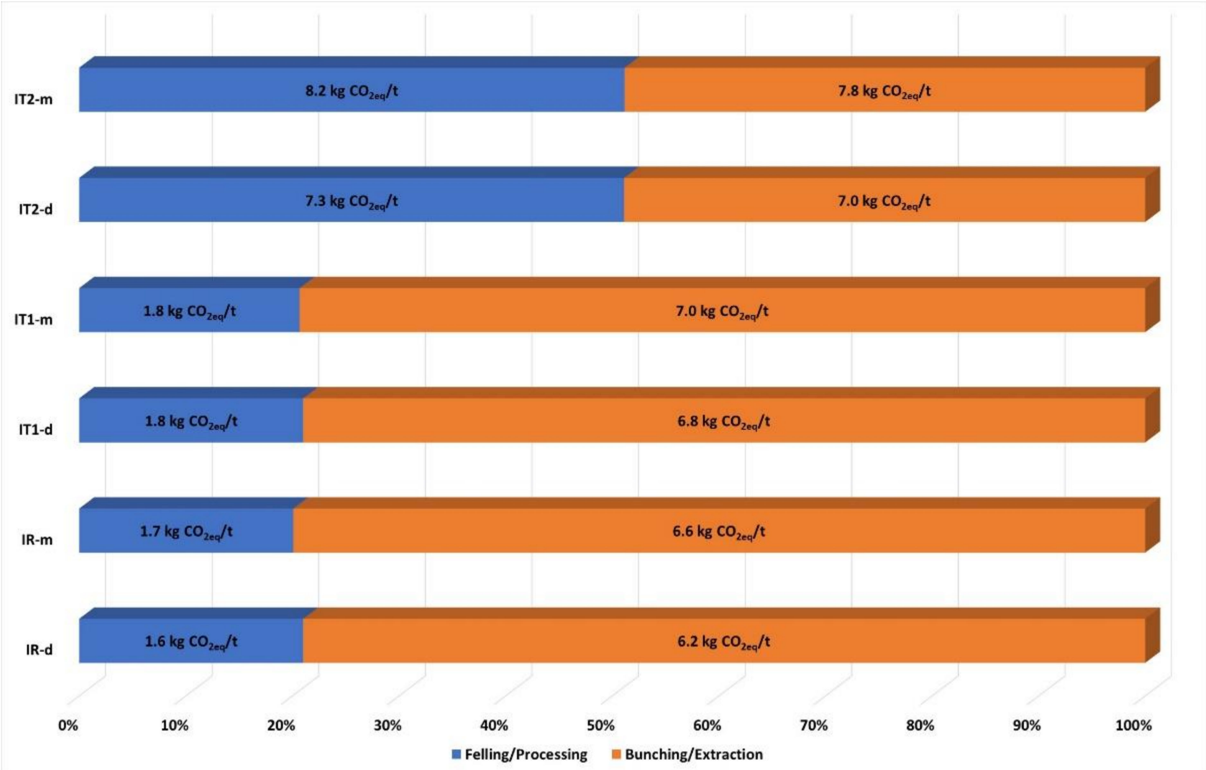

Figure A3. Percentage distribution of GHG emission in the harvesting sites studied, data shown for single operation and reported in CO_2 equivalent, data referring to fresh mass.

References

1. Azizi, M.; Faezipour, M.M.; Bayatkashkooli, A.; Taheri, F. Quantitative study of poplar plantations in three Iranian provinces. *For. Sci. Pract.* **2013**, *15*, 363–369. [CrossRef]
2. FAO. Poplars and other fast-growing trees—Renewable resources for future green economies, 2016 Synthesis of Country Progress Reports. In Proceedings of the 25th Session of the International Poplar Commission, Berlin, Germany, 13–16 September 2016; Working Paper IPC/15. Forestry Policy and Resources Division, FAO: Rome, Italy, 2016. Available online: http://www.fao.org/forestry/ipc2016/en/ (accessed on 1 June 2020).
3. Italian Inventory of Forests and Carbon Pools. 2005. Available online: https://www.sian.it/inventarioforestale/jsp/documentazione.jsp (accessed on 1 June 2020).
4. Anaraki, K.A.; Lashgarara, F.; Kiadaliri, H. Effect of socio-economic factors on development of poplar plantation in Guilan province (case study: Somesara). *Iran. J. For. Poplar Res.* **2012**, *20*, 346–356.
5. González-García, S.; Bacenetti, J.; Murphy, R.J.; Fiala, M. Present and future environmental impact of poplar cultivation in the Po Valley (Italy) under different crop management systems. *J. Clean. Prod.* **2012**, *26*, 56–66. [CrossRef]
6. Davison, J.; Riggs, W. Hybrid poplar production 1998–2003 in Eureka and Churchill Counties. *Univ. Nev. Coop. Ext. Fact Sheet* **2004**, 5–25.
7. Castro, G.L.; Fragnelli, G. New technologies and alternative uses for poplar wood. *Boletín Inf. Cideu* **2006**, *2*, 27–36.
8. Lashkarbolouki, E.; Modirrahmati, A.R.; Rahmani, R.; Kahneh, E.; Koopar, S.A.M. Phenology and growth characteristics of seven clones of Populus deltoides in Astaneh Ashrafie, Guilan. *Iran. J. For. Poplar Res.* **2010**, *18*, 527–538.
9. Colangelo, M.; Camarero, J.J.; Borghetti, M.; Gazol, A.; Gentilesca, T.; Ripullone, F. Size matters a lot: Drought-affected Italian oaks are smaller and show lower growth prior to tree death. *Front. Plant Sci.* **2017**, *8*, 135. [CrossRef]
10. Motta, R.; Nola, P. Growth trends and dynamics in sub-alpine forest stands in the Varaita Valley (Piedmont, Italy) and their relationships with human activities and global change. *J. Veg. Sci.* **2001**, *12*, 219–230. [CrossRef]
11. Magagnotti, N.; Spinelli, R.; Kärhä, K.; Mederski, P.S. Multi-tree cut-to-length harvesting of short-rotation poplar plantations. *Eur. J. For. Res.* **2021**, *140*, 345–354. [CrossRef]
12. Marchi, E.; Chung, W.; Visser, R.; Abbas, D.; Nordfjell, T.; Mederski, P.S.; McEwan, A.; Brink, M.; Laschi, A. Sustainable Forest Operations (SFO): A new paradigm in a changing world and climate. *Sci. Total Environ.* **2018**, *634*, 1385–1397. [CrossRef]
13. Picchio, R.; Latterini, F.; Mederski, P.S.; Tocci, D.; Venanzi, R.; Stefanoni, W.; Pari, L. Applications of GIS-Based Software to Improve the Sustainability of A Forwarding Operation in Central Italy. *Sustainability* **2020**, *12*, 5716. [CrossRef]
14. Schweier, J.; Blagojević, B.; Venanzi, R.; Latterini, F.; Picchio, R. Sustainability assessment of alternative strip clear cutting operations for wood chip production in renaturalization management of pine stands. *Energies* **2019**, *12*, 3306. [CrossRef]

15. Spinelli, R.; Lombardini, C.; Marchi, E.; Aminti, G. A low-investment technology for the simplified processing of energy wood from coppice forests. *Eur. J. For. Res.* **2019**, *138*, 31–41. [CrossRef]
16. Picchio, R.; Venanzi, R.; Di Marzio, N.; Tocci, D.; Tavankar, F. A Comparative Analysis of Two Cable Yarder Technologies Performing Thinning Operations on a 33 Year Old Pine Plantation: A Potential Source of Wood for Energy. *Energies* **2020**, *13*, 5376. [CrossRef]
17. Spinelli, R.; Magagnotti, N.; Lombardini, C.; Mihelič, M. A Low-Investment Option for the Integrated Semi-Mechanized Harvesting of Small-Scale, Short-Rotation Poplar Plant. *Small-Scale For.* **2021**, *20*, 59–72. [CrossRef]
18. Nikooy, M.; Esmailnezhad, A.; Naghdi, R. Productivity and cost analysis of skidding with Timberjack 450C in forest plantations in Shafaroud watershed, Iran. *J. For. Sci.* **2013**, *59*, 261–266. [CrossRef]
19. Wang, J.; Long, C.; McNeel, J.; Baumgras, J. Productivity and cost of manual felling and cable skidding in central Appalachian hardwood forests. *For. Prod. J.* **2004**, *54*, 45–51.
20. Naghdi, R.; Rafatniaa, N.; Sobhani, H.; Jalali, G.H.; Hosseini, S.M. A survey of the efficiency of timber jack 450C wheeled skidder in sheared forests. *J. Nat. Resour.* **2005**, *57*, 657–687.
21. Demir, M. Investigation of timber harvesting mechanization progress in Turkey. *Afr. J. Biotechnol.* **2010**, *9*, 1628–1634.
22. Picchio, R.; Pignatti, G.; Marchi, E.; Latterini, F.; Benanchi, M.; Foderi, C.; Venanzi, R.; Verani, S. The Application of Two Approaches Using GIS Technology Implementation in Forest Road Network Planning in an Italian Mountain Setting. *Forests* **2018**, *9*, 277. [CrossRef]
23. Picchio, R.; Latterini, F.; Mederski, P.S.; Venanzi, R.; Karaszewski, Z.; Bembenek, M.; Croce, M. Comparing Accuracy of Three Methods Based on the GIS Environment for Determining Winching Areas. *Electronics* **2019**, *8*, 53. [CrossRef]
24. González-García, S.; Krowas, I.; Becker, G.; Feijoo, G.; Moreira, M.T. Cradle-to-gate life cycle inventory and environmental performance of Douglas-fir roundwood production in Germany. *J. Clean. Prod.* **2013**, *54*, 244–252. [CrossRef]
25. Lima, K.S.; Meira Castro, A.C.; Santos Baptista, J.; Silva, U. Wood-Logging Process Management in Eastern Amazonia (Brazil). *Sustainability* **2020**, *12*, 7571. [CrossRef]
26. Sohrabi, H.; Jourgholami, M.; Jafari, M.; Shabanian, N.; Venanzi, R.; Tavankar, F.; Picchio, R. Soil recovery assessment after timber harvesting based on the sustainable forest operation (SFO) perspective in iranian temperate forests. *Sustainability* **2020**, *12*, 2874. [CrossRef]
27. Ozkaya, G.; Erdin, C. Evaluation of sustainable forest and air quality management and the current situation in europe through operation research methods. *Sustainability* **2020**, *12*, 10588. [CrossRef]
28. Lontsi, R.T.; Corre, M.D.; Iddris, N.A.; Veldkamp, E. Soil greenhouse gas fluxes following conventional selective and reduced-impact logging in a Congo Basin rainforest. *Biogeochemistry* **2020**, *151*, 153–170. [CrossRef]
29. Gusti, M.; Di Fulvio, F.; Biber, P.; Korosuo, A.; Forsell, N. The Effect of alternative forest management models on the forest harvest and emissions as compared to the forest reference level. *Forests* **2020**, *11*, 794. [CrossRef]
30. Naghdi, R.; Solgi, A. Effects of skidder passes and slope on soil disturbance in two soil water contents. *Croat. J. For. Eng.* **2014**, *35*, 73–80.
31. Startsev, A.D.; McNabb, D.H. Effects of skidding on forest soil infiltration in west-central Alberta. *Can. J. Soil Sci.* **2000**, *80*, 617–624. [CrossRef]
32. Cambi, M.; Grigolato, S.; Neri, F.; Picchio, R.; Marchi, E. Effects of forwarder operation on soil physical characteristics: A case study in the Italian alps. *Croat. J. For. Eng. J. Theory Appl. For. Eng.* **2016**, *37*, 233–239.
33. Jourgholami, M.; Majnounian, B. Productivity and cost of wheeled skidder in Hyrcanian Forest. *Int. J. Nat. Eng. Sci.* **2008**, *2*, 99–103.
34. Miyata, E.S. *Determining Fixed and Operating Costs of Logging Equipment*; General Technical Report NC-55; Department of Agriculture, Forest Service, North Central Forest Experiment Station: St. Paul, MN, USA, 1980.
35. Spinelli, R.; Magagnotti, N.; Lombardini, C. Performance, capability and costs of small-scale cable yarding technology. *Small-Scale For.* **2010**, *9*, 123–135. [CrossRef]
36. Picchio, R.; Spina, R.; Maesano, M.; Carbone, F.; Lo Monaco, A.; Marchi, E. Stumpage value in the short wood system for the conversion into high forest of a oak coppice. *For. Stud. China* **2011**, *13*, 252–262. [CrossRef]
37. Picchio, R.; Sirna, A.; Sperandio, G.; Spina, R.; Verani, S. Mechanized harvesting of eucalypt coppice for biomass production using high mechanization level. *Croat. J. For. Eng.* **2012**, *33*, 15–24.
38. Bodaghi, A.I.; Nikooy, M.; Naghdi, R.; Venanzi, R.; Latterini, F.; Tavankar, F.; Picchio, R. Ground-based extraction on salvage logging in two high forests: A productivity and cost analysis. *Forests* **2018**, *9*, 729. [CrossRef]
39. Picchio, R.; Maesano, M.; Savelli, S.; Marchi, E. Productivity and energy balance in the conversion into high forest system of a Quercus cerris L. coppice in Central Italy. *Croat. J. For. Eng.* **2009**, *1*, 15–26.
40. Hartsough, B. Economics of harvesting to maintain high structural diversity and resulting damage to residual trees. *West. J. Appl. For.* **2003**, *18*, 133–142. [CrossRef]
41. Picchio, R.; Magagnotti, N.; Sirna, A.; Spinelli, R. Improved winching technique to reduce logging damage. *Ecol. Eng.* **2012**, *47*, 83–86. [CrossRef]
42. Christie, C.J.-A. Improving the energy and fluid balance of workers involved in harvesting tasks. *Occup. Ergon.* **2010**, *9*, 119–126. [CrossRef]
43. Christie, C.J.-A. Relationship between energy intake and expenditure during harvesting tasks. *Occup. Ergon.* **2008**, *8*, 1–10.

44. Balimunsi, H.; Grigolato, S.; Picchio, R.; Nyombi, K.; Cavalli, R. Productivity and energy balance of forest plantation harvesting in Uganda. *For. Stud. China* **2012**, *14*, 276–282. [CrossRef]
45. Canagaratna, S.G.; Witt, J. Calculation of temperature rise in calorimetry. *J. Chem. Educ.* **1988**, *65*, 126. [CrossRef]
46. Klvac, R.; Fischer, R.; Skoupy, A. Energy use and emissions from the medium distance cableway system operation phase. *Croat. J. For. Eng* **2012**, *33*, 79–88.
47. Athanassiadis, D. Energy consumption and exhaust emissions in mechanized timber harvesting operations in Sweden. *Sci. Total Environ.* **2000**, *255*, 135–143. [CrossRef]
48. Vanbeveren, S.P.P.; Spinelli, R.; Eisenbies, M.; Schweier, J.; Mola-Yudego, B.; Magagnotti, N.; Acuna, M.; Dimitriou, I.; Ceulemans, R. Mechanised harvesting of short-rotation coppices. *Renew. Sustain. Energy Rev.* **2017**, *76*, 90–104. [CrossRef]
49. Danilović, M.; Tomašević, I.; Gačić, D. Efficiency of John Deere 1470D ECOIII harvester in poplar plantations. *Croat. J. For. Eng.* **2011**, *32*, 533–548.
50. Spinelli, R.; Magagnotti, N.; Sperandio, G.; Cielo, P.; Verani, S.; Zanuttini, R. Cost and productivity of harvesting high-value hybrid poplar plantations in Italy. *For. Prod. J.* **2011**, *61*, 64–70. [CrossRef]
51. Lotfalian, M.; Moafi, M.; Foumani, B.S.; Akbari, R.A. Time study and skidding capacity of the wheeled skidder Timberjack 450C. *Int. J. Sci. Technol. Educ. Res.* **2011**, *2*, 120–124.
52. Mousavi, R. Effect of log length on productivity and cost of Timberjack 450C skidder in the Hyrcanian forest in Iran. *J. For. Sci.* **2012**, *58*, 473–482. [CrossRef]
53. Mederski, P.S.; Borz, S.A.; Đuka, A.; Lazdiņš, A. Challenges in forestry and forest engineering—Case studies from four countries in East Europe. *Croat. J. For. Eng.* **2020**, *42*, 117–134. [CrossRef]
54. Gagliardi, K.; Ackerman, S.; Ackerman, P. Multi-product forwarder-based timber extraction: Time consumption and productivity analysis of two forwarder models over multiple products and extraction distances. *Croat. J. For. Eng.* **2020**, *41*, 231–242. [CrossRef]
55. Danilović, M.; Stojnić, D.; Karić, S.; Sučević, M. Transport of technical roundwood by forwarder and tractor assembly from poplar plantations. *Nov. Meh. Šumarstva Časopis Teor. Praksu Šumarskoga Inženjerstva* **2014**, *35*, 11–22.
56. Puttock, D.; Spinelli, R.; Hartsough, B.R. Operational Trials of Cut-To-Length Harvesting of Poplar in a Mixed Wood Stand. *Int. J. For. Eng.* **2005**, *16*, 39–49. [CrossRef]
57. Eriksson, M.; Lindroos, O. Productivity of harvesters and forwarders in CTL operations in northern Sweden based on large follow-up datasets. *Int. J. For. Eng.* **2014**, *25*, 179–200. [CrossRef]
58. Apăfăian, A.I.; Proto, A.R.; Borz, S.A. Performance of a mid-sized harvester-forwarder system in integrated harvesting of sawmill, pulpwood and firewood. *Ann. For. Res.* **2017**, *60*, 227–241. [CrossRef]
59. Williams, C.; Ackerman, P. Cost-productivity analysis of South African pine sawtimber mechanised cut-to-length harvesting. *South. For.* **2016**, *78*, 267–274. [CrossRef]
60. Cabral, O.M.D.J.V.; Lopes, E.D.S.; Rodrigues, C.K.; Filho, A.F. Impact of distance between strip roads on productivity and costs of a forwarder in commercial thinning of pinus taeda stands. *Croat. J. For. Eng.* **2020**, *41*, 243–249. [CrossRef]
61. Kaleja, S.; Spalva, G.; Stola, J. Productivity and cost of logbear F4000 forwarder in thinning depending on driving conditions. *Eng. Rural Dev.* **2018**, *17*, 1458–1463. [CrossRef]
62. Baldini, S.; Picchio, R.; Savelli, S. Analisi energetica nelle utilizzazioni di un ceduo di eucalipto con una meccanizzazione leggera. *J. Agric. Eng* **2007**, *3*, 49–56.
63. Vusić, D.; Šušnjar, M.; Marchi, E.; Spina, R.; Zečić, T.; Picchio, R. Skidding operations in thinning and shelterwood cut of mixed stands–Work productivity, energy inputs and emissions. *Ecol. Eng.* **2013**, *61*, 216–223. [CrossRef]
64. Valente, C.; Spinelli, R.; Hillring, B.G. LCA of environmental and socio-economic impacts related to wood energy production in alpine conditions: Valle di Fiemme (Italy). *J. Clean. Prod.* **2011**, *19*, 1931–1938. [CrossRef]
65. Bembenek, M.; Tsioras, P.A.; Karaszewski, Z.; Zawieja, B.; Bakinowska, E.; Mederski, P.S. Effect of day or night and cumulative shift time on the frequency of tree damage during CTL harvesting in various stand conditions. *Forests* **2020**, *11*, 743. [CrossRef]
66. Picchio, R.; Mederski, P.S.; Tavankar, F. How and How Much, Do Harvesting Activities Affect Forest Soil, Regeneration and Stands? *Curr. For. Rep.* **2020**, *6*, 115–128. [CrossRef]
67. Cambi, M.; Certini, G.; Neri, F.; Marchi, E. The impact of heavy traffic on forest soils: A review. *For. Ecol. Manag.* **2015**, *338*, 124–138. [CrossRef]
68. Naghdi, R.; Solgi, A.; Zenner, E.K.; Tsioras, P.A.; Nikooy, M. Soil disturbance caused by ground-based skidding at different soil moisture conditions in Northern Iran. *Int. J. For. Eng.* **2016**, *27*, 169–178. [CrossRef]
69. Grzywiński, W.; Turowski, R.; Naskrent, B.; Jelonek, T.; Tomczak, A. The impact of season on productivity and time consumption in timber harvesting from young alder stands in lowland poland. *Forests* **2020**, *11*, 1081. [CrossRef]
70. Chmielewski, S.; Porter, B. Valorization of the selected methods of harvesting and skidding of the pine stands in pre-final cut. *Tech. Roln. Ogrod. Les* **2012**, *3*, 23–26.