

Article

Energy Inputs in Motor-Manual Release Cutting of Broadleaved Forests: Results of Twelve Options

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Received: 18 July 2020; Accepted: 2 September 2020; Published: 4 September 2020



Abstract: Lignocellulosic biomass is used in various industries and its procurement involves a set of operations that are mainly done using equipment powered by internal combustion engines. The sustainability of forest operations may be characterized by balancing their energy inputs with those typically embodied in their outputted products. Forest tending operations are problematic because most of them cannot output marketable products while the data on their energy inputs are important for the forest management. Six of the most commonly used brushcutters equipped successively with discs and knives were tested to provide part of the data needed to run an energy analysis and to be able to characterize the energy inputs in release cutting operations by implementing the Gross Energy Requirements method. Fuel burning was found to have the greatest contribution (83–92%) in the total energy inputs (0.8–1.2 GJ/ha) of the studied operations and it was highly dependent on the efficiency of operations. Moreover, by simulation, it was identified that factors such as the assumed service life of equipment may significantly affect the outcomes of the analysis. Release cutting operations may be seen as important contributors in the energy balance of forest operations and data provided by this study may be of help for both forest management and more detailed and scaled analyses such as that of the Life Cycle Assessment.

Keywords: energy; input; balance; motor-manual; release cutting; operations; forestry

1. Introduction

The currently-faced concerns on fossil fuels depletion, environmental burdening, and energy security have led many states in the search of sustainable energy sources. One of the most common energy sources termed as being renewable is the lignocellulosic biomass, mainly due to its ability to store carbon [1] by growth and development and due to the relatively low energy inputs required to procure it [2]. While there are many lignocellulosic products that can be used to generate energy, and various feedstocks enabling them [3,4], forests have been seen as some of the main sources to provide raw materials for various industries, including here that of energy production. For instance, in the EU-28 alone, the use of wood and agglomerated wood products accounts for close to 50% of the gross inland energy consumption based on renewable sources [5].

To be able to provide the wood to the markets, forests require a set of operations to be deployed throughout their production cycle, starting with those aiming to restock the harvested areas [6] and ending with those consisting of harvesting [7]. While the type and number of interventions into the forests depend on the forest type, forest state, and forest management system [8], timely deployments,

in particular, are of a great importance in the production cycle of forests. However, timely interventions also mean that mechanization of operations is needed to be able to face specific requirements and cope with operational time windows, e.g., [9], which in some countries are limited and challenging. Having these in mind, forest operations need to be implemented sustainably [10]. Among other things, this means that a special attention needs to be given to saving energy and other resources [11] and it is particularly important since nowadays most of the forest equipment is powered by internal combustion engines which require for operation significant amounts of fossil fuels [12]. As such, the question arose on whether given forest operations are sustainable from an energy balance point of view. The subject has been addressed by a number of case studies dealing with timber harvesting operations, e.g., [13–17]. They have used the “energy analysis” as the underlying methodological approach, under the umbrella of the Gross Energy Requirements (GER) concept, which characterizes the flows of direct and indirect fossil energy into product or service-oriented systems [18], whereas the term “energy analysis” was commonly understood and used in the study of energy implied in the production of commodities and services [19]. As such, the concepts of GER are used in developing and framing an energy accounting balance based on the energy inputs and outputs and help in the attempt to understand if a product system is sustainable from this point of view; to reach this kind of sustainability, the amount of energy inputs into production needs to be less than the energy outputs stored in the produced commodities and, given its approach, the method itself accounts to a great extent for the environmental sustainability [17]. In forestry, however, the validity of energy analysis is reached beyond the analysis of a single step characterizing the forest production cycle. For example, to grow and maintain resilient and successful forests one needs to implement and account for several operations [20] with many of them being region specific [21]. Using a broader perspective is particularly important because it has been shown that many studies addressing environmental issues are truncated in their nature [22] while the data coming from those addressing particular components of a system is crucially important to build a clearer picture. Moreover, a part of the current situation, that prevents in some cases the development of studies to include the full production cycle of the forests, may be the result of missing data for some operations.

In the typical forest management, there are some operations that produce few or no tangible commodities (products) that could be used to run independent energy analyses to see if they fit in the concept of sustainability. In this category, most of the forest tending (release cutting, cleaning-respacing) operations may fall very well; they are critical because on their quality and number of interventions depends the success of future forests. Such tending operations may be deployed several times in the younger stages of a forest and some of them may produce vendible products only at their last iterations [23]. In addition, the carrier of these operations is typically not the same carrying the intermediary or final harvests that produce accountable products. As such, a part of the energy budget is frequently miscounted while it should be moved towards accountable products. Release cutting operations are commonly implemented to guide the outcomes of natural selection with the aim to promote economically valuable species [23]. However, there are few operational options which can be deployed in young and very dense forest stands; they may consist of chemical release or mechanical removal of undesired vegetation with the latter being done either manually or motor-manually [23]. Similar to other manual operations [24], manual release cutting is labor intensive [23] and ergonomically challenging, while the motor-manual approach can improve the productivity and ergonomics [25,26].

Brushcutters are used in forest operations [27] and in other industrial sectors such as that of short-rotation bioenergy production, e.g., [26,28] and some studies have pointed out that such operations meet acceptability when deployed in flat terrains, e.g., [26]. However, detailed energy analyses for brushcutting operations were not identified in the available literature. In particular, detailed data on the direct (fuel use) and indirect energy inputs are missing, while these kinds of data are important for operational management and payment systems, scalability in environmental impact studies, as well as for other strategic, tactical, and operational management attempts. Compared to fully mechanized systems, the performance of motor-manual operations is more likely to be affected

by the type of operation and operational environment, type and size of the tools used, and by the human work behavior and performance, e.g., [13,29,30]. These are just some of the factors that can bring heterogeneity in data and which may affect the outcome of any performance metric, including the energy requirements. Having these in mind, the main goal of this study was to estimate the direct and indirect energy inputs specific to the motor-manual release cutting operations deployed in mixed broadleaved forests located in flatlands. While the methodological approach was that of the Gross Energy Requirements, the study was complemented by time consumption and productivity estimates and it aimed to cover the variability given by the size of brushcutters and cutting devices typically used in such operations, by a series of field tests. Therefore, the objectives of this study were (i) to estimate the productive performance of using brushcutters in release cutting operations by a series of field tests, (ii) to account for direct and indirect energy inputs in such operations based on the outputs of the field tests and inputs available in the literature, and (iii) to simulate the aggregated data to address the uncertainty of results related to the main assumptions taken in the energy analysis.

2. Materials and Methods

2.1. General Approach and Boundaries of the Study

This study was designed to account for the energy inputs at the operational level. As such, the study was framed around the operation of brushcutters in release cutting interventions and included the estimation of productive performance metrics by observational field tests. The metrics which were estimated based on the field-collected data were further used in the estimation of direct energy inputs and they also served for the estimation of indirect energy inputs, under the Gross Energy Requirements method. Based on the results of field tests, an additional documentation of data was carried out to identify the materials included in the tools and their attachments, to allocate the materials based on their weight, to identify weight-based energy conversion factors for the energy inputs, and to gain knowledge on the service life of the equipment. To do so, the available literature, databases, local resellers of the tools, and professionals were consulted. Due to the approach used and difficulty in finding relevant data, the tools' manufacturing and repairing, as processes in the flow of energy, were left outside the scope of this study. Nevertheless, the results of the study were also interpreted in the light of including energy inputs associated to them. Moreover, a direct measurement of the energy spent by the workers in the operation was not possible to implement; as such the direct energy due to human physical effort was estimated based on the existing literature. Given some degree of uncertainty in the produced results, the study addressed also some modifications in the service life of tools and physical effort, by a scenario simulation.

2.2. Study Location and Experimental Setup of the Field Data Collection

This study is based on data collected in a forest located at approximately 46°09'26.50" N –21°16'36.98" E, ca. 100 m above sea level (Figure 1), in 12 plots which were delimited using a Stonex S8 N Plus (Stonex, Milan, Italy) GPS unit. Such units provide a location accuracy of ca. 2 cm; the field collected data was used to map the plots in which the tests were done, as shown in Figure 1. Forests in the area are dominated by broadleaves and they are commonly managed under the close-to-nature forestry concepts meaning that silvicultural interventions are done to promote a good forest stand development and to ensure the conditions of natural regeneration at the harvesting stage. Silviculture in these forests consists of tending operations (i.e., release cutting, clearing-respacing, and thinning) and harvesting which is done by selective extractions under the group shelterwood silvicultural system. Typical to the forest type taken into study is that during its youth and depending on its development context release cutting interventions may be done 2–3 times. The plots chosen for data collection were located on a flatland. At the time of field surveying, the forest was ca. 10-years old and it had a composition dominated by oak. The mean diameter was of ca. 4 cm, the mean height was of ca. 3 m, and the number of individuals per hectare was of ca. 3550. Specific to the plots taken into

study was that the intervention by release cutting was delayed relative to the forest age and there was a high amount of shrub vegetation in them. Therefore, the number of individuals as mentioned before refers to the tree species and not to the shrubs and other invasive species, for which an accounting prior to the study was difficult to make. In addition to the representativity of the forest as share and dimensional characteristics for the operation type surveyed, other criteria for choosing the described study location were related to the local availability of tools and experienced workers, terrain condition, and possibility to run the needed tests in the field.



Figure 1. Location of the field tests. Legend: (a)—Location of the study at the national level; (b)—location of the plots in the forest taken into study; (c)—map of the plots showing the name of the treatments by their code, where H stands for Husqvarna, S stands for Stihl, D stands for disc, and K stands for knife, as the active cutting devices, while the rest of each code indicates the tool model.

In relation to the terrain condition, a flatland was preferred due to the effects that the slope may have on the performance of motor-manual work which, by its variation, is known to affect the productive performance of work e.g., [31] and, by extrapolation, the energy inputs. While it was not possible to control in advance the density of individuals to be removed, a visual inspection was carried out before the field tests to choose a forest portion as homogeneous as possible. This step was carried out by the first author of this study, who had knowledge on the selection criteria of the trees to be removed and the layout of operations. The inspection also helped mark the boundary of the plots on which field tests were carried out. To exclude the variability that may come from the workers’ level of experience and their operational behavior, e.g., [32], this study used just one well-trained worker who tested by operation six models of brush cutters which were equipped successively, as active cutting devices, with both knives and discs. The tools were products of the Husqvarna and Stihl companies selected from the three most commonly used size classes, as shown in Table 1. Cutting discs and knives were newly purchased components, manufactured from steel, and they had a mass of 0.5 kg each. Based on the abbreviation of the tool model and type of cutting device used, twelve treatments were designed and tested in the field (Figure 1, Table 1).

Table 1. Description of the equipment tested.

Tool Model	Engine Power (kW)	Fuel Tank Capacity (l)	Tool Mass (kg)	Harness Mass (kg)	Active Cutting Device	Mass of Cutting Device (kg)	Treatment Code Used in This Study
Husqvarna 343 R	2.00	0.90	8.2	0.55	Knives	0.50	H343RK
					Disc	0.50	H343RD
Husqvarna 333 R	1.60	0.60	6.1	0.55	Knives	0.50	H333RK
					Disc	0.50	H333RD
Husqvarna 135 R	1.40	0.60	6.8	0.55	Knives	0.50	H135RK
					Disc	0.50	H135RD
Stihl FS 480	2.20	0.67	8.0	0.65	Knives	0.50	SFS480K
					Disc	0.50	SFS480D
Stihl FS 130	1.40	0.53	5.9	0.40	Knives	0.50	SFS130K
					Disc	0.50	SFS130D
Stihl FS 55	0.75	0.33	4.9	0.40	Knives	0.50	SFS55K
					Disc	0.50	SFS55D

2.3. Data Collection and Documentation

2.3.1. Operational Performance

Data regarding the time consumption and productivity was aggregated based on the results of observational field studies and it was complemented by some inputs provided by the worker; the time consumption structure was adapted to the concepts and definitions given in [33], while the estimation of productivity metrics was based on the guidelines described in [32]. As such, the concept used in this study included only the workplace time (*WT*, hours) which was assumed to be the sum of productive (*PT*), meal and rest (*MRT*), and tool maintenance and planning (*MPT*) time, and it was set to 8 h per day. *MRT* and *MPT* were set at one hour each per day, based on the data provided by the worker who indicated that he usually refuels the tool five times per day and he spends approximately half an hour per day to carry on the tool maintenance and to plan his work. While the described concept was used to estimate the energy inputs, to account for the variation in productivity, for each treatment, the productive time (*PT*) was estimated based on data collected by manual measurements in the field. This supposed the implementation of the continuous chronometry method [33], followed by a transformation of *PT* from seconds into hours for further analysis. To do so, for each treatment taken into the study, field observations were designed to capture at least 20 min of operation. This approach was used under the assumption of a low variability expected for the productive time within a work cycle because the specific work elements consisted only of worker's movement, decision, and cutting. In addition, a delimitation of work cycles framed around each removed individual was not possible at the field study time due to the short duration of the mentioned work elements. Time consumption was measured using a digital stopwatch at a 0.1 s accuracy. While the functional unit of this study was set to one hectare, both the operated area (*OA*, m²) and the number of individuals removed (*NI*) per treatment were taken into account as potential explanatory variables of the time consumption and productivity metrics. The operated area was calculated based on the GPS survey taken in the field. The number of individuals removed per treatment were counted and the diameter at the cut height (*D*, mm), taken at approximately 5 cm above the ground, was measured for each one using a small electronic caliper and a millimetric accuracy. All the relevant data collected manually was noted on a field book. Net productivity (*NP*, ha/h) and efficiency (*NE*, h/ha) were estimated based on the productive time and the operated areas measured in the field, at the treatment level. To estimate the gross productivity (*GP*, ha/h) and efficiency (*GE*, h/ha) a correction factor of 1.25 was used based on the assumptions described above for the *WT*, *PT*, *MRT*, and *MPT*.

2.3.2. Fuel and Lubricant Inputs

Fuel consumption was measured by using the refilling to full method which is described, for instance, in [32]. To do so, before starting each test, and after warming up the equipment and carrying out some accommodation work outside the designated area, the fuel tank was filled to full for each treatment. Then, the worker proceeded with the operations and, at the end of each test, the fuel tank was refilled to full obtaining this way, by difference, the amount of fuel mixture burned during the operation. For refilling and measurement, graded glass cylinders (1 mL accuracy) and methods similar to those described in [13] were used. Fuel mixture was prepared according to the instructions of the manufacturers and it accounted for 2% of mineral oil per liter of fuel. Based on the operated area and the amount of fuel mixture consumed, the rate of fuel consumption was estimated per hectare and this data was used to estimate the direct fossil energy inputs by scaling it at the level of each treatment.

2.3.3. Estimation of Energy Inputs

Estimation of energy inputs (EI , MJ/ha) was based on the Gross Energy Requirements (GER) method which accounts for the direct and indirect energy inputs [18]. For that, the measurements taken in the field formed the basis for scaling based on the assumptions for time consumption structure, productivity metrics, and data on the share of materials incorporated into the tools and their specific embodied energy. The approach was complemented by estimates of the energy spent by workers in operations.

The direct energy inputs (DEI , MJ/ha) taken into the study were those associated to fuel mixture (DEI_f , MJ/ha), lubricants (DEI_l , MJ/ha), and human labor (DEI_{hl} , MJ/ha); they were estimated based on the energy stored in fuels and lubricants and on the data on physiological effort, respectively. Given the fact that there was no available data on the energy consumption related to human labor in motor-manual release-cutting operations, a rate of 0.038 MJ/minute was adopted, as being an educated guessed value for the operations surveyed. It is a fact, however, that the human energy requirements may vary quite widely depending on the sex, type of operation undertaken, tool used, operational and environmental conditions, e.g., [34] cited in [15,35]. For instance, Picchio et al. [15] have used a value set at ca. 0.05 MJ/minute for the general timber harvesting work, but one may assume that brushcutting operations developed in flat terrains could be less physiologically intensive [26]. Procedurally, the energy inputs from fuel mixture (DEI_f , MJ/ha) were estimated for each treatment based on the net efficiency (NE , ha/h) figures and the amount of fuel mixture consumed per hour (FC , kg/h). For that, the measured quantities of two-stroke fuel mixture were converted from milliliters into kilograms using conversion factors of 0.9 and 1.3 L/kg for gasoline and lubricating oil, respectively, and the inputs were calculated based on the values of the stored energy described by [36] and [37] cited in [15], and set at 55.3 MJ/kg. Direct energy inputs specific to the lubricant used for the active components of the tools (DEI_l , MJ/ha) were estimated based on quantitative data provided by the local practice and they were assumed to be of 5 mL per day and per treatment. Conversion into energy inputs used a value of stored energy of 83.7 MJ/kg, based on the same references as provided above, and the net efficiency rate estimated for each treatment.

Indirect energy inputs are commonly referred to as the energy stored into the materials that make up the machines, equipment, or tools. For accounting, it is common to determine or to estimate the proportion of different raw materials within a given equipment and to compute their masses, which may help in establishing the energy stored into them, e.g., [14,15,38]. Then, using the knowledge on the energy requirements for extraction and manufacturing processes involved in the production of raw materials, one can estimate the energy stored in each component. In contrast to direct energy inputs, which are related to the time of operation, indirect energy inputs are distributed over the service life of a given equipment, a reason for which the service life needs to be estimated as accurately as possible. As such, for the tools, this study assumed a service life of 3000 h, a figure that was based on the local practice related to the use of brushcutters in tending operations. While some references have reported much lower figures for forest operations equipment [39], which were probably related

with the level of technology used in the past, it is quite common for the new generation of tools to hold their service life much longer, e.g., [40]. The same figure (3000 h) was adopted for the harness and it was based on the local practice. For the discs and knives, the service life was that corresponding to the operation time until the depletion of their functional purpose. It was set at 400 and 530 h, respectively, and it was based on the local material purchasing and replacement records. Energy content of the component materials integrated into the base tool, harness, disks, and knives was documented from different sources as shown in Table 2.

Table 2. Energy contents and share of materials incorporated into the base tools, harnesses, and active cutting devices.

Type of Material	Energy Content (MJ/kg)	Material Share (%)					
		Tool ³		Harness ⁴		Disk ⁵	Knife ⁵
		HusqvarnaStihl	HusqvarnaStihl	HusqvarnaStihl	HusqvarnaStihl		
Aluminium	360.0 ¹	8	6	5	5	-	-
Copper	671.0 ²	8	6	-	-	-	-
Nylon	335.0 ²	4	2	65	70	-	-
Polypropylene	159.0 ²	10	12	10	10	-	-
Rubber	92.8 ²	2	4	5	5	-	-
Steel	67.5 ¹	68	70	15	10	100	100

Data sources: ¹ Documented from [36,37], cited in [15]; ² documented from the EPiC database [41]; ³ estimates provided by local resellers; ⁴ estimates based on weighting of the harness components; ⁵ real figures extracted from selling catalogues.

Based on the proportion of materials (Table 2), their masses were calculated by taking as a reference the total mass of each tool part, as shown in Table 1. The results were multiplied by the energy content of each material, then the data was adjusted by taking into consideration the service life figures per components and the net efficiency rates per treatments.

2.4. Data Analysis

Data analysis relied mainly on the computation of descriptive statistics needed to characterize the operational environment, time consumption, productivity metrics, and energy inputs under the “base scenario”, which was characterized by the data generated by this study. The analysis was done at the treatment level but, where relevant, the results were also textually presented at the study level. Whether possible and based on logical assumptions, dependence relations between variables were checked by the means of least square simple linear regression assuming a confidence threshold set at $\alpha = 0.05$. The power of dependence relations was evaluated by the coefficient of determination (R^2 statistic) while the significance of predictors was assessed by the p-values checked against the confidence threshold. Given the scope of the study, only the most relevant data have been reported in detail while the underlying relations were reported textually as the results of the used statistical metrics. Moreover, given the high dependency of energy inputs on the service life assumed for the studied equipment, as well as the uncertainties related to the amount of energy spent by the workers in operation, some scenarios were considered for the two. The first set of scenarios was developed to check the effect of service life on the energy inputs by considering the “base scenario” as a reference and decrements of the service life to 75, 50, and 25% for the active cutting devices, tools, and harnesses. The results of these scenarios were compared by considering the EI metric and the treatments taken into the study. In the case of energy spent by the workers, the “base scenario” (0.038 MJ/min) was considered as a reference to compare the changes induced by energy expenditure rates set at 0.03 and 0.05 MJ/min, respectively. For a better identification of the changes, the results of these scenarios were compared by considering the DEI_{hl} metric.

All the steps involving data aggregation, data processing, statistical analysis, as well as part of the artwork developed and used in this study were supported by the use of the 2016 version of Microsoft Excel software (Microsoft, Redmond, WA, USA).

3. Results

3.1. Descriptive Statistics of Operational Conditions

Table 3 shows the relevant descriptive statistics of the variables characterizing the operational environment. At the treatment level, there was an evident variability in terms of operated area and number of individuals removed. It is worth mentioning that the removal intensity was found to vary between approximately 3 and 4.6 individuals per square meter; the diameters at the cut level varied between less than 0.5 and more than 6.5 cm but, in average, the diameter of the removed individuals was close to 2 cm.

Table 3. Descriptive statistics of operational conditions.

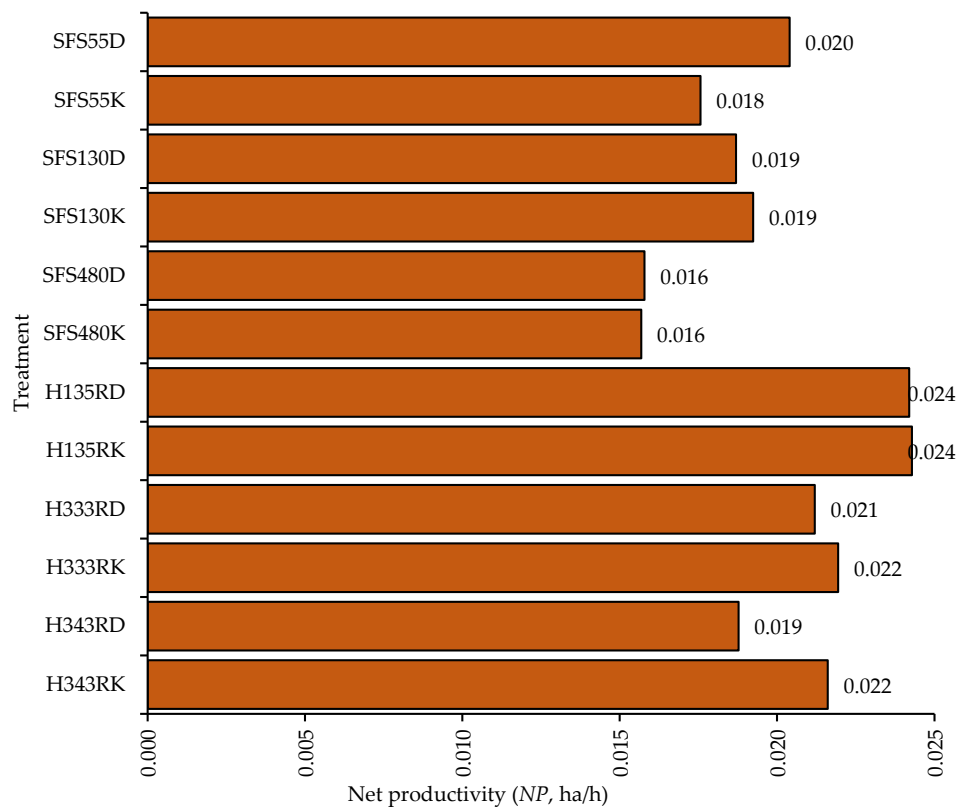
Treatment Code	Operated Area (OA, m ²)	Number of Individuals Removed	Removal Intensity (ind./m ²)	Average Diameter ¹ (cm)
H343RK	155.86	563	3.6	1.7 ± 0.7
H343RD	105.00	479	4.6	1.9 ± 0.7
H333RK	175.96	499	2.8	1.6 ± 0.8
H333RD	85.00	253	3.0	2.2 ± 0.6
H135RK	85.00	264	3.4	2.6 ± 0.4
H135RD	138.00	464	3.1	2.6 ± 0.4
SFS480K	92.85	392	4.2	2.3 ± 1.1
SFS480D	80.00	352	4.4	2.4 ± 1.0
SFS130K	131.50	457	3.5	2.0 ± 1.0
SFS130D	85.00	287	3.4	2.5 ± 0.8
SFS55K	145.50	493	3.4	1.6 ± 0.5
SFS55D	85.00	288	3.4	2.1 ± 0.7

Note: ¹ Standard deviation included.

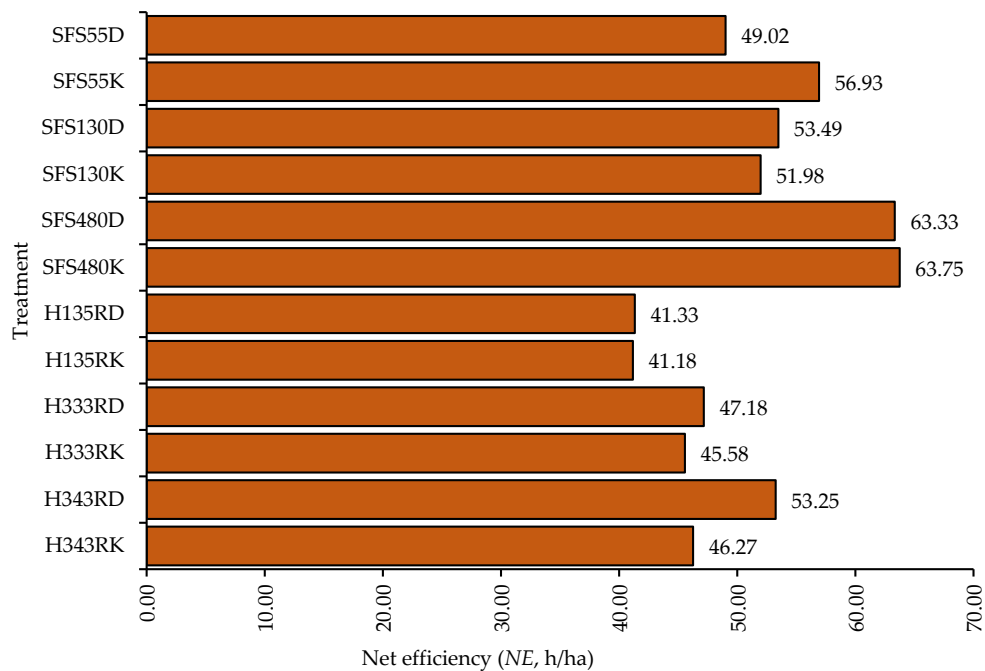
While the average values indicate that the operational conditions were aligned to the type of equipment tested, it is evident that in those cases in which the worker approached individuals having larger diameters, the efficiency of cutting may have been dropped. However, those cases in which the individuals had four or more cm in diameter at the cut level were few (data not shown herein). At the treatment level, the observed operational time varied between 21 and approximately 50 min, but in most of the cases it exceeded 30 min (data not shown herein).

The productive time consumption (*PT*, h) depended to a great extent on the size of operated area (*OA*, ha) and the number of individuals removed (*NI*). Taken apart, both the *OA* and *NI* (results not included here) explained the variation of time consumption in proportions of 78 ($R^2 = 0.78$) and 79% ($R^2 = 0.79$), respectively, and acted as significant predictors ($p = 0.0001$, $\alpha = 0.05$) in the explanation of productive time consumption variation. While this was expected, the dependence relations between the removal intensity (*RI*, individuals/ha), net efficiency (*NE*, h/ha), and net productivity (*NP*, ha/h), respectively, were weaker ($R^2 = 0.49$ and 0.45 , respectively).

Figure 2a shows the estimates of net productivity while Figure 2b shows the estimates of net efficiency, as they were produced at the treatment level. As indicated in the mentioned figures, the highest levels of productivity were those specific to H135RD and H135RK treatments, which characterized the plots having the highest mean diameter at the cut level (Table 3) and a removal intensity close to that characterizing the average conditions at the study level. At the opposite side were treatments SFS480D and SFS480K, for which the productivity was the lowest; also, they corresponded to the highest removal intensity (Table 3). Following the statistical check, no significant trends or dependence relations were found between the tool mass and efficiency or productivity of operations ($R^2 < 0.1$).



(a)



(b)

Figure 2. Breakdown of the treatment-level estimates on the net productivity (NP, ha/h) (a) and net efficiency (NE, h/ha) (b).

Therefore, it seems that there could have been other effects explaining the variation of time consumption, efficiency, and productivity, which were probably related to other external factors than the diameter of removed trees, removal intensity, tool mass, and type of cutting attachment used. These statements are supported by the results of the statistical checks as mentioned above.

Altogether, in the average conditions of this study, which could be fairly described by a removal intensity of approximately 3.6 individuals/m² and an average diameter at the cut level of approximately 2 cm, the mean productivity was found to be of approximately 0.02 ha/h while the net efficiency was found to be of approximately 51 h/ha.

3.2. Energy Inputs

This study has set the system's boundaries around the workplace, therefore only the energy inputs associated to this framework were estimated and taken into further analysis. Right at the beginning, it should be mentioned that the energy balance would have been highly offset in a negative way due to the small amounts of biomass removed by the operations surveyed. It is also a fact that this kind of biomass is not further utilized and it is commonly left into the forest [7].

Table 4 shows an overview on the total energy inputs (*EI*, MJ/ha) broken down on the two main components: Direct (*DEI*, MJ/ha) and indirect (*IEI*, MJ/ha) energy inputs. As shown, there was an evident variation in the data summarized for these categories of energy inputs. However, the direct energy inputs accounted for the most, and in particular that from burning fossil fuels. This category accounted for shares ranging between approximately 83 and 92% of the total energy inputs. Next in line was the direct energy input coming from human work which accounted for 7–13%, which was associated with the high labor demands per functional unit, and the indirect energy input coming from the energy incorporated into the tool components which was less than 2%, irrespective of the treatment. The latter was the effect of service life span set for the tools, active cutting devices, and harnesses.

Table 4. Breakdown of energy inputs on categories and treatments.

Treatment Code	Indirect Energy Inputs (<i>IEI</i> , MJ/ha)			Direct Energy Inputs (<i>DEI</i> , MJ/ha)			Total Energy Inputs (<i>EI</i> , MJ/ha)
	Attachment	Tool	Harness	Human Labor	Fuel	Lubricants	
H343RK	3.9	20.2	2.3	105.5	1079.2	4.2	1215.3
H343RD	3.4	23.2	2.6	121.4	1195.5	4.8	1351.0
H333RK	3.8	14.8	2.2	103.9	1141.5	4.1	1270.4
H333RD	3.0	15.3	2.3	107.6	1181.5	4.3	1313.9
H135RK	3.5	14.9	2.0	94.2	1273.5	3.7	1299.5
H135RD	2.6	14.9	2.0	94.2	1273.5	3.7	1391.1
SFS480K	5.4	23.6	3.9	145.4	1081.6	5.8	1265.5
SFS480D	4.0	23.4	3.8	144.4	1004.2	5.7	1185.7
SFS130K	4.4	14.2	1.9	118.5	763.7	4.7	907.4
SFS130D	3.4	14.6	2.0	122.0	708.9	4.8	855.6
SFS55K	4.8	12.9	2.1	129.8	1138.8	5.2	1293.6
SFS55D	3.1	11.1	1.8	111.8	1063.3	4.4	1195.6

Therefore, in the operations and operational conditions such as those described by this study, one could expect, in average, a total energy input of approximately 1.2 GJ/ha, out of which the direct energy inputs will account for more than 98%. Most of the latter are the effect of burning fuel, while the fuel consumption was also highly dependent on the net efficiency rates estimated at the treatment level (Figure 3). As shown in Figure 3, the fuel consumption per hour of operation was inversely proportional to the efficiency of operation which, at a first glance, may seem to be a paradox. However, a faster operation probably supposed a more intensive use of the tool's engine, a fact that has been transposed in higher fuel consumptions. As a rule of scaling, the tools size can be expected to affect the fuel intake, but this also depends on the appropriateness of the tool to the operational conditions and

on the operational conditions themselves. In this regard, under the conditions of this study, the tool size was not a relevant factor in explaining the fuel consumption.

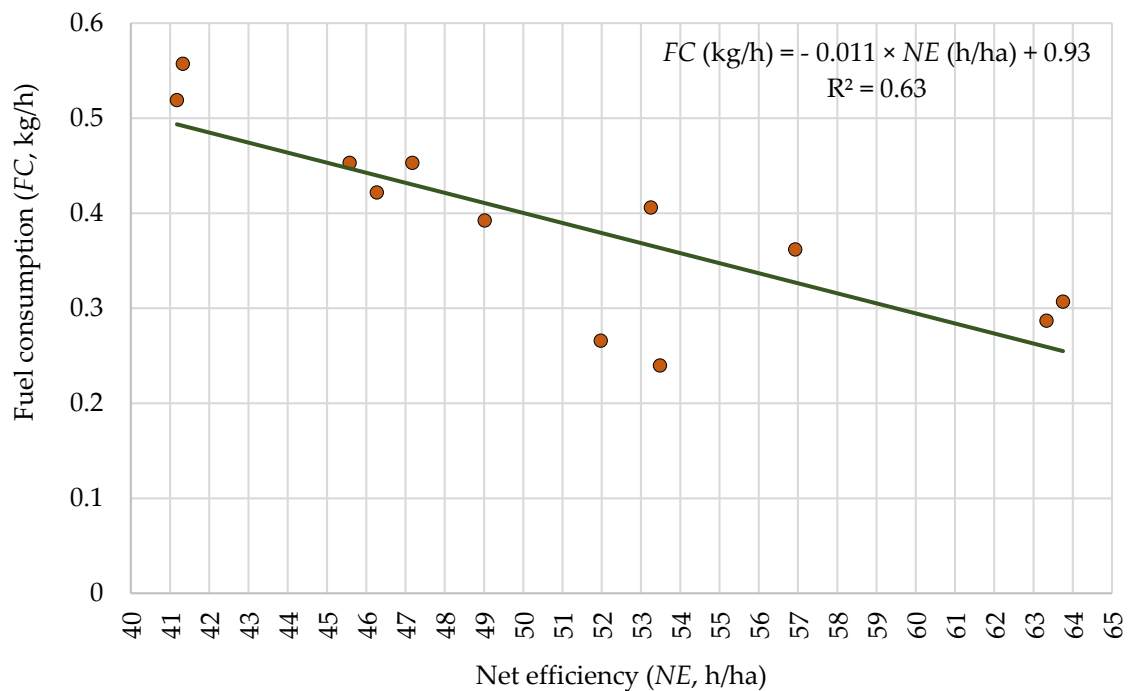


Figure 3. Dependence relation between the fuel consumption (FC , kg/h) and net efficiency rate (NE , h/ha).

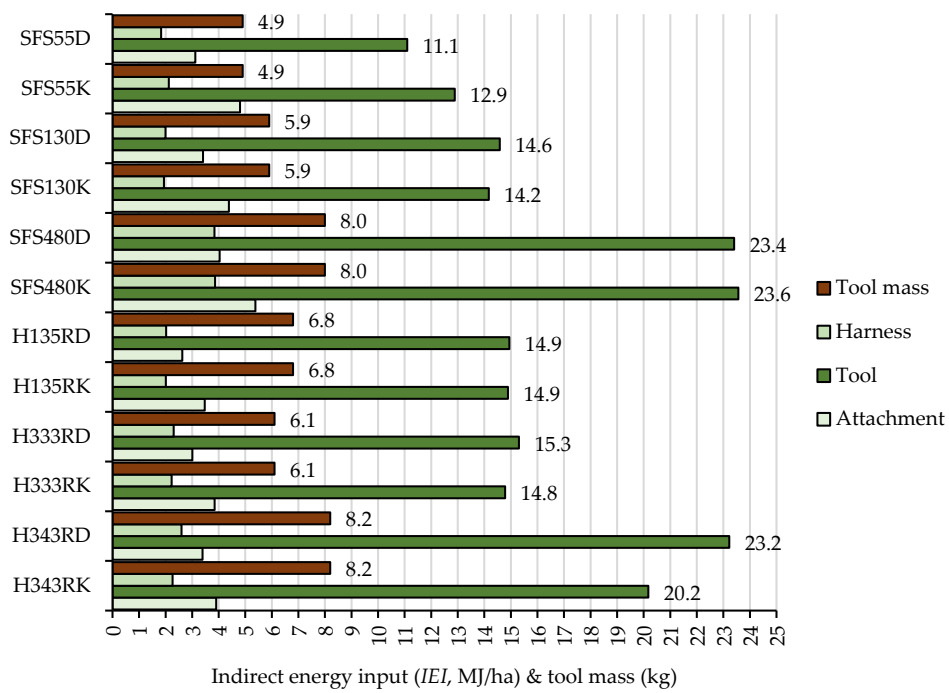
As a fact, besides the dependence relation shown in Figure 3, it was found that the heaviest tools were those characterized by fuel consumptions close to the average of this study. Moreover, the highest fuel consumptions were those of the tools from the middle class (treatments H135RK and H135RD, tool weight of 6.8 kg), while the lowest were those of the tools close to the light category (SFS130K and SFS130D, tool weight of 5.9 kg). The difference between fuel consumption of using either discs or knives was difficult to account for and appreciate because there was also a variability of operational conditions; as such, for the same tool model there were three cases in which the use of discs was found to be less fuel demanding compared to that of using knives, two cases in which the results were quite vice versa, and one case in which the results on fuel consumption were similar.

Since the greatest share of indirect energy inputs was that related to the energy stored into the components of the tools, Figure 4a attempts to explain the variation of this parameter by plotting the figures of energy inputs coming from the active cutting attachment, tool, and harness against the weight of the tools. As shown, there was some correspondence between the tool weight and indirect energy coming from the tool itself, which is, at least to some extent, an effect of scale. As such, the mentioned parameters were highly correlated ($R = 0.93$) in the case of the base tool, an association relation which was also true for the indirect energy coming from the harnesses and their masses ($R = 0.77$).

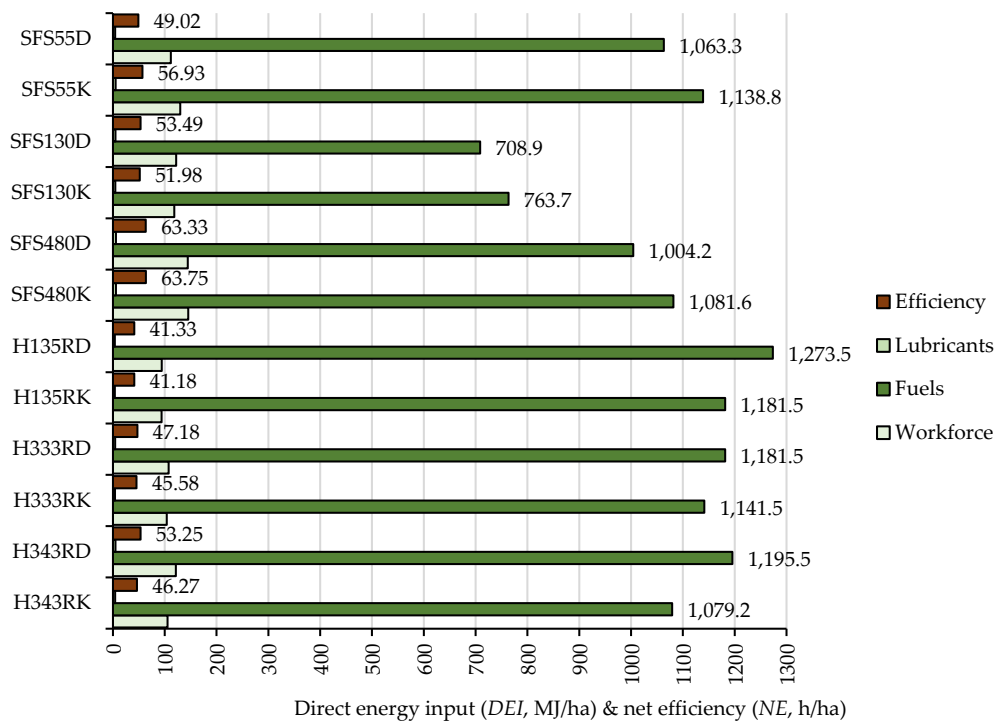
Figure 4b, on the other hand, shows the variation of direct energy inputs as a pairwise comparison with the net efficiency rate. While the energy inputs related to the human labor were completely correlated with the net efficiency ($R = 1.00$), which was an expected effect given the approach used for their estimation, the energy inputs specific to fuel burning were less related to this metric, showing an inverse and weak correlation ($R = -0.36$).

In other words, it seems that the productive performance of operations was not the only factor explaining the amounts of fuels burned and the direct energy inputs coming from this category. Moreover, there could be an inverse association between the two, a fact that is supported by the results shown in Figure 3. Additional factors that may contribute to this kind of variation may rest

at the interaction between the assumptions made for the service life of components and efficiency of operations.



(a)

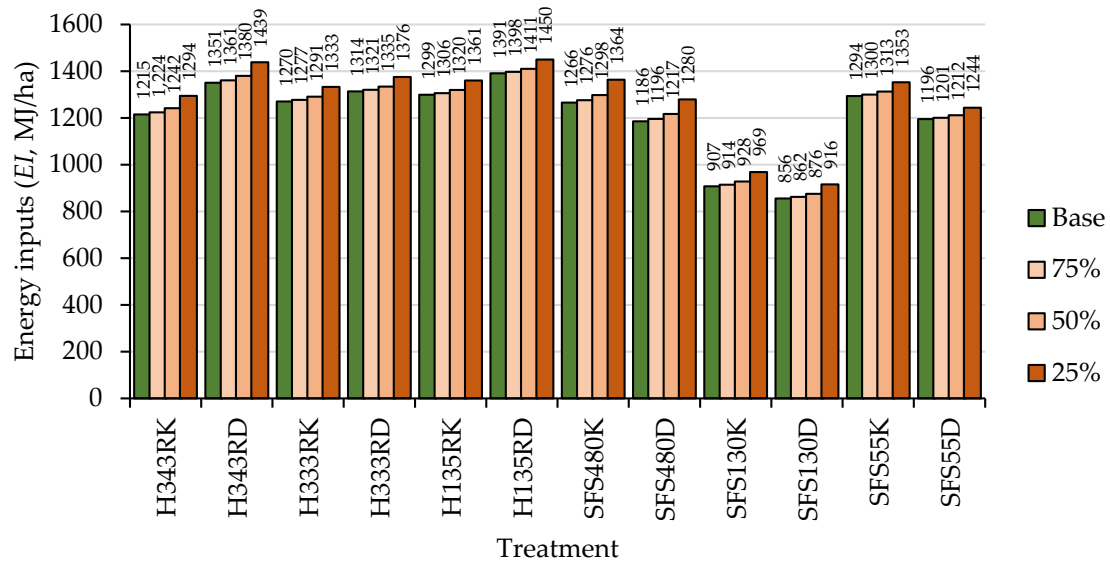


(b)

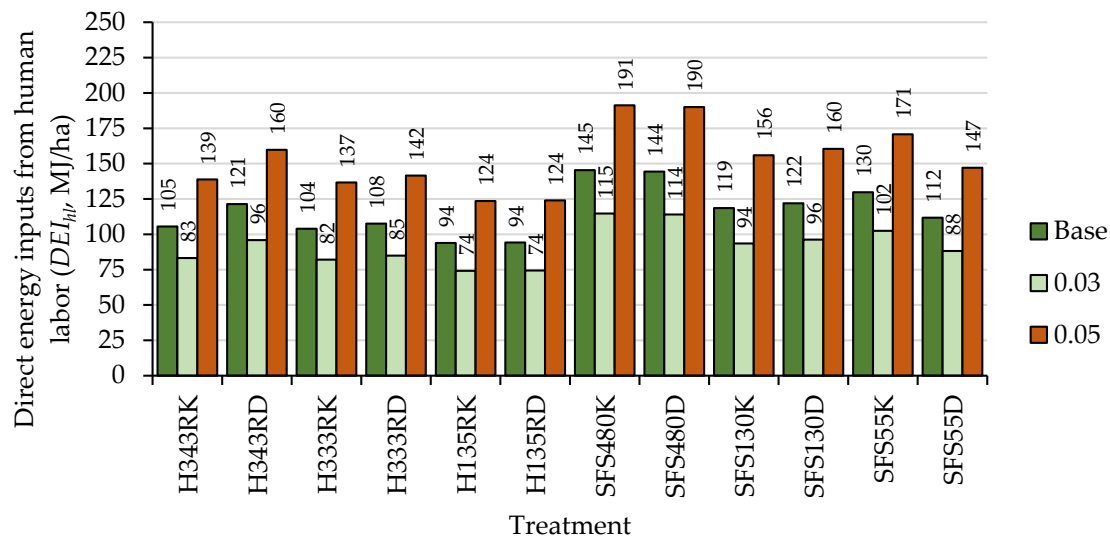
Figure 4. Inter-treatment variation of indirect energy inputs (*IEI*, MJ/ha) and direct energy inputs (*DEI*, MJ/ha) plotted against tool masses (a) and operational efficiency (b), respectively.

3.3. Scenarios and Data Uncertainty

Figure 5 shows the results of the two scenario simulations taken into the study. In regards to the assumptions made on the service life (Figure 5a), these were strongly related to the energy inputs in operations. The magnitude of the latter was also affected to some extent by the efficiency of operations. As such, for a reduction of service life to 75% of that used as a “base scenario”, the increment of EI was rather minor, being in the range of 0.4–0.9%. At the opposite side, for a reduction of service life to 25% of that used in this study, the increment of EI was significant, being in the range of 4.0–7.9%.



(a)



(b)

Figure 5. Effects of assumptions made on the service life (a) and direct energy expenditure due to human labor (b). Legend: Base—results obtained based on the assumptions of this study—“base scenario”, 75%—results obtained based on a reduction of service life by 25%, 50%—results obtained based on a reduction of service life by 50%, 25%—results obtained based on a reduction of service life by 75%, 0.03—results obtained based on a human energy expenditure of 0.03 MJ/min, 0.05—results obtained based on a human energy expenditure of 0.05 MJ/min.

The most evident differences were those associated with the lowest operational efficiencies (SFS480D and SFS480K). The assumptions made for energy expenditure due to human labor affected the figures of the respective direct energy input in a similar way (Figure 5b). The highest differences (positive and negative) were related to the treatments showing the lowest work efficiency. Compared to the “base scenario”, the differences in DEI_{hl} (MJ/ha) were of ca. -21% in the case of 0.03 and of ca. $+32\%$ in the case of 0.05 scenario, respectively.

4. Discussion

The results on productivity metrics found by this study were close to those reported by the national forest work rates which were developed for similar operations, assuming the use of a Stihl tool under the most difficult operational conditions in terms of removal intensity [42]. For such conditions the net productivity rate was set at 0.018 ha/h validating to some extent the average results found by this study (average productivity of 0.02 ha/h). It is worth mentioning that the release cutting operations surveyed by this study were delayed relative to the forest stand age in which they should have been deployed. Under the average conditions of this study, the removed biomass was likely to be less than 5 m³/ha. Assuming this figure, the energy input would be of ca. 0.24 GJ/m³, that is 240 MJ/m³. For comparison purposes, and depending highly on the tree size, assumptions made, and other local conditions specific to motor-manual tree felling and processing by chainsaws, the energy inputs in such operations were found to be in the range of ca. 4–60 MJ/m³ [13,14,16]. For timber winching and skidding operations, one could expect increments in the energy inputs in relation to the wood transportation distance and payload size, to name just a few of the relevant factors. A recent study by Berendt et al. [38] has shown that winching operations by the means of a forest mini-crawler may require energy inputs of ca. 16 MJ/m³ while Vusic et al. [17] have found a significant difference in the energy inputs specific to skidding operations deployed in thinning (ca. 110 MJ/m³) and regeneration cuts (ca. 60 MJ/m³), respectively. Moreover, by a study developed on three cut-to-length harvesting systems, that supposed motor-manual tree felling and processing, followed by the extraction and transport of wood, Picchio et al. [15] have found energy inputs ranging between ca. 430 and 560 MJ/dry ton, with the lower figure being the effect of employing gravity in timber extraction by using chutes.

Since the fuel burning was the process that accounted for most of the energy inputs, it is worth mentioning that the amounts found by this study were quite variable, ranging from ca. 0.25 to 0.55 kg/h, results that are in line with most of the assumptions and figures on fuel consumption given by the producers of tools and by other studies, e.g., [43]. From this point of view, the difference brought by this study is that the fuel consumption was measured in operations, removing this way some of the potential biases related to the fuel consumption figures and showing also a high data heterogeneity. While the hourly fuel inputs in motor-manual operations are generally low due to the small size of the engines used, e.g., [13,44], what really counts for the energy input scalability is the operational efficiency and productivity. In an integrative approach, which considers the timber released to the market as a functional unit, the amount of energy inputs may vary also depending on the technical difficulty of operations and forest growth dynamics. In Sweden, for instance, the amount of fuels burned for silvicultural cleaning, therefore the energy inputs, were found to depend on the geographical location which affects forest growth [2]. However, what is commonly agreed by several studies [15–17,38,45–47] is that fuel burning brings the most important contribution in the energy inputs of forest operations.

The results reported herein, stand for a single intervention by release cutting and are limited to the operational conditions described by this study. This could be interpreted as a first limitation of the study since this kind of operation may be deployed several times (1–3) in the production cycle of a forest, depending on various biological and site factors [23]. Therefore, the real energy inputs will depend on the number of deployments and the changes of operational environment between them (i.e., density and size of the individuals to be removed). To what extent there will be a significant variability in the work performance and energy inputs as an effect of the repeated intervention by this kind of operation needs to be checked by other studies. What is clear, however, is that the operational

conditions found in plots subjected to this kind of silvicultural interventions may affect the work performance [42] and by doing so, they will affect also the energy inputs.

Another effect that needs to be accounted for is that of the assumptions made on service life of the equipment used. This study has used figures based on the local experience which were cross-checked by those reported by others. However, the extent to which these figures will apply to other contexts depends largely on the experience of workers and on what degree a tool is maintained in a good condition. It was found that motor-tools falling in the middle class are better utilized in terms of annual use and require less maintenance, but this applies to chainsaws [40]. That was the reason for which, a simulation was done in this study, revealing significant differences in the energy inputs as an effect of service life, especially for those cases in which the service life was very short (25%) compared to the “base scenario” used here. A good maintenance, on the other hand, will require the use of additional energy as some faulty parts of the tool will be replaced by new ones. This may come as direct (human labor and other inputs associated with maintenance and repairing labor) and indirect (parts to be replaced) energy inputs and will affect the material inventory taken as a reference in this study by adding new components and by dismantling the faulty ones. However, the effect of these assumptions and facts will be less important in the energy balance, at least for the indirect inputs, since they were found to account for ca. 2% in the overall budget of this study; part of the time spent for repairing and maintaining the tool, on the other hand, could disable the use of the tool in operations. Tool manufacturing, which was not included in this study due to missing data, could add to the general energy inputs. A study by Berendt et al. [38] accounted for energy inputs from machine manufacturing processes by a figure of ca. 15 MJ/kg coming from the use of electricity, oil, coal, natural gas, liquefied petroleum gas, district heat, and diesel. By assuming the same figure and the total mass of the tools taken into the study (including the active cutting devices and harnesses), then one may account very well for an addition of ca. 90–140 MJ to the energy input budget, figures which stand for 7.5 to 11.6% more energy inputs. Accordingly, transportation of workers to the sites of operations and back, could add more to the energy inputs and could vary largely in relation to the transportation distance.

Another limitation of this study is that of using the informative data on components, as provided by resellers, which could be biased to some extent. For comparison, Engel et al. [48] have used quite different proportions of the materials embodied in tools but their study referred to chainsaws which hold a different construct concept. However, many studies have concluded that the contribution of indirect energy category in the energy inputs is less important as share, e.g., [38], therefore, biases related to the shifts in the proportions of materials are less likely to significantly affect the general outcomes of the estimates given herein. A similar interpretation may be given to the energy spent by the workers in operations, as a more active operational involvement is likely to require more human energy, a fact that depends also on other factors mentioned in this study. Inter-individual work behavior and performance, on the other hand, are factors that may change significantly the results by their variability, which may cause increments or decrements in the efficiency of work as well as shifts in the fuel consumption. This study assumed a simplified scenario in relation to the utilization rate of the tool; however, calendar events such as the holidays, medical leave, and downtime due to closed operational windows need to be accounted in finer-scale studies.

By taking into consideration the above described limitations, further studies need to be deployed to clarify some important things needed for the attempt to scale the data to the forest production cycle. Problems related to the variability of operational conditions, close-to-real service life figures, accurate tool manufacturing data, exact component shares and masses, human energy spent in labor, data on transportation and maintenance processes, and inter-individual variability of human performance need to be researched in the future to provide more reliable estimates. Until doing so, the results of this study may be used as a reference for the energy requirements in release-cutting operations deployed in broadleaved forests and they could be important for the science and practice since such forests are spread on large territories in Europe and around the world [49].

5. Conclusions

Motor-manual release cutting operations implemented by the means of brushcutters are important contributors to the energy budget of forest operations, as they may account for ca. 1.2 GJ/ha for a single operational intervention. This means that one could expect much higher values if the release cutting operations will be deployed according to silvicultural guidelines in terms of number of interventions per production cycle of such broadleaved forests. Specifically, fuel burning was the greatest contributor to the energy inputs of release cutting operations, by a share as high as 83–92%. The factors which were found to explain these outcomes were the size of operated area and the number of individuals removed which affected proportionally the productive time consumption and have reflected themselves in the work efficiency. Higher work efficiency rates transposed in higher direct energy inputs from human labor and fuel use while the contribution of indirect energy inputs to the overall budget was less than 2%. In general, the outcomes of this study were found to be less related to the size of tool and type of cutting device used in operations. The results reported herein apply to the operational conditions described by this study and for a better data scalability other problems need to be researched in the future mainly to address data variability given by operational conditions and inter-individual operational behavior since these hold the highest potential to affect the performance of operations and the fuel inputs.

Author Contributions: Conceptualization, N.B. and S.A.B.; data curation, N.B.; formal analysis, S.A.B.; investigation, N.B.; methodology, N.B. and S.A.B.; resources, S.A.B.; writing—original draft, S.A.B.; writing—review and editing, S.A.B. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Acknowledgments: The authors acknowledge the technical support of the Department of Forest Engineering, the Forest Management Planning and Terrestrial Measurements, the Faculty of Silviculture and Forest Engineering, and Transilvania University of Brasov in developing this study. The authors would like to thank the persons involved in field data collection and to the forest managers from the region of study for agreeing and granting the permits needed to carry on the field study.

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

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