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Review

The State of the Art of Forest Operations in Beech Stands of Europe and Western Asia

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Abstract: Beech (*Fagus* spp.) is one of the most common tree species in Europe and Western Asia. The implementation of sustainable forest Operations (SFOs) in beech forests is therefore crucial in terms of sustainable forest management. This review summarises the state of the art concerning time-motion studies carried out in beech forests, defining the work productivity and the related costs of different harvesting systems applied in these stands. The main focus in recent years on felling and processing operations has been the introduction of fully mechanised systems in beech forests, obtaining satisfactory results in terms of work productivity. However, the working performance is still lower than in coniferous stands. Skidding and forwarding resulted in suitable techniques for ground-based extraction, both showing a clear inclination towards increasing working performance when applying higher levels of mechanisation. Aerial extraction by cable yarders is particularly important in beech forests, considering that these are often located in steep terrains. Further efforts should be dedicated to enhancing the training for operators to extend the application of aerial extraction systems, which ensures good levels of work productivity and limited soil disturbances. In summary, this review aimed to give a clear insight into forest operations in beech forests which could be useful for forest managers, forest engineers and researchers in the sector of sustainable forest operations.

Keywords: sustainable forest operations; work productivity; harvesting costs; fully mechanised harvesting; skidding; forwarding; aerial extraction systems

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1. Introduction

Beech, here meant as *Fagus sylvatica* L. and *Fagus orientalis* Lipsky, is the most important and widespread broadleaf species in Europe and Western Asia [1,2]. Beech grows in a wide range of different environments. It is remarkable to observe that in Central Europe it is a component of lowland and highland [3,4] forests, while in the Mediterranean context, it often represents the timberline [5–7]. Beech forests play a primary role in the context of climate change mitigation [8–10] and biodiversity conservation [11]. They are also primary sources of timber and firewood [12,13].

The implementation of proper and sustainable management of beech forests is crucial to preserving all the ecosystem services they provide [14]. Putting into practice sustainable forest operations (SFOs) is one of the main aspects in the context of sustainable forest management (SFM) [15]. The term sustainability refers to the goal of achieving social well-being, without compromising environmental resources, through fair economic well-being [16]. It is therefore a concept based on three main aspects, the so-called pillars of sustainability—the economy, the environment and society [17]. The terms of SFOs particularly refer to the application of cost-effective logging that does not compromise environmental wellness and ensures safe and ergonomic working conditions for the operators [18]. SFOs in beech forests are of primary importance, considering some particular features of these stands. Beech forests are indeed often located in steep terrains [19]. Moreover, the architecture of beech trees still represents a challenge for fully mechanised harvesting systems [20].

In consideration of the importance of these forests, this paper aims to define the state of the art in the framework of forest operations in beech stands, summarising the results of the various time-motion studies that have been carried out in beech forests in the last 20 years (2003–2022). The purpose of the review is to give the readers a comprehensive framework of work productivity, associated costs and main issues to be solved regarding the various harvesting systems that are currently applied in beech forests, also with the aim of proposing future research directions in the topic. Following this introduction, there is a section on materials and methods that describes the literature search criteria. Then, there are two sections, one for felling—processing and one for bunching—extraction. The manuscript concludes with suggestions for future research.

2. Materials and Methods

The first step in a literature search was to consult the Web of Science and Scopus. Further documents, in particular conference proceedings and technical reports, were found through the Google Scholar database. The applied research keywords were: beech; *Fagus* spp.; forest operations; work productivity; time consumption; costs; logging; harvesting; skidding; forwarding and yarding. These keywords were related to the Boolean operators AND and OR. Then the snowball approach was used to find further sources of literature, starting from the reference lists of some of the most recent publications on the topic. The final selection was limited to papers in English published from 2003 to 2022.

Further selection was made after reading the titles and abstracts and finding specific criteria, which were: the paper must report the values of work productivity of a given harvesting system measured by time-motion studies; beech must be the main species of the stand with at least 50% in terms of the number of individuals, basal area, and standing volume; work productivity can be reported in PMH (productive machine hours, excluding delay time) or SMH (scheduled machine hours, including delay time), but the kind of productivity has to be clearly specified in the manuscript. As a result, there were 41 papers identified as suitable to be included in the topic of the review.

The percentage of papers dealing with the different forest operations and the geographical distribution of the various investigated studies are reported in Figures 1 and 2, respectively. A consistent part of the studies dealt with bunching-extraction operations, with skidding, which was the most often applied extraction technique, followed by cable yarding, while forwarding was the least investigated. Regarding felling-processing operations, motor-manual and mechanised felling and processing at the stump were equally investigated, while less attention was given to processing operations at the landing site (Figure 1). The highest number of papers were from Italy (9), followed by Turkey and Germany (5) (Figure 2).

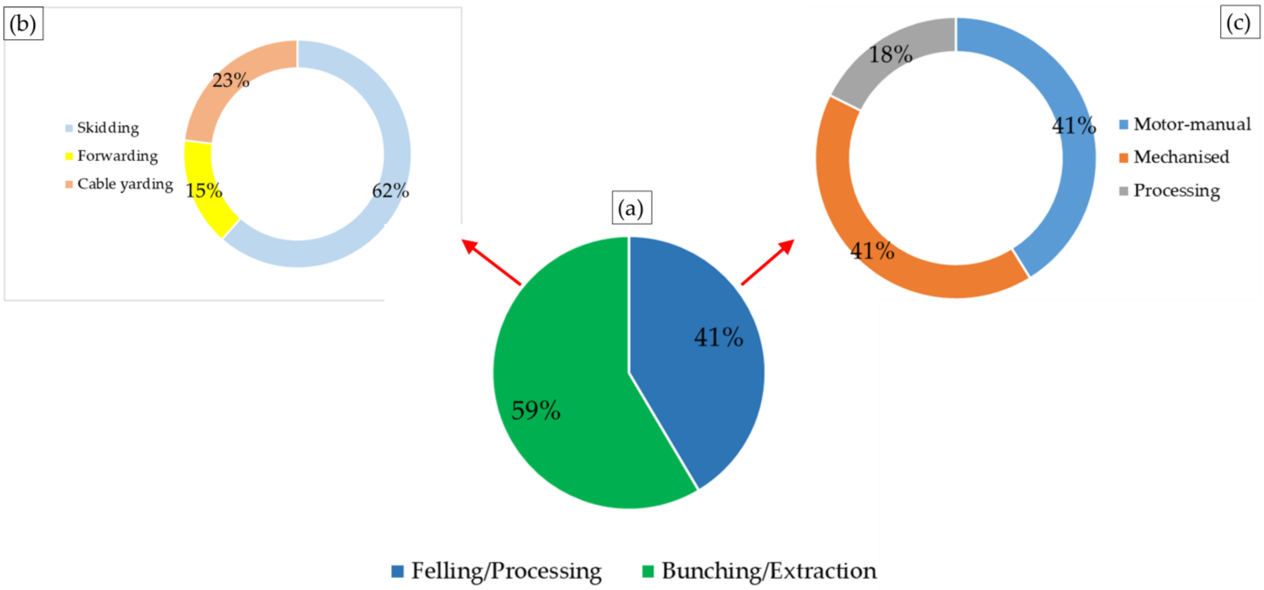

Figure 1. Summary of forest operations in beech forests from the investigated literature. (**a**) Percentage share of the investigated studies between studies dealing with felling-processing and bunching-extraction. (**b**) Percentage share of studies dealing with bunching-extraction, i.e., studies dealing with skidding, forwarding and cable yarding operation. (**c**) Percentage share of studies dealing with felling-processing, i.e., studies dealing with motor-manual felling-processing operations, mechanised felling-processing operations and processing operations at the landing site.

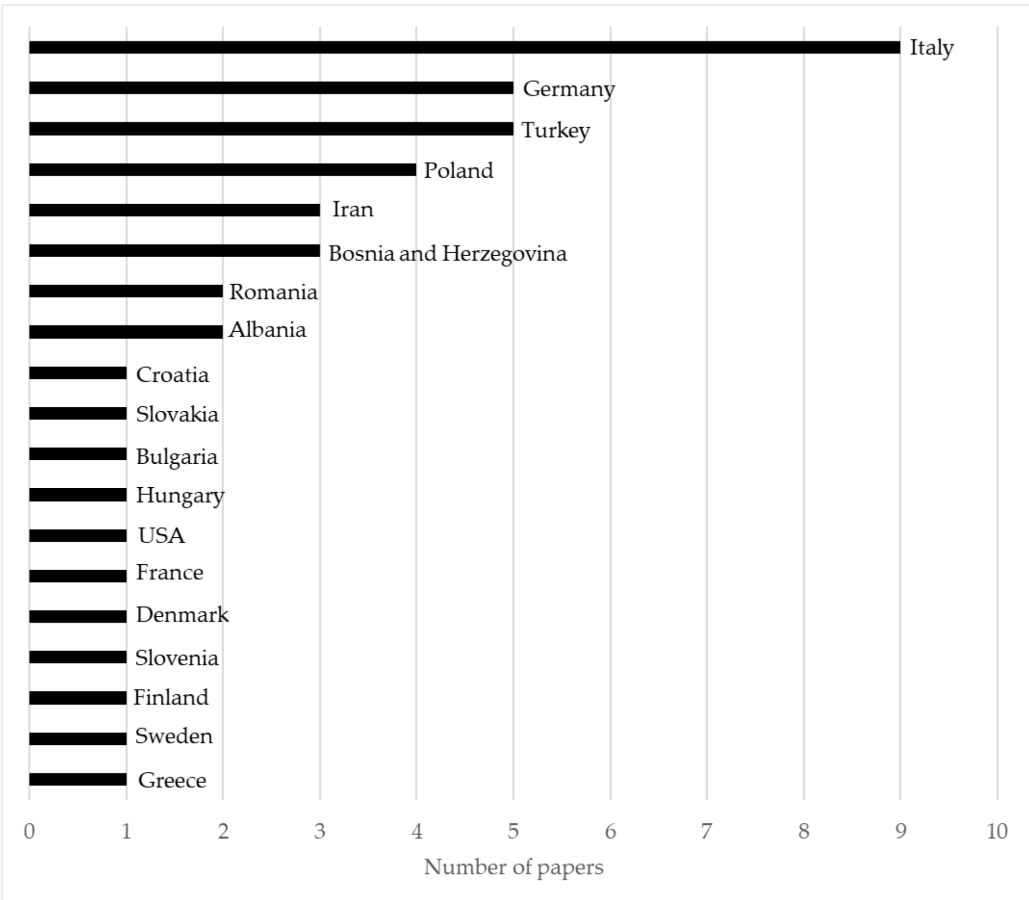

Figure 2. Distribution of the investigated studies among countries.

3. Felling and Processing Research Results

3.1. Motor-Manual Felling and Processing

Although in recent years there has been more and more interest in the application of fully mechanised harvesting methodologies in broadleaf stands [20], motor-manual felling by chainsaw is still the most important and applied methodology in beech forests [21]. Work productivity of motor-manual felling in beech stands strongly depends on the kind of intervention and on the dimension of the felled trees. As expected, thinning interventions in young stands with low-diameter trees resulted in lower productivity and higher costs per biomass unit in comparison to felling larger trees in single-selection cutting interventions.

In thinning interventions, work productivity for felling and processing by applying the cut-to-length (CTL) system was reported to be in the range of 0.40–3.50 m^3 SMH^{-1}, mostly depending on the average dimension of the felled trees [22,23]. Work productivity and related costs can be decreased by applying alternative harvesting systems, for instance the Tree Length System (TLS). This consists of just a preliminary pre-processing at the stump by removing tops and branches, while final processing is carried out at the landing site [24], where easier working conditions such as flat terrain and open space facilitate the operation. In thinning interventions in even-aged beech stands, felling and processing costs were in the range of EUR 8 m^{-3} applying the short wood system (SWS) with an average tree dbh (diameter at breast height) of 20 cm and EUR 1.80 m^{-3} applying TLS with an average tree dbh of 70 cm [24]. A similar price of EUR 8.58 m^{-3} was reported for felling and processing operations for beech stand thinning, with an average tree dbh of 21 cm [25].

Work productivity was much higher in selection-cutting intervention, mostly as a consequence of the bigger dimensions of the trees. In this case, working productivity can reach 20.6 m^3 SMH^{-1} and 56.5 m^3 PMH^{-1} by the application of the CTL system [26,27]. A recent study also investigated the use of the electric chainsaw for cutting different woody species [28]. For all the species, the level of performance of the electric chainsaw was lower than with a petrol chainsaw of similar power, but interestingly, beech was the species in which the gap was relatively large, suggesting that several technical optimisations of this kind of machine are needed to apply the electric chainsaw for cutting beech trees [28].

3.2. Mechanised Felling and Processing

Fully mechanised harvesting methodologies, for example, feller-bunchers (machines that cut and pile the trees) or harvesters (machines that are also able to perform the processing operation), were initially developed and applied in coniferous stands, but nowadays there is increasing interest in introducing them in broadleaf forests. These methodologies have shown higher work productivity and better ergonomic conditions for forest operators [29]. However, harvesting and processing timber from broadleaved species is more difficult than from coniferous tree species, as a consequence of thicker branches and higher wood density [20].

While the application of feller-bunchers is somewhat easier, not implying processing operations, there are major challenges with regard to the introduction of harvesters for broadleaf species logging. There are two possible approaches to performing this task. The first one consists of applying modified harvester heads, designed for multi-stem harvesting [30], while the second approach consists of applying conventional harvester heads but changing the way branches are separated from the main stem. Branch separation from the main stem is indeed no longer performed with the pivotable gripping arms but instead with the chainsaw used for tree felling by placing the felling head on the branch to be removed [31]. Currently, there are no initiatives to develop harvester heads that are specific for broadleaf logging [20]. Therefore, the literature on studies of the application of harvesters in beech stands all refer to the second approach described above, i.e., the application of conventional harvesters.

The values of working productivity presented in the current literature are, as also happens for motor-manual felling, largely dependent on the dimensions of the felled trees. The range is particularly high; in particular, the lowest productivity of about 3.5–6.0 m^3 SMH^{-1}

was reported in thinning interventions with trees 8–10 cm dbh and about 110 m^3 ha^{-1} of standing volume [32], in line with the 5.35 m^3 SMH^{-1} reported by Slugeň et al. (2014) working with bigger trees but in slope class II (about 20%) [33]. Higher values of 10.4 m^3 SMH^{-1} were observed by Horváth et al. (2012), with an average dbh of felled trees of 27 cm [31]. The highest values of working productivity were instead given by two different studies carried out in Germany by Labelle et al. (2018; 2019), with working productivity ranging from 28 to 43 m^3 PMH^{-1} working with trees over 35 cm dbh [34,35]. The authors reported, however, only values of net productivity and highlighted significantly lower performance (31% decrease) in comparison to the same harvester working in a spruce stand [35]. Finally, the only study found in the literature, regarding the application of feller-bunchers for whole-tree harvesting of beech trees for bioenergy purposes, revealed an impressive productivity in the range of 60–75 m^3 SMH^{-1} [36], further highlighting how the main bottleneck for the application of fully mechanised systems in beech stands is processing rather than felling.

3.3. Processing at the Landing Site

To the best of the authors' knowledge, there was limited data on processing operations at the landing site, with only three studies found in the reference period for the present review. All these studies focused on processing beech wood for energy purposes, specifically two for the production of firewood and one for wood chips.

Comparing the productivity of five firewood processing machines, Manzone and Spinelli (2014) reported productivity ranging from 1.1 to 2.1 $t_{f.m.}$ SMH^{-1} (tonnes of fresh material per SMH), resulting in processing costs in the range between EUR 20 and 39 $t_{f.m.}{}^{-1}$ [37]. Higher productivity was shown for the processing of firewood by chainsaw at the landing site and with the application of a harvester. Four chainsaw operators reached a productivity of 7.4 $t_{f.m.}$ SMH^{-1} and the harvester 14.7 $t_{f.m.}$ SMH^{-1}, resulting in processing costs of EUR 19.20 and 12.00 $t_{f.m.}{}^{-1}$ respectively [38]. Wood chip production from beech logs by a drum chipper powered by a 95 kW farm tractor showed a higher productivity of 23.71 m^3 SMH^{-1} [39]. It is interesting to note that processing operations, which are often not considered as much as felling and extraction by scientific time-motion studies, represent a significant cost in the overall production of beech wood, mostly when dealing with fuel wood.

3.4. Summary Table

The numerical results of the various studies dealing with felling operations are given in Table 1. Productivity using a chainsaw showed a high range of variability, ranging from about 1 m^3 SMH^{-1} [22] to more than 20.6 m^3 SMH^{-1} [26]. High variability was also shown by mechanised systems, with values ranging from 3.3 [32] to 75 m^3 SMH^{-1} [36].

Table 1. Summary of data from the reviewed studies dealing with felling operations. Empty cells indicate that that parameter was not immediately retrievable from the given study.

Intervention	Machinery	Wood System	Average dbh (cm)	Slope Class *	Productivity (m^3 SMH^{-1})	Cost (EUR m^{-3})	Notes	Reference
Group selection	Chainsaw	SWS–TLS	21–35	II–III		1.80–8.00	Lower productivity for SWS method	[24]
Single selection	Chainsaw	CTL	88	I–III	20.6	1.05		[26]
Thinning	Chainsaw	CTL	20–50	II	0.40–1.75			[22]

Table 1. *Cont.*

Intervention	Machinery	Wood System	Average dbh (cm)	Slope Class *	Productivity (m^3 SMH^{-1})	Cost (EUR m^{-3})	Notes	Reference
Thinning	Chainsaw	CTL	50–60	III	3.50			[23]
Thinning	Feller-buncher	WTH			60–75			[36]
Selective regeneration cutting	Harvester	CTL	27		10.4			[31]
Thinning	Harvester	CTL	8–10	I	3.3–5.6			[32]
Thinning	Harvester	CTL	35–50	I	29–43		Data refer to net productivity	[34]
Thinning	Harvester	CTL	30–39	I	28–29		Data refer to net productivity	[40]
Thinning	Harvester	CTL	22–27	I	5.35			[33]

* Slope classes: I class—0%–20%; II class—20%–40%; III class—40%–60%.

4. Bunching and Extraction Research Results

4.1. Skidding and Hauling

Skidding is an extraction technique that implies partially or fully dragging logs on the soil [41]. It has been the most investigated technique concerning forest operations in beech stands. In the literature database for this review, skidding was studied for different levels of mechanisation, ranging from extraction by animals to forestry-fitted farm tractors and to specific forest machineries such as cable or grapple skidders.

Extracted timber amount and extraction distance were the factors that had a major influence on work productivity.

The lowest productivity for skidding operations in beech stands was found in a salvage logging intervention in Iran after windthrow, with values of 1.54 m^3 SMH^{-1}. Such a low value is obviously related to the fact that the intervention was salvage logging, with downed trees that negatively influenced working performance [19].

In conditions of comparable extraction distance and terrain slope, there is, as expected, a growing trend of productivity moving from a low to a higher mechanisation level.

For instance, with logging interventions in slope class II (20%–40%) and a 100 m extraction distance, skidding by animals showed a productivity of 3.8 m^3 SMH^{-1}, while skidding with a forestry-fitted farm tractor equipped with a winch achieved values of 6.25 m^3 SMH^{-1} [42]. Slightly higher values of 8.85–14.58 m^3 SMH^{-1} were revealed by a forestry-fitted farm tractor equipped with a winch working in slope class II and with an extraction distance of 55 to 105 m, resulting in an average skidding cost of EUR 6.60 m^{-3} [43,44]. Similar performance and skidding costs were shown by a study carried out in the same region with similar machinery [45].

With increasing skidding distance to about 200–300 m and smaller tree dimensions skidding productivity by a forestry-fitted farm tractor decreased to about 2–4 m^3 SMH^{-1}, with related skidding costs which can reach EUR 10–15 m^{-3} [46,47].

Increasing the level of mechanisation further increased productivity levels. In fact, the application of cable skidders instead of forestry-fitted farm tractors allowed keeping productivity levels at about 2–9 m^3 SMH^{-1}, also at skidding distances higher than 500 m and up to 1700 m, with costs of EUR 4–7 m^{-3} in thinning and group selection interventions [22,48,49]. At lower skidding distances of 200–300 m and in interventions in mature stands with large-dimension trees, the productivity of cable skidders was much higher, i.e., 14.7 m^3 SMH^{-1}, but lower than for grapple skidders, which can reach up to 32.8 m^3 SMH^{-1} working in the same conditions [50].

Some studies also reported the performance of two innovative machineries to perform merely the bunching operation by winching (hauling), that is, bringing the logs from the stand to the closest road and then transporting them by forwarding to the landing site. The first study investigated the performance of a prototype of a winch that can be installed on an excavator to winch logs in steep terrains (40% and higher), showing productivity of 7.6–8.5 m^3 SMH^{-1} for a winching distance of 27–55 m [51]. The second study investigated instead the working performance of remote-controlled mini forestry crawlers to perform the same task described above, achieving a productivity of 6.55 m^3 SMH^{-1} [25]. Interestingly, both solutions showed a better performance than a conventional forest winch installed on a forestry-fitted farm tractor working at a winching distance of 50 m [52].

4.2. Forwarding

The forwarding technique consists of extracting logs from a loading deck without direct contact with the ground. Only three studies dealing with forwarding were identified in the literature database of the present review; two of them investigated the performance of a proper forwarder, while another studied the productivity of the forwarding technique applied with low (animals) and medium (mini tractors) levels of mechanisation.

Forwarding logs of beech wood one meter in length by animals on terrain slope ranging from 15% to 40% and for an extraction distance of 55–950 m, resulted in an average productivity of 3.53 m^3 SMH^{-1}, while the same assortment extracted by forwarding with mini tractors on slopes of 10%–20% and extraction distances of 270–360 m resulted in gross working productivity of 2.47 m^3 SMH^{-1} [53].

Regarding the application of a high mechanisation level, i.e., using a forest forwarder, Suadicani and Talbot (2010) reported a productivity of 9.5 m^3 SMH^{-1} for forwarding beech sawlogs and firewood with an extraction distance of 68 m in flat terrain, corresponding to an extraction cost of EUR 9 m^{-3} [54]. Higher productivity, even with a much higher extraction distance of about 1 km and with a terrain slope of 25%, was reported by Zimbalatti and Proto (2010), which showed about 15 m^3 SMH^{-1} for forwarding operations by the forwarder in shelterwood interventions in beech stands in Southern Italy [55]. This suggests the high suitability of forwarders in beech stands, also in terrains that are not flat, and their ability to achieve high work productivity in different working conditions.

4.3. Aerial Extraction Systems

Since beech forests are often located in steep terrains, aerial extraction systems were largely investigated in this kind of stand. In particular, the productivity and costs of cable yarders in logging interventions in beech forests were the focus of six papers in the reference period for this review. Also for cable yarders, yarding distance and extracted volume were the major influencing factors for work productivity. Mini cable yarders suitable for thinning interventions in the framework of small-scale forestry achieved a productivity of 1.5–2.4 m^3 SMH^{-1}, resulting in yarding costs of EUR 24–30 m^{-3} in thinning interventions in a beech stand located in slope class III (40%–60%) with a yarding distance of about 100 m [56]. With the same yarding distance, more powerful models are able to achieve productivity higher than 10 m^3 SMH^{-1} [42] or have similar productivity but with yarding distances four times longer [57]. However, both for mini yarders and regular ones, downhill extraction shows lower working productivity than uphill extraction [56,57]. Working productivity in group shelterwood interventions was much higher, thanks to the higher dimensions of the trees, with 8.8 m^3 SMH^{-1} and 8.41 m^3 SMH^{-1} reported, respectively, by Munteanu et al. (2019) with a yarding distance of 326 m [58] and Stoilov (2021) with yarding distances of 160–250 m [59]. The same studies reported yarding costs for group shelterwood in beech forests in the range between EUR 7 m^{-3} and EUR 13 m^{-3} [58,59]. One study also analysed the working productivity of a cable car unconventionally applied for beech timber extraction in Albania. With yarding distances of 800–900 m and in a clear-cut intervention, this unconventional system reached a productivity of 4.73 m^3 SMH^{-1} [23].

4.4. Summary Table

Data retrieved from the various studies dealing with extraction operation are given in Table 2. Both for skidding and forwarding work productivity increased moving from small-scale systems to modern forest machinery. Forwarding productivity ranged from values of about 2.5 m^3 SMH^{-1} for small-scale systems [57] to 15 m^3 SMH^{-1} for modern forwarders [55]. Skidding productivity ranged from about 1.5 m^3 SMH^{-1} in salvage logging interventions [19] to more than 30 m^3 SMH^{-1} in final shelterwood cuttings [60].

Table 2. Summary of data from the reviewed studies dealing with extraction operation. Empty cells indicate that that parameter was not immediately retrievable from the given study.

Intervention	Extraction Technique	Extraction System	Wood System	Average dbh (cm)	Slope Class *	Extraction Distance (m)	Productivity (m^3 SMH^{-1})	Cost (EUR m^{-3})	Notes	Reference
Selection cutting	Forwarding	Animals	CTL	15–20	II	55–950	3.53			[42]
Thinning	Forwarding	Forwarder	CTL	36	I	68	9.5	9		[54]
Shelterwood	Forwarding	Forwarder	CTL		II	1000–1100	14–15			[55]
Selection cutting	Forwarding	Mini tractors	CTL	15–20	I	270–360	2.47			[53]
Thinning	Hauling	Forestry-fitted farm tractor with winch	TLS	15–30		50	1.92–4.54			[42]
Thinning	Hauling	Prototype for winching logs	CTL		III	27–55	7.6–8.5	14.1–15.7	Values refer only to winching operation	[51]
Thinning	Hauling	Remote-controlled mini forest crawler	WTH	21	I–III	17.5	6.55	13.93		[25]
Selection cutting	Skidding	Animals	CTL	20–50	II	100	3.80			[42]
Group selection	Skidding	Cable skidder	SWS–CTL	21–35	II–III	500	2.68–3.12	4.50–7.03	Lower productivity values and higher cost for SWS wood system	[61]
Group shelterwood	Skidding	Cable skidder	TLS		I	1700	3.12			[48]
Salvage logging	Skidding	Cable skidder	CTL	58	II	308	1.54			[19]
	Skidding	Cable skidder	CTL		I	490	3.41–9.13			[49]
Final shelterwood felling	Skidding	Cable skidder	TLS	42–48	I	200–300	14.70			[50]

Table 2. *Cont.*

Intervention	Extraction Technique	Extraction System	Wood System	Average dbh (cm)	Slope Class *	Extraction Distance (m)	Productivity (m^3 SMH^{-1})	Cost (EUR m^{-3})	Notes	Reference
Thinning	Skidding	Forestry-fitted farm tractor with winch	CTL	20–50	II	100	6.25			[42]
Thinning	Skidding	Forestry-fitted farm tractor with winch	CTL		II	55–105	8.85–14.85	3.50–9.60		[43]
Thinning	Skidding	Forestry-fitted farm tractor with winch	CTL	22		25–250	1.75–2.70	9.18–14.19		[47]
Thinning	Skidding	Forestry-fitted farm tractor with winch	CTL		II–III	140–320	7.70–11.35	4.50–8.60		[45]
Selection cutting	Skidding	Forestry-fitted farm tractor with winch	CTL	30	II	216	3.70	9.90		[46]
Thinning	Skidding	Grapple skidder	CTL	20–50	II	1200	1.80–2.15			[22]
Final shelterwood felling	Skidding	Grapple skidder	TLS	42–47	I	200–300	21.00			[60]
Final shelterwood felling	Skidding	Grapple skidder	TLS	42–48	I	200–300	32.80			[50]
Clear cut	Yarding	Cable car		40	II–III	800–900	4.73			[23]
Selection cutting	Yarding	Cable yarder	CTL	20–50	II	100	10.09			[42]

Table 2. *Cont.*

Intervention	Extraction Technique	Extraction System	Wood System	Average dbh (cm)	Slope Class *	Extraction Distance (m)	Productivity (m^3 SMH^{-1})	Cost (EUR m^{-3})	Notes	Reference
Thinning	Yarding	Cable yarder	CTL	40	II	400	1.69–4.08		lower productivity values for downhill yarding	[57]
Group shelterwood	Yarding	Cable yarder	CTL	60	II	326	8.80	7.40		[58]
Group shelterwood	Yarding	Cable yarder	CTL	34	III	160–250	8.41	13.00		[59]
Thinning	Yarding	Mini cable yarders	WTH	17–19	III	67–118	1.50–2.40	24–30		[56]

* Slope classes: I class—0%–20%; II class—20%–40%; III class—40%–60%.

5. Conclusions

The plethora of different stand characteristics and localisations that are typical of beech forests imply great variability in harvesting productivity and related costs. Taking into account this great variability, this review aimed to summarise the findings in terms of time-motion studies conducted in beech forests in the last 20 years.

The main findings and related suggestions for future research can be summarised as follows:

- Although motor-manual felling and processing by chainsaw are still predominant, a growing interest is expected towards the introduction of fully mechanised methodologies (fellers and harvesters) in beech forests. Research on this topic has been productive in recent years, highlighting that mechanising felling and processing operations in beech stands is possible, but that there are still different issues to be solved to achieve the productivity levels typical of these machineries in coniferous stands. The development of dedicated harvester heads specifically for broadleaf species is still far from being realised, and there are actually no research initiatives on this topic [20]. Therefore, the efforts of researchers and forest managers should be directed towards increasing the technical skills of forest operators in working with harvesters with conventional heads and applying modern technologies such as augmented reality, which can ensure effective training without compromising the safety of beginner operators [62].
- The introduction of fully mechanised felling and processing operations in beech stands is not only limited by the intrinsic characteristics of beech trees, but also by the fact that beech stands are often located in steep mountainous terrains, mostly in the Mediterranean and Western Asia zones. In light of this, it should be interesting to implement and scientifically test the economic and environmental performance of winch-assisted harvesting in beech forests. Winch-assist systems have been proven to be suitable for introducing full mechanical harvesting in difficult terrain conditions, increasing both work productivity and ergonomics for the operators [63]. Furthermore, it is interesting to observe that these systems generally show lower soil disturbance as compared to traditional harvesting systems [64]. Therefore, their introduction in the framework of beech silviculture, after proper scientific evaluation and subsequent training of the operators, could be beneficial for the implementation of SFOs in beech forests.
- Concerning ground-based extraction, different techniques and machineries are suitable for beech stands. Both skidding and forwarding reached comparable productivities under similar working conditions. As expected, the higher the mechanisation level, the higher the productivity. However, further time-motion studies are welcome to extend the amount of literature for comprehensive reviews and meta-analyses of the topic [65]. It is important to compare different ground-based extraction options from an environmental point of view, understanding at a deeper level the implications that a given extraction system has on various aspects of forest ecosystems, which include soil, biodiversity, natural regeneration and ecological processes [66–69].
- Aerial extraction via cable yarders is a recommended solution in the case of harvesting in steep terrains. Besides satisfactory work productivity, these methodologies can limit soil disturbances, mostly when working with fully suspended loads [70]. It is therefore imperative to comprehend that operator training is fundamental to encouraging the use of these harvesting systems in the context of SFOs in beech forests.

In conclusion, this work has sought to define the state of the art in the framework of forest operations in beech stands. The results of 41 papers of a high scientific level were gathered. The criteria of choice included time-motion studies that have been carried out in beech forests in the last 20 years (2003–2022). It is worth highlighting that we referred to publications in the English language; it is possible that other similar works could have been published in different languages or, however, are not available from the investigated repositories; this represents the main limitation of this review.

The findings, however, provide a better understanding of harvesting systems for beech stands, namely the work productivity and associated costs, and they also highlight the main issues that still remain unsolved.

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