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Benchmarking operational conditions, productivity, and costs of harvesting from industrial plantations in different global regions

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ABSTRACT

There has been a global increase in the demand for woody biomass in the last decade. The imperative to achieve the highest production per unit of land while preserving natural forest resources has expanded intensive forest cultivation in industrial plantations. The development of a global bioeconomy is expected to further increase the demand for biomass for material and energy use from industrial forest plantations. Efficiently planning supply from these timber sources requires up-to-date information on current harvesting systems. This study aims to provide an overview of existing systems and their performance in industrial plantations located in seven relevant global regions. Eight regional experts combined knowledge, supported by relevant literature, to create a unique database for benchmarking harvesting systems regarding their productivity and supply costs. Current mechanized systems can reach harvesting productivity exceeding 100 m^3 per productive machine hour (PMH), while roadside costs range between 5 and 20 USD m^{-3} solid volume. Harvesting systems are modified continuously to adapt to plantations' characteristics and industrial requirements in the different regions. Local socioeconomic factors and the historical sectorial evolution in each region significantly impact the selection of harvesting systems, mechanization levels, type of machinery, and resulting harvesting costs. Expanding plantations to more marginal lands requires further research on adapting agricultural/construction machinery to steep terrain plantations. International literature tends to represent large-scale, highly mechanized systems well. In contrast, fewer studies are available for characterizing small-scale systems, particularly in developing regions.

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Forest operations; productivity; costs; industrial plantations; roundwood; benchmarking

Introduction

There has been a growing global demand for wood for material and energy uses in the past decades (FAOSTAT 2020). The need to achieve high production per unit of forest land while preserving natural forest resources has led to the development of intensified forest cultivation modules based on fast-growing species, densely planted and managed with a high input level, capable of maximum returns. These forests fall under the definition of "forest plantations." More specifically, in this study, "industrial plantations" are defined according to Jürgensen et al. (2014) as "Forests of primarily introduced and native species, established through planting or seeding mainly for the production of wood or nonwood products."

Industrial plantations differ fundamentally from natural forest stands since they serve different ecological, economic, and social functions. More specifically, Industrial plantations are commercially planned for optimum woody biomass production in monocultures, where *Pinus, Eucalyptus, Populus, and Acacia* are the most common commercial species (FAO 2006).

The supply of roundwood from this forest category has increased significantly recently, reaching an estimated volume of 561 M m^3 in 2012, representing 33.4% of the global roundwood annual harvest (Jürgensen et al. 2014). The first ten countries in order of wood supply from plantations were identified to be Brazil, the United States, China, India, Chile, New Zealand, Australia, South Africa, Thailand, and Indonesia (Jürgensen et al. 2014).

According to the INDUFOR Databank, the global area of these plantations reached 54 Mha in 2012, with the US (13 Mha), China (7 Mha), and Brazil (7 Mha) having the most extensive areas (Barua et al. 2014). A recent remote sensing mapping of "industrial plantations" estimated that seven tropical countries reached approximately 10 Mha by 2014 (Petersen et al. 2016). However, uncertainties still exist in mapping current industrial plantation areas and their regions.

The expansion of industrial plantations is expected to increase in the next decades. According to FSC/INDUFOR (2012) projections, the area dedicated to "industrial plantations" could reach 91 M ha by 2050, almost doubling the current existing area. Under these conditions, it is expected

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that industrial plantations could supply between 1 and 2 billion m^3 per year, thus meeting more than 50% of the global roundwood demand by 2050 (FSC/INDUFOR 2012). In addition, under ambitious climate change mitigation targets, the production of wood from industrial plantations could increase to approximately 3–4 billion m^3 by 2050 (Lauri et al. 2017).

Harvesting operations in plantations can contribute to 30–40% of roundwood production cost (i.e. including tree establishment, cultivation and harvesting) (Barrios et al. 2008; Bendlin et al. 2016). Together with road transportation, they can account for over 50% of the final wood production cost (Minette et al. 2008; Machado et al. 2014; Favreau and Ristea 2017) and sometimes exceeding 70% (Pulkki 2001).

The homogeneity of plantation systems and the generally favorable terrain conditions in which they are established are ideal for mechanizing harvesting operations to maximize efficiency and minimize wood supply costs (Zhang et al. 2019). However, expanding industrial plantations has led to planting trees in sites that are more difficult to mechanize, such as steeper slopes and environmentally sensitive areas. Accordingly, there is a growing interest in designing new harvesting systems and machinery for plantations that can operate in increasingly challenging site conditions (McEwan et al. 2020).

Therefore, the geographical allocation of future plantation investments requires a better understanding of current harvesting systems, their performances, and related costs. In this context, a comparison of different global regions is necessary to reveal both similarities and differences though-benchmarking exercises, where the competitiveness is evaluated from different perspectives (Siry et al. 2006; Cubbage et al. 2010, 2014; Lundbäck et al. 2021). In the case of wood harvesting, some international benchmarking examples under standardized cost accounting methodologies have recently been reported (Di Fulvio et al. 2017; Ghaffariyan et al. 2017).

Thus, this study aims to benchmark harvesting systems in industrial plantations across different global regions. This study analyses harvesting systems' efficiencies from various sources, including experts' input, literature studies, and datasets from the investigated regions. The study also includes cost rate estimates for applied systems and cost ranges per unit of harvested products.

Another primary goal of the study is to provide a snapshot of the state-of-the-art systems deployed in industrial plantations to harvest wood for material uses. The methodological approach and results of this study are intended to guide future research and industrial development in forest operations and evaluate regional competitiveness.

Materials and methods

Data collection and system boundaries

Forest operation experts (i.e. the coauthors of the present study) from different global regions and with local expertise in their respective geographical areas provided data for this study from their specific global region. Most experts involved in this study are forest operations researchers who participated in previous benchmarking studies (Di Fulvio et al. 2017). The remaining experts are researchers who led previous studies on forest operations in industrial plantations within their respective regions. The experts identified and compiled the most relevant information sources and publications in their regions in a shared database. Each expert provided productivity and cost figures for their region's most relevant and current harvesting systems.

The literature selected by the regional experts included a characterization of harvesting systems used in harvesting plantations, providing estimates of system productivity and costs.

The regional experts investigated studies in their respective regions by using web browsing, entering combinations of words such as plantation type ("industrial/roundwood plantation"), names of species ("Eucalyptus, Poplar, Pine"), operation names ("harvesting," "logging"), and names of their respective regions (e.g. "the US"). After the web search, each expert screened the studies for relevance, excluding those not deemed relevant (i.e. not representative of site/machine conditions).

Preference was given to scientific papers published between 2010 and 2021 to facilitate comparability of technologies and costs. Data sources, ranked in order of preference, included primary scientific articles, technical reports, Doctoral/MSc Theses, and local publications and unpublished datasets provided by the authors.

The boundaries of the harvesting systems encompassed all operations from the stump to the roadside landing/landing site (hereafter referred to as "landing"). These operations included tree felling, extraction of trees or tree sections to the landing, and processing trees/tree sections into logs and/or woodchips. The primary product under consideration was wood for material used as logs or woodchips. However, some of the studies selected presented integrated systems that produced both wood for material use and energy-wood biomass. In the latter case, only the extraction and processing of roundwood were considered, excluding any additional operation dedicated to the extraction and processing of energy-wood assortments. For a more comprehensive description of the working environment in each region, site characteristics were considered, where applicable. Information on the working environment included main tree species, rotation length, management type, yield (removal per hectare), harvested tree size, extraction distance to the landing, slope, and final use of the harvested products (assortments), as the main features impacting harvesting operations.

Harvesting systems were identified in each study and classified according to the type of assortment extracted (to the landing) and assigned to three broad categories: Full-Tree (FT) (extraction of the whole tree), Tree-Length (TL) (extraction of delimbed and topped trees), Cut-To-Length (CTL) (extraction of log assortments).

The collection of information for individual harvesting operations included a description of machinery and the workforce used in each work step (felling, extraction, processing) along with work efficiencies/productivity, preferably provided as solid volume over bark (m^3) per Productive Machine Hour (PMH) (working time excluding delays). In addition to net productivity, delays and technical utilization rates were recorded when available.

The following costs were also collected: operational cost rate per Scheduled Machine Hour (SMH) (SMH=working hours including delays), cost of each operation per unit of product over bark (USD m^{-3}), and cost of the harvesting system per unit of product over bark (USD m^{-3}).

Data harmonization

Given the benchmarking from different observations/sources, the study required a standardization to common units based on some standard conversion coefficients. Weights of products were converted to solid volumes over bark (m^3 solid) according to green wood densities provided in the respective studies or according to the density factors presented in Miles and Smith (2009).

Conversion between PMH and SMH was obtained using work delays recorded in each single-machine study. Alternatively, if the information was missing or irrelevant, typical technical utilization rates for forest operations were sourced from Brinker et al. (2002) for the different operations.

Costs were collected in local currencies (LCU) and then converted to US Dollars (USD) using historical exchange rates related to the year of publication of each paper/report as per www.exchangerates.org.uk and https://www1.oanda.com/currency/converter/. No other attempts were made to harmonize costs (inflation rates, GDP growth), and only costs collected from studies published between 2010 and 2020 were assumed to be comparable.

Data handling

An expert group was established in 2019, comprising experts from various regions: Australia, Brazil, East Asia, Europe (one each from Italy and Spain), South Africa, and the United States. These regions were chosen for their representation of current industrial plantation areas. Unfortunately, some other relevant regions, such as India, Chile, New Zealand, and Indonesia, were not included due to the inability to reach experts capable of supporting the benchmarking initiative.

In the first phase (2019), a template for extracting and collecting information from selected studies was designed and distributed to the regional experts (see Supplementary Information I).

Each regional expert was requested to complete at least two templates (summary of two studies) during this initial phase, allowing a period of familiarization to identify the most relevant literature. Subsequently, in the second phase, the experts conducted a broader literature search and provided a “synthesis report” (approximately 500 words); this included a description of typical industrial plantation modules, systems, productivity, and cost ranges in their region/s. Based on this comprehensive review, 68 studies were identified and added to a shared database.

Each observation/study collected in the master database contained a “Study ID” and related features. The identified studies provided varying information, depending on their scope. Some focused on specific harvesting operations (tree felling, extraction), while others considered the entire harvesting system (from stump to roadside) or reviewed various systems applied in a region.

The records in the database were then grouped by region (and species inside broader regions): Australia (11 records), Brazil (20 records), East Asia (5 records), European poplar (4 records), Iberian Eucalyptus (4 records), South Africa (15 records) and US (9 records).

The oldest study in the dataset dated back to the year 2000; however, most of the studies collected (57) were from within the designed target period (2010–2021).

The attributes were systematically compiled in an Excel database for each study, including the variables listed in Table 1. If a study included multiple working conditions/harvesting systems, separate records were created. The full observed ranges for each variable were extracted (min.-max.). However, only the statistics (average, standard deviation) were extracted if data were presented in aggregated statistical form.

The primary descriptors of working conditions and productivity in the different regions (Annex I) were statistically compared. For this purpose, the average for each study/observation was first computed, while the variation range was also extracted (where available). Pearson’s correlation tests were conducted in the R statistical software package on the average of the variables extracted from each study, and the correlation was deemed significant for p-value <0.05.

Results

Regional experts’ overviews

This section presents a summary description of regions of interest, plantation characteristics (Table 2), typical harvesting

Table 1. Variables that were extracted from each study and included in the database.

Variable name	Description	Unit
Year	Date when the study was conducted	
Country	The country where the study took place	
Tree species	Primary tree species in the plantation	
Silviculture operation	Operation observed in the study (e.g. clearcut, thinning)	
Product	Main product produced in the operation (i.e. sawlogs, pulpwood logs, veneer, pulpwood chips)	
Age	The age of the plantation at the time of the observed operation	Year
Stem volume	Tree stem volume	m^3 solid
Stand volume	The volume of stem wood per hectare of the plantation	m^3 ha^{-1}
Distance to road	Distance of stand to roadside/landing	m
System	Harvesting system (i.e. CTL, TL, FT)	
Machine	Description of the machine used in each operation and harvesting system (e.g. large harvester, medium forwarder, skidder)	
Productivity	Hourly productivity of each operation	m^3 PMH^{-1}
Delays	Delays time measured/reported for the operation	% SMH
Hourly cost	Hourly cost of each operation	LCU SMH^{-1}
Operation cost	Cost of each operation per unit of product	LCU m^{-3}
System cost	Cost for the whole harvesting system per unit of product (up to roadside)	LCU m^{-3}

Table 2. Regional context, cultivation schemes and products reported by regional experts.

	Regional context	Cultivation schemes and products
Australia	The total commercial plantation area was 1.93 M hectares (ha) in 2018, of which about half were softwood species (1.04 M ha, dominated by *Pinus radiata*) and half hardwood species (0.9 M ha, dominated by *Eucalyptus globulus* and *Eucalyptus nitens*) (ABARES 2019). The primary purpose of commercial plantation forestry is wood production. The total roundwood harvested totaled 32.9 M m^3 in 2017–18, corresponding to a 27.7% increase over 2008–09. About 86.7% of the logs harvested (28.8 M m3) occurred in plantations, and only 13.3% (4.1 M m^3) occurred in native forests. The roundwood harvested in softwood plantations corresponded to 10.9 M m^3 of sawlogs and 6.7 M m^3 of pulpwood logs and other logs. Around 0.8 M m^3 of sawlogs and 10.5 M m^3 of pulpwood logs and other logs were harvested from hardwood plantation estates (ABARES 2019).	Rotation ages in Radiata pine plantations range between 25 and 40 years. These plantations are thinned 2–3 times during the rotation age, and in some cases, trees are also pruned to produce high-value clear logs. At the end of the rotation, the tree size ranges between 0.8 and 1.5 m^3. Rotation ages in *Eucalyptus globulus* and *Eucalyptus nitens* plantations range between 10 and 15 years. These plantations may have an early thinning during the rotation (Acuna et al. 2017). At the end of the rotation, tree size ranges between 0.5 and 1 m^3, depending on on-site quality.
Brazil	Brazil has 500 M ha of forested area, and 9.8 M ha are commercially planted with hybrid *Eucalyptus* spp. and *Pinus* spp. FSC, PEFC, and ISO certifications cover 6.7 M ha of these plantations SNIF (Boletim SNIF 2018). Eucalyptus plantations contribute 1.2 % of the Brazilian GDP, with gross revenues of R$ 244.6 billion (49 billion USD) (IBA Relatório 2022).	Typical Eucalyptus rotations are usually between 6–7 years, and the national MAI (mean annual increment) of these plantations is 35.3 m^3 ha^{-1} year$^{-1.}$ Coppice regeneration in *Eucalyptus* plantations is an economically viable alternative to replanting in Brazil, even though it yields only 70 % of the original stand volume (Guedes et al. 2011).
South East Asia	The rate of *Eucalyptus spp*. plantation establishment has increased sharply in the past decade. The overall plantation area in the region exceeds 10 M ha. Teak (*Tectona grandis*) is one of the most important tropical timber species in natural forests and plantations. Rubberwood (*Hevea brasiliensis*) offers the most attractive and readily available wood-based resource for biobased feedstocks from plantation forestry in Thailand. In 2014, the rubberwood plantation area was 2.75 M ha, and the majority of the plantation (70%) is located in the Southern part of Thailand. The total Rubberwood production is approximately 5 Million t year^{-1}. Smallholders own a large proportion of mature rubber plantations.	Eucalyptus is mainly used as a raw material for pulp and paper industries, sawn timber, veneer, and wood chips, especially in Thailand, Vietnam, Malaysia, China, and India Eucalyptus is generally grown in plantations (blocks, along roadsides, along canals, or on the border of paddy fields), with 5–10 years rotation, depending on the end-use product, the intensity of management/silviculture, soil fertility, and clone selection. The standing volume at the harvesting time ranges between 50 and 100 m^3 ha^{-1}. Typical assortments are logs extracted from stems for different uses, including sawlogs, veneer logs, pulpwood, and residues for bioenergy use. Teak is commonly used in manufacturing outdoor furniture, boat decks, construction, indoor flooring, countertops, and as a veneer for indoor finishing. Initially, the rotation was 80 years for teak, but recently, it has been shortened to 20–40 years, depending on the region. Teak plantations require thinning to remove poorly formed trees and to reduce the overall stand density to the final harvest (200 to 300 trees/ha). In Thailand, two thinnings are usually conducted between 15 and 25 years; the final harvest is at 30 years. The rubberwood trees have a rotation period of 25–30 years. After latex production declined, rubber trees were cut down. Now, wood from rubber trees, apart from harvesting the latex, is used as timber and fuel.
European poplar	Hybrid poplar (*Populus x Euroamericana*) plantations represent a traditional crop and a strategic fiber source in many European countries (Britt 2000), Cardias-Williams and (Thomas 2006), as well as in the temperate regions of North America and Asia (Heilman 1999), (Sedjo 1999). China, France, India, Italy, and Turkey each already produce over 1 M m^3 of poplar wood (IPC 2008).	Poplar is generally grown in industrial plantations, established at final density and clearcut after 7 to 30 years, depending on climate, soil fertility, varietal (or clone), and product target (Cogliastro et al. 1997). Intermediate rotations of 10 to 15 years are typical in the Mediterranean, where poplar plantations are geared to support a thriving veneer industry (Hongyuan 1992), (Castro and Zanuttini 2008). Central Europe's most extended rotations are typical in countries such as Belgium and France, where poplar is also used for veneer and sawlog production (Cuchet et al. 2004). Growth rates vary between 15 and 45 m^3 ha^{-1} year^{-1}, resulting in a stand stocking at harvest that ranges from 200 to over 600 m^3 ha^{-1} (Picchio et al. 2008). Most plantations are designed to deliver high-quality timber, so value recovery is often a critical issue. Shorter rotations generally apply to those stands exclusively designed for pulp production, once popular in North America (Spinelli et al. 2008) and now spreading in Eastern Europe (Jansons et al. 2014).
Iberian Eucalyptus	In Europe, the Iberian Peninsula is the region with the highest concentration of Eucalyptus plantations, comprising an area (mostly *E. globulus*) with around 620,000 ha in (Spain MAPA 2020) and 845,000 ha in Portugal (ICNF 2019). The harvest levels of Eucalyptus have increased by around 3 M m^3 (with bark) in the last ten years (from ca. 4 to ca. 7 M m^3). According to the latest Spanish Forest Statistics Yearbook (Anuario de Estadística Forestal 2019), which compiles data collected in 2017, 86% of the harvest of evergreen species corresponded to Eucalyptus spp. The volume stock of *E. globulus, E. camaldulensis, and E. nitens* accounted for 79.6 M m^3, 5.5 M m^3, and 1 M m^3, respectively. These stocks are concentrated primarily in the northwest regions of Spain.	*E. globulus* plantations in the Iberian Peninsula are internationally recognized for their good yields. Annual volume increments can reach 50 m^3 ha^{-1} year^{-1}, with averages ranging between 7 and 30 m^3 ha^{-1}year^{-1} (Muñoz 2007); optimal rotations range between 8 and 12 years when trees are grown for the production of cellulose pulp (Rodriguez and Borges 1999).

(*Continued*)

Table 2. (Continued).

	Regional context	Cultivation schemes and products
South Africa	The 1.21 Mha of South African plantations only accounts for 1% of the country's total land area (FSA 2017). Of the 1.21 Mha, softwoods (i.e. Pinus spp.) total about 619.000 ha, while the remaining area consists of hardwoods (i.e. *Eucalyptus* and *Acacia* spp.). Of the total plantation area, 57% is managed for pulpwood, 38 % for structural timber, 3% for mining timber, and 2% for other purposes (FSA 2017). The total plantation round wood production during 2016/2017 was 18.3 Mm^3, of which 37% was softwood and 63% hardwood. Total plantation roundwood sales were R10.1 billion (ca. 500 M USD) for the same period (FSA 2017). Of the 619,000 ha of softwood, 74% is managed for structural saw timber and 26% for pulpwood production. In contrast, around 87% of all the hardwood volume ends up in the pulp mills in South Africa. The pulp and paper industry consumes approximately 66% of all fiber supplied by the commercial forest industry in South Africa (FSA 2017).	Rotation lengths differ significantly depending on management objectives. Softwood structural timber is grown between 20 and 30 years before clear felling with at least three selections, thinning, and pruning during their lifetime. A final thinning will reduce the stem count to approximately 250 to 350 stems ha^{-1}. The final volumes for these stands are 250 to 450 m^3 ha^{-1} of standing biomass at clear felling. Hardwood pulpwood, in contrast, is clear-felled between 10 to 15 years (site dependent) (ca. 125–150 m^3 ha^{-1}), and softwood pulpwood felled at around 15 years (at ca. 120 to 150 m^3 ha^{-1}). There is a hardwood structural production process, and the rotation ages around 25 years.
United States	Plantation forestry is minimal in the US since only approximately 11% of the timberland is planted (22 M ha). Most of the planted forest in the US is in the southern US states (67%-14.5 M ha). To a large degree, actively managed plantations are privately owned (Stanturf and Zhang 2003). In the southern US, plantations are mostly pines, comprising loblolly pine (*P. taeda*) in the coastal plains; slash pine (*P. elliottii*) in Florida and adjacent states; and increasingly longleaf pine (*P. palustris*) for restoration. In the western US, west of the Cascade Mountain range, Douglas-fir (*Pseudotsuga menziesii*) plantations are dominant. In the northern and midwestern states of the US, native Eastern cottonwood (*Populus deltoides*) is the fastest-growing tree. Interest in Aspen for fiber production has led to an interest in hybrid poplar in the Lake States, especially Minnesota. Eucalyptus plantations are primarily located in northern California. In Maine, hybrid larch (*Larix* spp.) was planted by one company for several years (Stanturf and Zhang 2003).	Pine plantations are harvested at 15–30 years for roundwood logs. Eucalyptus and poplar plantations for pulpwood chips are harvested after 6–10 years. Hybrid poplar plantations in the Pacific Northwest are mostly harvested at ages not exceeding 15 years for sawlogs and pulpwood chips, as a more favorable regulatory environment for intensive management and tax advantages.

systems, their performances, and typical costs (Table 3) as provided by the experts involved in the benchmarking study. It complements the figures reported in Table A1, relying on expert knowledge.

Benchmarking harvesting conditions in industrial plantations

Timber from Eucalyptus plantations is mainly destined for pulpwood production. Their rotation length (3–15 years) is generally shorter than that of Pine, which can produce both sawlogs and pulpwood (14–40 years) (Figure 1). Poplar rotations are between 10–23 years if aimed at a mix of different assortments (e.g. in Italy). Yield from plantations ranges from 50 to 700 m^3 ha^{-1}. Generally, the harvest volume correlates with rotation length ($r = 0.568$, $p = 0.034$). However, it is interesting to note the difference in the main annual increment (MAI) between Eucalyptus (33 m^3 ha^{-1} year^{-1}) and Pine (21 m^3 ha^{-1} year^{-1}) in Brazil. This can be explained by factors such as planting densities, site differences, and silviculture management between the two species in the various countries. The lowest harvest volume per hectare was observed in Eucalyptus plantations in East Asia, where the volume usually remains under 100 m^3 ha^{-1} due to the high demand for industrial raw materials in that region.

The mean stem volume at harvest is also correlated with rotation length ($r = 0.720$, $p = 0.001$) (Figure 2). The stem volume of Eucalyptus plantations is generally lower than 0.5 m^3 tree^{-1}, whereas pine is generally higher. This is mainly due to longer pine rotation lengths to produce high-value products (e.g. sawlogs, veneer logs, etc.), resulting in stem sizes as large as 2.0 m^3 in Australia. At harvest time, the stem volume of Poplar for pulpwood production in the US is similar to that of Eucalyptus. In contrast, a stem volume of approximately 1.0 m^3 is cut when Poplar is used to produce veneer, sawlogs, and pulpwood in Europe.

Benchmarking operational productivity

The productivity of harvesters is significantly correlated with stem volume ($r = 0.766$, $p = 0.003$) (Figure 3). The highest productivity is observed with the large stems in Australian pine plantations, where a single grip harvester can produce more than 100 m^3 PMH^{-1}. Similar productivity is also observed in South African pine operations. In contrast, lower harvester productivity is observed in Eucalyptus plantations, which results from the harvest of smaller stem volumes; in this case, a productivity of 50 m^3 PMH^{-1} is achievable for stem volumes of 0.5 m^3. A primary difference between the use of harvesters in Eucalyptus and pine plantations is that, in the former case, the machine is also used for debarking pulpwood at the stump, while in pine operations, debarking is usually performed at mills. Under the considered range of conditions, productivity increased at a rate of 4.2 m^3 PMH^{-1} per 0.1 m^3 of stem volume under a linear modeling approximation.

The productivity of feller-bunchers weakly correlates with stem volume ($r = 0.367$, $p = 0.330$). It is generally double that of harvesters, exceeding 100 m^3 PMH^{-1} in most pine operations compared to single-grip harvesters. Relatively high productivity is observed in stem volumes below 0.5 m^3 in Eucalyptus plantations (Figure 4). The higher productivity of feller-

Table 3. Harvesting systems, productivity and costs ported by the regional experts.

	Harvesting systems	Productivity and Costs
Australia	Most harvesting operations are conducted on relatively flat terrain with maximum slopes that do not exceed 15–20%; therefore, they are predominantly harvested with ground-based equipment. Cable logging or winch-assisted operations are less common and account for less than 10% of the total log harvest. FT, CTL, and in-field chipping (IFC) are the three major harvesting systems. The FT and CTL systems are the predominant systems in *Eucalyptus globulus*, *Eucalyptus nitens* and Radiata pine plantations, while IFC is the predominant system in *Eucalyptus globulus* plantations (Lambert et al. 2006) (Annex 1). The CTL system is the most common in Radiata pine operations. The harvester-processors cut about six to eight log types during harvesting, including 3.7, 4.9, 5.5, and 6.1 m long sawlogs and 2.4–3.6 m long pulpwood logs. Onboard computers installed on harvesters are widespread in Radiata pine operations to collect standard forest production data StanforD data (Strandgard et al. 2013), (Skogforsk 2014) for optimizing cross-cutting and maximizing the value recovery from the log types cut during harvesting. CTL is preferred in Radiata pine operations where the mix of products is complex (i.e.> 10 log assortments). For example, this is the case when tree size is relatively small (< 0.5 m^3), when tree quality is poor (bad tree form and high occurrence of branches), or when site fertility is poor. The CTL system is preferred to allow nutrients to remain on the site. The FT and the CTL systems are popular in *Eucalyptus globulus* and *Eucalyptus nitens* operations (Acuna et al. 2017), (Ghaffariyan et al. 2019). Harvesters and processors cut short (about 5 m) and long (about 10 m) pulpwood logs during harvesting. Onboard computers installed in harvesters are rarely used in these hardwood operations, but some companies are starting to install onboard computers to collect StanforD data. The IFC operations in Australia are conducted on flat areas where operating space for locating the DDCs (delimber-debarker-chipper) landings is not a limitation. Woodchips are hauled to ports or static chip mills, whereas logging residues are either returned to the stump on poor-quality sites or chipped and sold as energy biomass on good-quality sites (Acuna et al. 2012).	The cost of the most common harvesting systems usually ranges between 11.5 and 23.6 USD/m^3 (Annex 1). These costs depend on several factors, including tree size, tree form and site quality.
Brazil	As the area of planted forests increased in Brazil, their silvicultural mechanization intensified, and harvesting equipment became larger and heavier (Suzuki et al. 2014); hence, harvesters have been replaced by feller-bunchers, which are more cost-effective in tree cutting (Bertin 2010). (Lopes and Pagnussat 2017) reported on the influence of technology, operator training, population conditions, mechanical availability, and operational efficiency in Brazilian plantations.).	During the first rotation of clear-cuts on flat terrain, a harvester produces between 19 and 31 m^3 PMH^{-1}, and forwarder productivity varies between 26 and 36 m^3 $PMH^{-1\cdot}$ The harvesting and forwarding hourly operational costs (i.e. in April 2018) are described by (Carvalho et al. 2018) to be respectively ca. 90 USD SMH^{-1} and 73 USD SMH^{-1}. Thus, the cost of the harvesting system for logs at the roadside would vary between 4.9 and 7.5 USD m^{-3}. The feller-buncher operation is suitable for Eucalyptus coppice because it handles multiple stems from each stump. For example, a eucalyptus feller-buncher operation in Brazil, on flat terrain, reaches productivity between 40 and 50 m3 PMH^{-1}, with operational costs around 1.00 USD m^{-3} (i.e. with average productivity of 48 m^3 PMH^{-1}) (Nascimento et al. 2011). (Miyajima et al. 2016) show that the slope is a limiting factor; on average, the feller-buncher productivity was 124 m^3 PMH^{-1} for undulating slopes and up to 142 m^3 PMH^{-1} on flat terrain. For the skidder operation, (Lopes et al. 2014) indicate an average cost of 1.60 USD m^{-3} and productivity varying from 59 to 62 m^3 PMH^{-1}. However, it is still necessary to de-branch, debark, and cut-to-length the felled and skidded trees using a forestry wood processor, which adds an extra 2.13 USD m^{-3} (Simões et al. 2014).

(*Continued*)

Table 3. (Continued).

	Harvesting systems	Productivity and Costs
South East Asia	*Eucalyptus*: The dominant logging system consists of semi-mechanized harvesting operations. It includes essential manual work, where felling and crosscutting are the only motor-manual activities. Motor-manual felling is performed by one chainsaw operator who is exclusively responsible for felling trees and cross-cutting the stem sections. Next, a group of workers performs de-branching with a bush knife. Sectioning or marking assortments are manual operations performed by only one worker on-site. Subsequently, crosscutting is performed again by a chainsaw operator. Several workers carry the logs by hand and pile them at the harvesting site. Loading concludes the harvesting operation and is carried out manually by a group of workers or with a front-end grapple loader. The fully mechanized harvesting operation involves a small harvester and farm tractor with a timber trailer. The harvester felled, delimbed, measured the stems, and cut them into different assortments specified by the mill, and the timber trailer attached to a farm tractor transported the logs to the roadside. The loading of vehicles for long-distance transportation to mills is performed with a front-end grapple loader. However, fully mechanized harvesting is limited and is usually applied only in large-scale operations because of the high initial investment.*Teak*: the logging method that is commonly applied is the TL method. In this method, trees are felled, delimbed, and topped at the stump area by a chainsaw; then, trees are skidded to the roadside by an elephant, farm tractor, or skidder, depending on slope limitation and available resources. A self-loading truck or a front-ended grapple loader performs the primary transportation of logs. At log the landing, trees are crossed cut into 3, 4, and 6 m long logs and stacked into a pile for auction.*Rubberwood*: harvesting in Thailand applies both FT and CTL methods. Harvesting techniques can be divided into 1) cutting above the stump and 2) uprooting the stump. For the FT method, trees are felled by chainsaw, extracted by tractor or elephants to the roadside, and then trees are processed into short logs (2 m) and loaded onto the truck either by staffing or mechanized loading by an excavator. Where CTL is implemented, trees are pushed and pulled by a modified bulldozer or excavator until their stumps are uprooted. Then, it was followed by delimbing, cross-cutting with a chainsaw at the stump area, manually stacking, and mechanized loading to the truck by excavator or front-ended grapple tractor.	*Eucalyptus*: The mean felling and processing productivity are 0.5–4 m^3 SMH^{-1} for the semi-mechanized system (Manavakun 2014), (Engler et al. 2016), with costs per product unit that range between 1.8 and 5 USD m^{-3}. The productivity of a fully mechanized harvesting system varies between 50–60 tonne day^{-1}, depending on extraction distance. *Teak*: In terms of productivity according to work phase can be summarized that felling by chainsaw 25–30 m^3 PMH^{-1}, skidding by elephant 5–10 m^3 PMH^{-1}, skidding by farm tractor 10–25 m^3 PMH^{-1}, skidding by skidder 15–20 m^3 PMH^{-1}, and primary transportation with self-loading truck 7–8 m^3 PMH^{-1} (Rianthakool et al. 2018). The average harvesting cost is about 8–11 USD m^{-3}, depending on the equipment used (Rianthakool et al. 2018). *Rubberwood*: Productivity of tree felling by chainsaw varies between 20–60 m^3 PMH^{-1}, delimbing 7–21 m^3 PMH^{-1}, cross-cutting 5–11 m^3 PMH^{-1}, stacking 9–21 m^3 PMH^{-1}, manual loading 3–6 m^3 PMH^{-1} and mechanized loading 16–22 m^3 PMH^{-1} (Rianthakool and Sakai 2014).
European poplar	Harvesting techniques vary from place to place, but they all reflect the favorable work conditions offered by clear-cuts in flat terrain where poplar plantations are established (Picchio et al. 2008). When good-quality stems are appropriately merchandied, the yield of high-value veneer logs often exceeds 50% of the total volume. For that reason, most owners still look at mechanized cut-to-length harvesting with suspicion and favor motor-manual processing, which they deem more accurate (Marshall et al. 2006). In that case, trees are felled motor-manually or with a feller-buncher, and they are preferably processed with chainsaws before or after extraction to the roadside, depending on terrain conditions. In summer, many cutovers can be accessed with trucks; hence, extraction is unnecessary. The large trees obtained from the older Central European stands may exceed the size limits of mainstream CTL equipment and are processed motor-manually.	Mean felling and processing productivity is 6 and 9 m^3 SMH^{-1}, respectively, for the motor-manual and semi-mechanized systems, the latter consisting of mechanical felling by feller-buncher followed by motor-manual processing (Spinelli et al. 2011a). In contrast, fully mechanized felling and processing will raise productivity to over 20 m^3 SMH^{-1} (Puttock et al. 2005). Poplar plantations offer such favorable conditions to mechanized harvesting that they are the only forest environment in Central Europe where harvesters can reach the same high-productivity levels as Nordic countries (Spinelli et al. 2010). Previous studies suggest mechanized processing does not significantly reduce value recovery (Spinelli and Magagnotti 2011b). Depending on tree size and harvesting technique, felling and processing costs will vary between 3 and 17 USD m^{-3}. In addition to this cost, an extraction cost of approximately 11 USD m^{-3} should be added. Concerning shorter-rotation stands established for pulpwood production, abundant data are available for North America (Spinelli and Hartsough 2006). However, very little productivity data is available from Europe, where these plantations are still new and are only coming to the harvesting age. Early experiences suggest that an effective harvesting technique consists of mechanical felling and bunching, skidding to the roadside with a grapple skidder or an adapted farm tractor, and processing with a grapple saw or a slasher. Correctly deployed, this system incurs a total harvesting cost of 20 USD m^{-3} (Spinelli et al. 2012).

(*Continued*)

Table 3. (Continued).

	Harvesting systems	Productivity and Costs
Iberian Eucalyptus	A semi-mechanized system is usually employed for harvesting Eucalyptus stands destined for producing paper pulp; thus, the felling and cutting of the stems into logs is performed manually with a chainsaw, followed by mechanized processing with a processor's head. The stems are usually cut into 2.5 m logs and then stacked for later transport to the loading area by a forwarder. A two-pass harvesting system is quite popular in Spain, where forestry residues are collected separately after the felling and cutting of stems have been completed. In the second phase, the residual forest biomass (branches, leaves, and bark that remain on the ground after removing stems) is compacted and bundled by a dedicated bundling machine. Bundles are then extracted by forwarders to the loading area and transported to end customers by trucks. Once at the factory, the bundles are chipped and used to produce the electricity required in the pulp production process or sold as a surplus to the National Electricity System (Sánchez-García 2016). In some areas, productivity studies are underway to explore efficiency gains and safety improvements that may result from fully mechanized systems. These systems include a harvester for felling the trees and processing the stems, usually cut into logs of over 5 m.	A wide range of productivity and costs can be observed in the region, depending on the level of mechanization, extraction distances, and scale of the operations.
South Africa	Regarding harvesting systems applied in South Africa, a study by (Wenhold et al. 2019) showed that 57% of operations are fully mechanized, and the rest are motor-manual based for all species and products. All hardwood pulpwood is debarked in the field, whether manually or mechanically. Regardless of the product, all softwoods are debarked at mill sites using various mechanical equipment. Mechanized CTL harvesting systems are becoming more prevalent in South Africa, but TL systems will remain in use for the foreseeable future, particularly in softwood pulp, veneer, and structural timber harvesting, where no debarking in-field is necessary. These TL systems mainly comprise motor-manual felling in tandem with cable skidders or being fully mechanized, including feller-bunchers and grapple skidders. There is a 35%:65% split between motor-manual and mechanized systems for hardwood pulpwood operations. The larger pulp companies have moved firmly to mechanization, while smaller landowners still use the more conventional motor-manual with manual debarking, stacking, and loading for secondary transport. The decision is primarily driven by the availability of capital to purchase mechanized systems and an economy of scale.	The productivity of the different operations ranges from 25 m^3 PMH^{-1} for semi-mechanized systems to 85 m^3 PMH^{-1} and more for feller-buncher and grapple skidder systems. In mechanized CTL operations, productivity in clear felling (average tree size of about 0.7 to 1.0 m^3 and species dependant), is between 50 and 80 m^3 PMH^{-1} for a harvester and 25 to 35 m^3 PMH^{-1} for a forwarder. The cost/m^3 is between R125/m^3 (7 USD) and R150/m^3 (8 USD), but the benefits of mechanized over motor-manual remain improved operational safety, improved product quality, and potentially higher rates of production associated with mechanization. These increases in productivity range from 9 to 12 m^3 PMH^{-1} for the harvester and 18 to 22 m^3 PMH^{-1} for forwarding (Hogg et al. 2011). However, the emergence of excavator-based harvesters as potentially suitable alternatives to purpose-built machines has opened a debate about the most suitable cost and productivity within the South African forestry environment and context. The number of excavator-based machines in South Africa and worldwide attests to their suitability in easy terrain, where leveling technology is not required. However, in steeper terrain, the outcomes are not that clear. A study in hardwood pulpwood stands indicates that the productivity of an excavator-based harvester decreases by 0.048m^3 PMH^{-1} for every 1% increase in slope (Ackerman et al. 2018). Purpose-built machines are not significantly affected by the slope. A purpose-built harvester was found to have a higher mean productivity (16.24 m^{3}PMH^{-1}) greater than the excavator-based machine (13.00 m^3 PMH^{-1}), but this extra productivity came at a price as the excavator-based machine was more economical per cubic meter. The mean harvest cost for the purpose-built machine was 6.60 USD m^{-3}, while the excavator-based machine achieved a mean cost of 5.06 USD m^{-3} (Ackerman et al. 2018).
United States	The systems applied in the loblolly pine plantations use traditional FT harvesting with a chainsaw or feller-buncher, followed by skidders, loaders, and delimbers. A recent study by (Conrad et al. 2013) described a harvest system of fiber in a loblolly pine (*Pinus taeda* L.) plantation. The study in the Coastal Plain of North Carolina assessed harvesting productivity and costs with and without biomass energy extraction. Feller-buncher systems are operated in eucalyptus plantations in California (Spinelli et al. 2002). The cost of recovering sawlogs from pulpwood-sized plantations and cottonwood short-rotation farms was investigated in the past (Spinelli et al. 2008). The harvesting system used was the full-tree system, including a manual selection of stems suitable for sawlogs, mechanical felling, and bunching, forwarding to a landing, mechanized processing, and feeding into a chain-flail delimber-debarker-chipper (DDC) of pulpwood size stem sections.	Results of the (Conrad et al. 2013) study described conventional roundwood (only tree-length) southern pine commercial clearcut extraction system to be at 70.6 m^3 PMH^{-1}, with an average cut and load cost of 7.95 USD m^{-3} (for roundwood loaded on truck). In the integrated option (roundwood and chips), the system productivity rate was 58 m^3 PMH^{-1} (49.3 t PMH^{-1}) for roundwood extraction and 17.9 m^3 PMH^{-1} (15.2 t PMH^{-1}) of woodchips for energy (Conrad et al. 2013). A similar study, in 28–33-year-old clearcut pine plantations (*Pinus elliottii* and *Pinus taeda*) was conducted in Georgia by Baker et al. (2010), in integrated harvesting of roundwood and woodchips with similar productivity (42–68 m^3 PMH^{-1}) and costs for roundwood (6.9 USD m^3). Eucalyptus: Felling and bunching productivity ranged from 24 to 32 m^3 PMH^{-1}. The productivity of the skidder/loader was 48–93 m^3 PMH$^{-1,}$ and the delimber-debarker-chipper was 30–38 m^3 PMH^{-1}. The cost of the whole system ranged between 8- and 13 USD m^{-3}, depending on the tree size (Spinelli et al. 2002). Cottonwood: In the case of pulpwood production, productivity for a feller-buncher reached 42 m^3 PMH^{-1}, 92 m^3 PMH^{-1} for forwarding, 17 m^3 PMH^{-1} for processing and 60 m^3 PMH^{-1} for the DDC. Trees/tree sections with smaller diameters are sorted into pulpwood production. Manual selection of trees suitable for sawlogs significantly increased total costs, representing 73% of the additional costs for sawlogs, compared to the exclusive production of pulpwood (Spinelli et al. 2008).

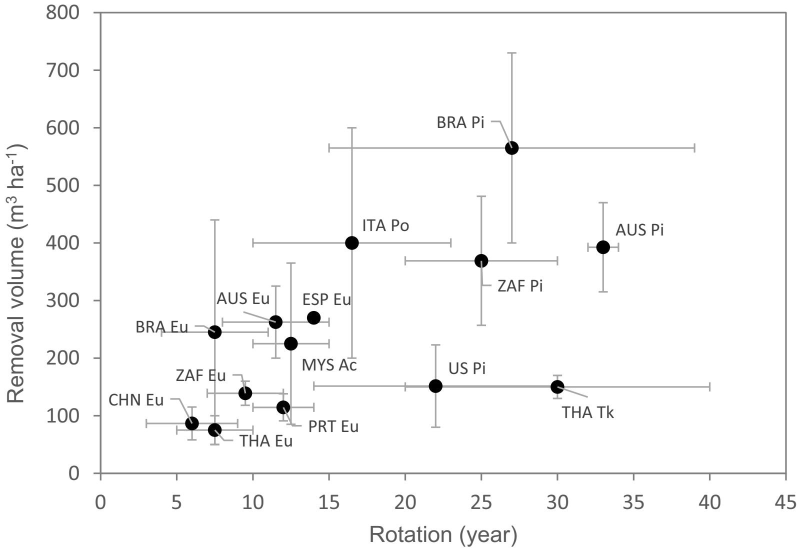

Figure 1. Removal volume as a function of rotation length (Pi = pine, Eu = Eucalyptus, Po = Poplar, Ac = Acacia, Tk = Teak). Dots and grey lines represent the average value and the variation range between x and y axes, respectively. (Country codes in the figure: AUS = Australia, BRA = Brazil, CHN = China, ESP = Spain, ITA = Italy, MYS = Malaysia, PRT = Portugal, THA =Thailand, US = United States, ZAF = South Africa).

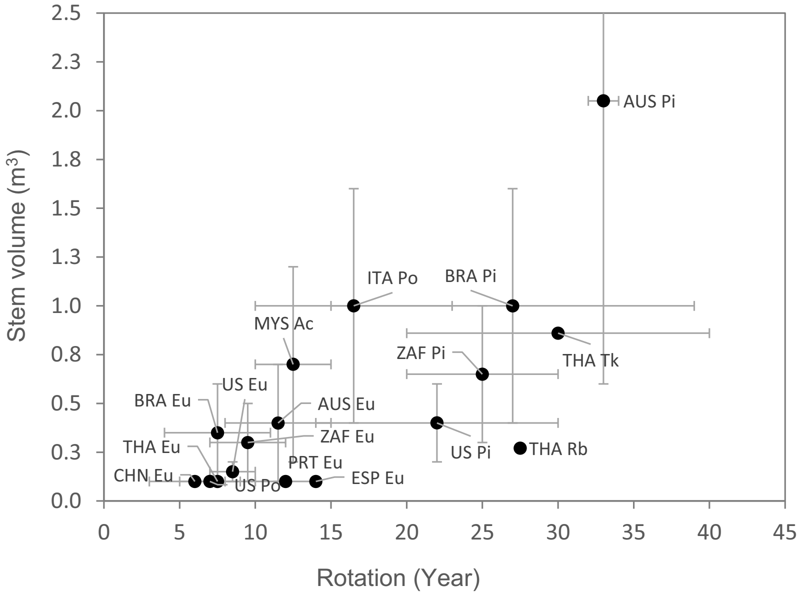

Figure 2. Individual stem volume as a function of rotation length (Pi = Pine, Eu = Eucalyptus, Po = Poplar, Ac = Acacia, Tk = Teak, Rb = Rubberwood). Dots and grey lines represent the average value and the variation range in the x and y axes, respectively. (Country codes in the figure: AUS = Australia, BRA = Brazil, CHN = China, ESP = Spain, ITA = Italy, MYS = Malaysia, PRT = Portugal, THA =Thailand, US = United States, ZAF = South Africa).

bunchers, when compared to harvesters, is explained mainly by the fact that feller-bunchers only fell and bunch trees, without incurring extra processing time associated with delimbing, debarking and crosscutting trees. Multiple stems offset the impact on productivity in smaller tree volumes, although this advantage is lost when the felling head can not accumulate multiple stems. This is the case, for example, of feller-bunchers operating in poplar plantations in Italy, where stems need to be laid down carefully for further grading to minimize losses and maximize stem value recovery.

The productivity associated with the extraction of roundwood with a forwarder in CTL systems varied between 9.0 and 86.0 m^3 PMH^{-1}, with the highest productivity reached in the case of Australian pine operations (Figure 5). Generally, productivity tended to be correlated with removal volume per hectare ($r = 0.607$, $p = 0.148$) and inversely correlated with extraction distance ($r = -0.600, p = 0.207$). However, the relations are not statistically significant, given the limited number of observations and the high background noise originating from other influencing factors often excluded from the measurements.

Depending on factors such as extraction distance, number of log grades, and slope, a CTL system might be balanced with one harvester and one forwarder. In some cases, for example,

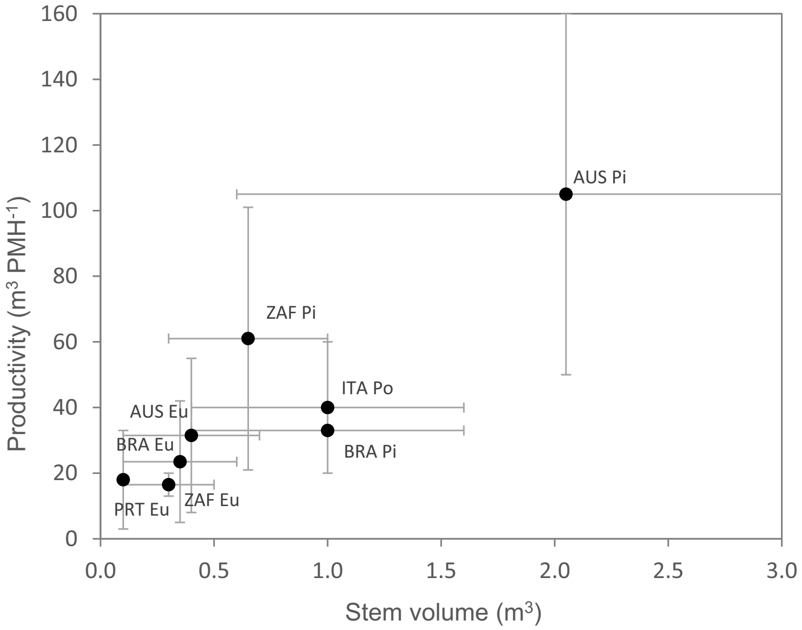

Figure 3. Harvester productivity in Eucalyptus (Eu), Pine (Pi), and Poplar (Po) plantations as a function of stem volume. Dots and grey lines represent the average value and the variation range in the x and y axes, respectively. (Country codes in the figure: AUS = Australia, BRA = Brazil, ITA = Italy, PRT = Portugal, ZAF = South Africa).

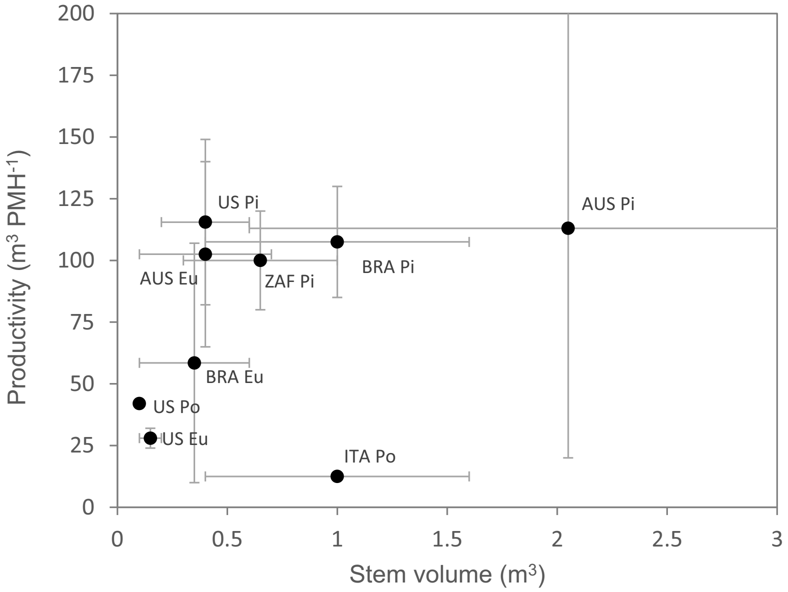

Figure 4. Feller-buncher productivity in Eucalyptus (Eu), Pine (Pi), and Poplar (Po) plantations as a function of stem volume. Dots and grey lines represent the average value and the variation range in the x and y axes, respectively. (Country codes in the figure: AUS = Australia, BRA = Brazil, ITA = Italy, US = United States, ZAF = South Africa).

when the productivity of the harvesters is much higher than that of forwarders, more than one forwarder is required to maintain the balance of the system (e.g. Pine plantations in South Africa and Australia). Long extraction distances reveal that forwarders travel on forest roads to carry logs to unloading areas (e.g. Spain) in some operations. In other cases, forwarders are used to extract logs to the roadside, unloading points, and load logging trucks.

Skidder productivity is not significantly correlated with removal volumes and extraction distances ($p > 0.05$), given the limited number of observations and the influence of other confounding factors (Figure 6). These factors include removal volume, bunch size (which affects the number of trees moved per trip), terrain conditions, and tree size (diameter and volume). Skidders are generally used for shorter extraction distances and carrying smaller payloads than forwarders. In the analyzed studies, the average overall extraction distance was 248 m (min. 50 m, max. 705 m) for skidders and 380 m (min. 105 m, max. 200 m) for forwarders. Skidding productivity may reach maximum values generally higher than the ones observed for forwarders. Thus, the maximum productivity of grapple skidders reached 120 m^3 PMH^{-1} in the US and South African Pine plantations. Grapple skidders generally work with feller-bunchers in FT systems. In some

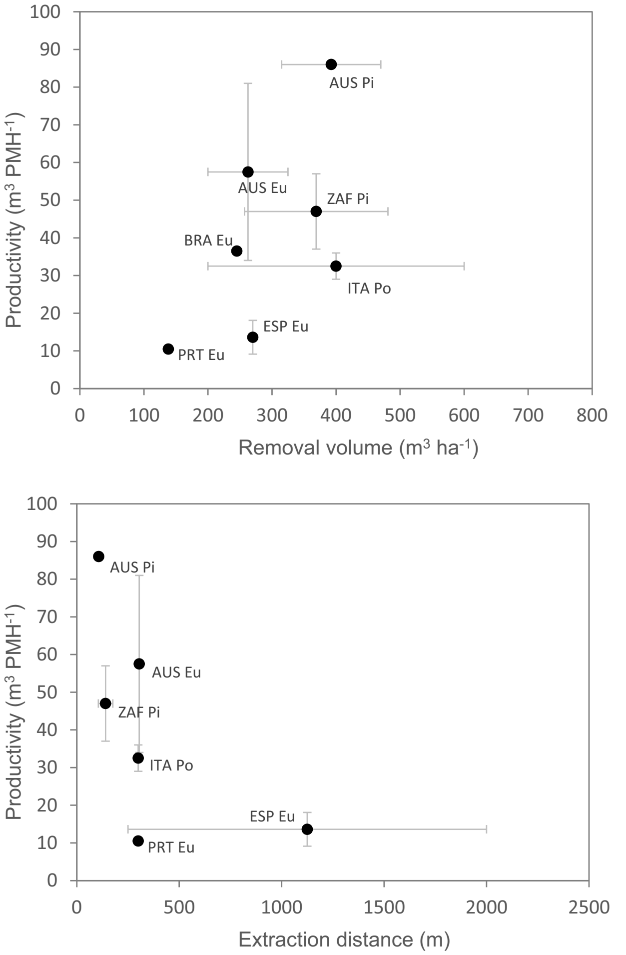

Figure 5. Forwarder productivity as a function of removal volume per hectare (top) and extraction distance (bottom) in Eucalyptus (Eu), Pine (Pi), and Poplar (Po) plantations. Dots and grey lines represent the average value and the variation range in the x and y axes, respectively. (Country codes in the figure: AUS = Australia, BRA = Brazil, ESP = Spain, ITA = Italy, PRT = Portugal, ZAF = South Africa).

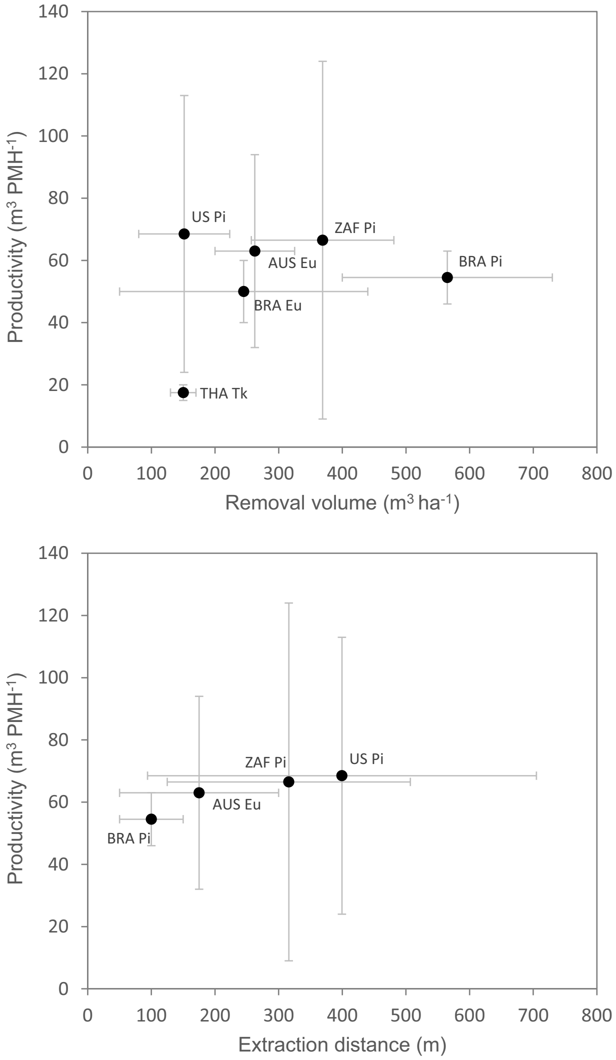

Figure 6. Skidder productivity in Eucalyptus (Eu), Pine (Pi), and Teak (Tk) plantations as a function of removal volume per hectare (top) and extraction distance (bottom). Dots and grey lines represent the average value and the variation range in the x and y axes, respectively. (Country codes in the figure: AUS = Australia, BRA = Brazil, THA =Thailand, US = United States, ZAF = South Africa).

cases (e.g. in the US, Pine plantations), their productivity is well balanced with that of a feller-buncher. In contrast, in other cases (e.g. Brazilian or Australian Eucalyptus plantations), it is significantly lower than for feller-bunchers, requiring more than one skidder to maintain system balance.

Processor productivity varied between 5.0 and 139 m^3 PMH^{-1}. These machines generally work at landings in FT systems (feller-buncher, grapple/cable skidder). Productivity of processors is generally correlated with stem volume in the case of single stem handling (e.g. in pine plantations); however, this was not the case when combining all the studies in the dataset ($r = -0.296$, $p = 0.628$), given the considerable heterogeneity of working conditions (Figure 7).

Motor-manual-based operations (motor-manual felling and processing, manual stacking for tractor/trailer-based forwarding to roadside) generally have a productivity below 15 m^3 PMH^{-1} (Figure 8). The only case where they exceeded this threshold was in teak plantations in Thailand (tree felling only). In the same region (South-East Asia), the lowest productivity was observed when operating with small stems in Eucalyptus plantations. Medium productivity levels were observed in Eucalyptus trees' felling in Iberia and Italian poplar trees' felling-processing. The large variety of systems based on motor-manual operations makes it difficult to compare them directly and perform statistical analyses; however, the observations reported indicate their productivity level compared to mechanized systems.

Benchmarking harvesting systems and their costs

Of the 85 observed harvesting systems, the majority (45) represented CTL harvesting, followed by FT (35) and TL (5) harvesting. CTL was the dominant system observed in Europe and East Asia. FT systems were the most frequent in the US. Although CTL was the most frequently observed system in Brazil and South Africa, many cases dealt with FT. Similarly, CTL was the dominant system in pine plantations and FT in Eucalyptus plantations in Australia. TL systems were observed in fewer cases and countries (South Africa, East Asia, and the US) (Figure 9).

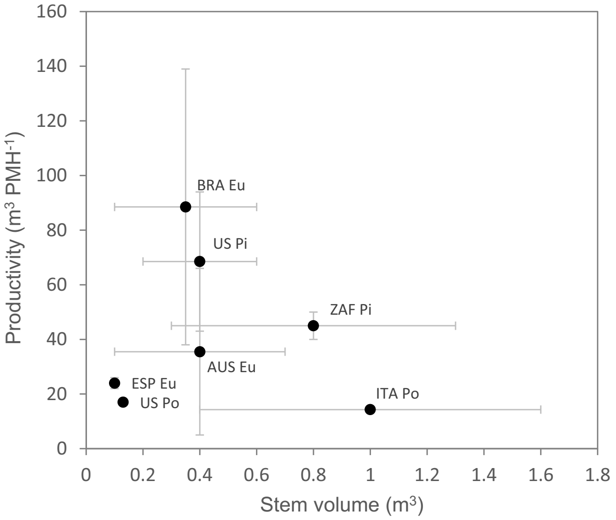

Figure 7. Processor productivity in Eucalyptus (Eu), Pine (Pi), and Poplar (Po) plantations as a function of stem volume. Dots and grey lines represent the average value and the variation range in the x and y axes, respectively. (Country codes in the figure: AUS = Australia, BRA = Brazil, ESP = Spain, ITA = Italy, US = United States, ZAF = South Africa).

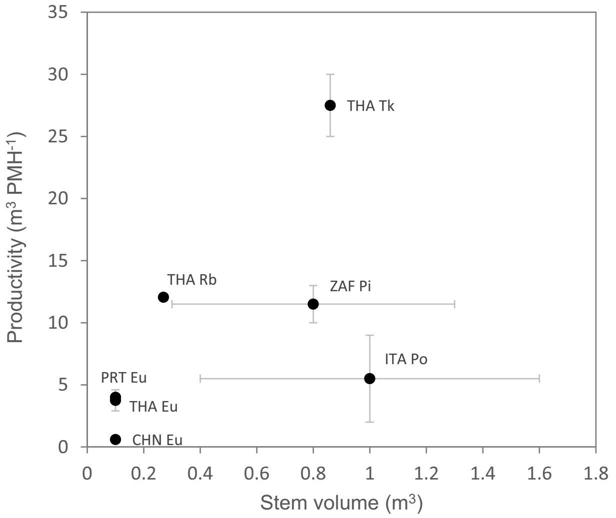

Figure 8. Productivity of motor-manual operations in Eucalyptus (Eu), Pine (Pi), Poplar (Po), Teak (Tk), and Rubberwood (Rb) plantations as a function of stem volume. (ZAF Pi = South Africa felling with chainsaw, ITA Po = Italy felling and processing with chainsaw, PRT Eu = Portugal felling with chainsaw, CHN Eu = China felling and processing with chainsaw and manual extraction, THA Eu = Thailand felling and processing with brush saw and extraction with farm tractor, THA Tk = Thailand felling with chainsaw, THA Rb = Thailand felling and processing with chainsaw). Dots and grey lines represent the average value and the variation range in the x and y axes, respectively.

Based on studies published between 2010 and 2020, forest-to-landing harvesting and extraction costs are generally lower than 30 USD m^{-3} (Figure 10). The lowest harvesting costs (under 5 USD m^{-3}) are observed in Eucalyptus plantations in South-East Asia (China, Thailand), due to low labor costs of the motor-manual based systems applied in these regions. Similar costs were also achieved in Eucalyptus harvesting in Brazil due to high productivity in mechanized systems, high yields, and relatively low labor costs. After these two regions, South Africa and the US appear to be the most cost-competitive regions. In contrast, harvesting costs in Eucalyptus plantations in Iberia and Australia generally exceed 10 USD m^{-3}, mainly due to difficult terrain/site conditions (Iberia) and high labor costs (Australia). The highest costs are reported in operations that involve processing high-value stems (e.g. veneer logs), such as Poplar in Italy or Paraserianthes in the Philippines.

A breakdown of the costs by operation in each harvesting system reveals that felling and processing accounted for the largest cost share (generally over 50% of the total cost in CTL systems) (Figure 11). This figure can increase to 80% in FT systems, due to high processing costs. Processing costs increase, particularly with single stems (e.g. a slasher deck in South Africa), and decrease when multiple stems are processed (e.g. multi-stem processing of Eucalyptus in Brazil). Among mechanized CTL systems, forwarding costs may exceed felling and processing costs, mainly when logs are extracted over relatively long distances (e.g. in the Iberian Eucalyptus case). In contrast, it remains under 50% of the total cost in plantations with shorter extraction distances (Australia, Brazil, and South Africa).

Discussion

Similarities and differences across regions and systems

This study gathered data from both literature and personal communications by experts to provide an overview of current harvesting systems and their performance in industrial plantations. Based on this, it is possible to point out some similarities and differences that are relevant to understanding current trends and future evolution in the sector.

In terms of wood products, two extremes can be observed; some systems aim at high-value recoveries and high fiber volume recovery, as in poplar plantations in Italy (Spinelli et al. 2011) and the US (Spinelli et al. 2008), where specific quality requirements need to be met (i.e. veneer, sawlogs, pulpwood products combination). Accordingly, the harvesting systems in these regions are designed to integrate motor-manual selection operations (manual bucking of logs) with mechanized felling and extraction. Similar trends can be observed in fully mechanized systems in Australian pine plantations, where up to ten different products can be included in optimizing value recovery with on-board computers.

At the other end of the spectrum, it is the mass production of pulpwood, which is typical of Eucalyptus plantations that are expanding in different regions. Here, it is theoretically possible to maximize the level of mechanization and potentially apply multiple stem handling systems. However, the degree of mechanization is still governed by regional socio-economical and local operational factors.

Mechanized systems, which maintain high productivity and minimize labor input, are generally preferred in most regions, regardless of labor cost (Australia, Brazil, Iberia, South Africa, US).

However, semi-mechanized systems, based on motor-manual operations, are still applied in regions with relatively low labor costs and limited capital available for investment in mechanized equipment. An example is Eucalyptus plantations in East Asia, where despite low productivity associated with

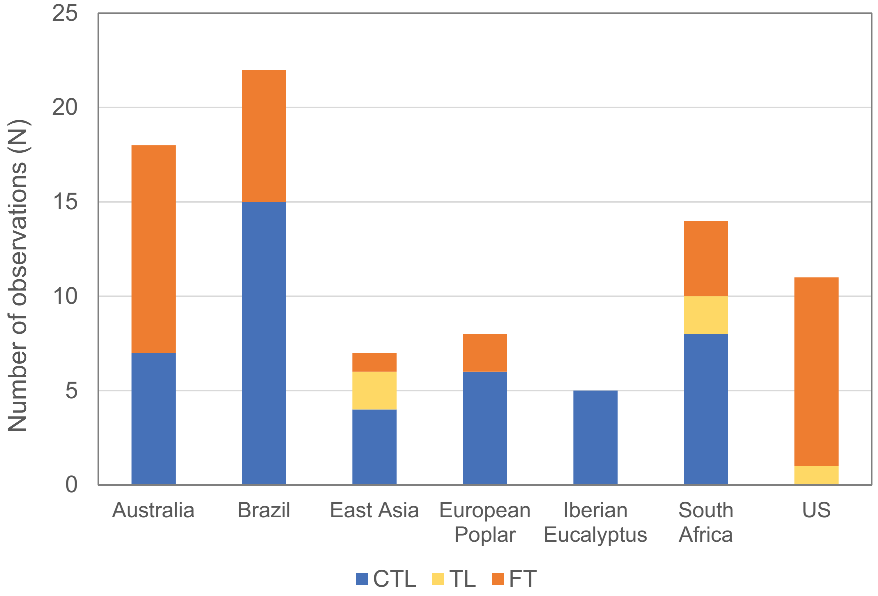

Figure 9. Number of observations by harvesting system and study region.

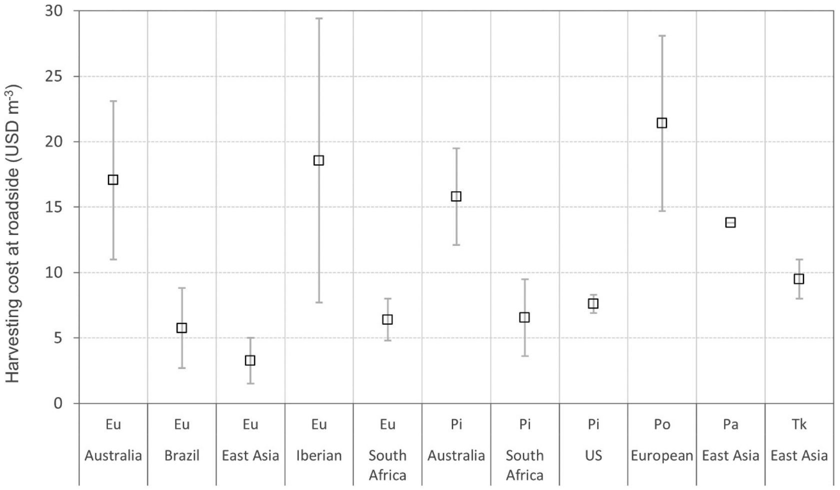

Figure 10. Regional harvesting costs at the roadside (felling, extraction to roadside, and stem processing) for the species included in the study (Eu = eucalyptus, Pi = Pine, Po = Poplar, Pa = Paraserianthes, Tk = Teak) during the period 2010–2020. Squares represent the average value; the grey lines are the cost variation ranges (min, max).

manual/motor-manual work, costs per m^3 are competitive and comparable to those achieved with fully mechanized systems applied in the other regions (Figure 10).

General socio-economic conditions, development of the plantation industry, scale of operations, integration of forest operations in the industry, and business size can influence the selection of equipment and systems in each region. Typical of Brazil and Australia, purpose-built harvesters imported from abroad by large-scale forest companies/contractors co-existed with excavators acquired by smaller contractors on the local market and converted into forest harvesters by adding harvesting heads (also imported from abroad). This investment strategy allows small companies to reduce their investment effort, operate at low hourly operational costs, and maintain high productivity levels. It is also a sensible strategy wherever high import taxes are a reality (Seixas and Ferreira Batista 2012, 2014).

A similar phenomenon can be observed in Thailand, where small contractors invest in labor-intensive operations, whereas larger companies prefer purchasing and retrofitting machinery. Similarly, in South Africa, motor-manual felling is still applied in small-scale operations, whereas fully mechanized systems are applied in large-scale operations. Therefore, capital availability remains a pivotal factor regardless of regional economics.

In some very industrialized countries, like Italy or Spain, motor-manual felling in plantations is still a common practice due to the relatively smaller scale of operations compared to some other regions where the operation scale is relatively larger (Australia, Brazil). The ownership of single small woodlots in Italy or Spain (e.g. <5 ha) can play a significant role in equipment selection, discouraging large investments. The selection of smaller and more basic equipment is also driven by local knowledge available for assistance with specialized forest machinery. This can lead forest entrepreneurs to focus on small equipment or simpler systems based on conventional farm/construction machinery they are already familiar with.

In the US and Iberia, FT and CTL systems are the most common, consistent with the historical development of forest harvesting systems in these regions (i.e. the US and Europe). In other regions, CTL and FT systems are observed to largely co-exist.

In most regions, pulpwood from Eucalyptus plantations is delivered at the industry gate without bark, which is left at the stump or piled at the landing. Therefore, debarking is an additional factor to be considered when designing and planning operations and systems in Eucalyptus plantations if compared to conifers plantations (Murphy et al. 2017).

Full-tree processing is still a significant bottleneck in what are essentially hot systems (Hogg et al. 2010), given the short interaction between feller-buncher felling, subsequent grapple skidder extraction, and debarking/processing with processors. In those cases, the number of log grades also determines the system to use. For many assortments, it might be challenging to process and stack the logs at the landing, particularly in areas with restricted landing/storage space. Here, CTL might be the option. For these reasons, in South Africa, FT systems based on single-stem processing are being replaced by CTL systems with processing and debarking capabilities at the stump (Norihiro et al. 2018). Given the easier removal of bark when wood moisture content is still high, the need to debark trees shortly after harvest further favors CTL operations.

In other regions, there is a tendency toward increasing multi-tree handling in Eucalyptus stands, mainly when stem size ranges between 0.1 and 0.5 m^3 (Bertin 2010). This is so, given that multi-stem handling can reduce the incidence of processing times (bucking, delimbing) and, consequently, the total cost at the roadside of FT systems (Figure 11).

An opposite strategy for coping with hot FT systems in Eucalyptus plantations has been delimbing-debarking-chipping units, which appeared to be a cost-competitive alternative in Australia and the US (Strandgard et al. 2019).

The productivity level shown in this study for specialized harvesters is 40–50 m^3 PMH^{-1} for stem volumes of 0.5 m^3. The highly structured (geometric layout) working environment typical of industrial plantations has allowed achieving these high productivity levels, even when using non-purpose-built equipment. However, given the ongoing expansion of plantations to more challenging sites (e.g. in Brazil or South Africa), a substantial amount of research is being conducted to study the factors (e.g. steep terrain) that can affect the efficiency of the operations in these conditions (Miyajima et al. 2016; Ackerman et al. 2018).

Strengths and weakness of the study

This study included an overview of current systems applied to the harvesting of industrial plantations located in several global regions. Experts from different regions supported and complemented findings from the literature and improved the understanding of trends.

While not exhaustive globally due to the relatively small sample size, the study focused on specific regions where plantations are well-established or still expanding. Some regions, like East Asia, posed challenges in accessing data, mainly due to a language barrier in understanding local literature or conversing with local experts.

The study acknowledges its limitations, as there may be studies carried out by local universities or research institutes that are not published in peer-reviewed journals and were not fully accessible. In some regions, such as the US, a noticeable trend in the last ten years is the abundance of studies on harvesting plantations for energy wood or integrated timber and energy wood production (Ghaffariyan et al. 2017). Conversely, the number of recent studies exclusively focused on the harvesting of roundwood in Eucalyptus or Poplar plantations is finite. This limitation hinders a full comparison of economic performances in the US with those achieved in other regions. The literature gap emphasizes the need for new studies in this field to update current performances and enhance the modeling of future sectoral developments through up-to-date datasets.

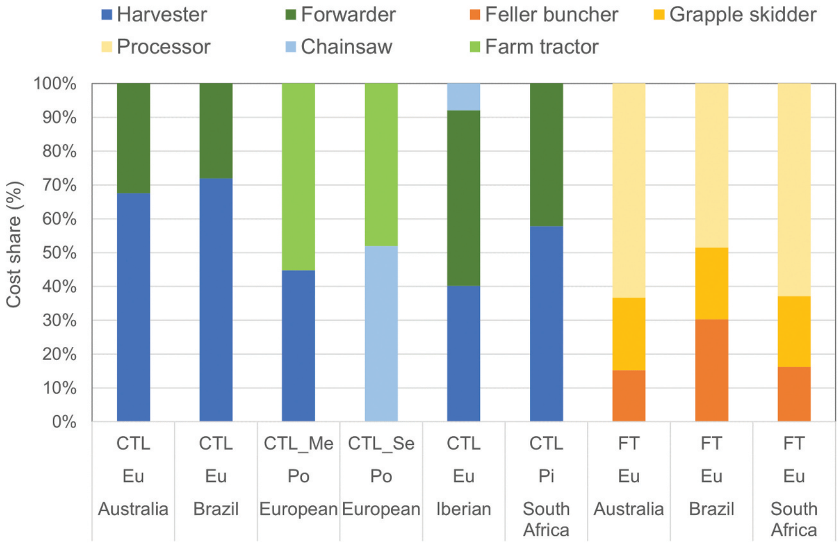

Figure 11. Cost breakdown by harvesting system (CTL, FT) and plantation type (Eu = Eucalyptus, Pi = Pine, Po = Poplar) in the study regions. Me = fully mechanized, Se = semi-mechanized.

Most of the collected studies were based on large-scale operations, and as a result, our study may not represent well small-scale semi-mechanized operations which remain prevalent in many regions. For example, according to our Brazilian expert, motor-manual felling is still widely practiced in the region, yet we could not find published studies reporting productivity and costs for this type of operation in that specific region.

To harmonize the collected data from different studies and regions, we applied standardized factors, converting the data to a common reference unit. For example, the conversion between net and gross productivity was obtained through utilization rates. In some cases, specific factors from the studies were available, or we applied relevant ones for the particular region, as seen in Wenhold et al. (2019) for South Africa. In other cases, we had to rely on more general utilization factors, as described in our methodology. It's important to acknowledge that this approach may have introduced some bias in the comprehensive representation of the local equipment status and usage (Abbas et al. 2021).

In some of the studies analyzed, we encountered units that proved challenging to compare across the dataset. For instance, in one study, the productivity was measured in "trees per hour," which had to be supplemented with stem volume figures to establish a standard volumetric measure (m^3 solid PMH^{-1}). Despite numerous initiatives to establish common data collection standards (Magagnotti et al. 2013; Ackerman et al. 2014), there is still a need to standardize data collection methodologies in forest operation research. Another aspect requiring a standardized approach was the treatment of exchange rates from local currencies to USD. Due to the continuous and rapid fluctuations of exchange rates over time, we could not fully account for the yearly variations in economic competitiveness. However, we opted for this approach due to its simplicity. While there are more sophisticated methods for standardizing monetary values and comparing costs across regions (Di Fulvio et al. 2017), they would entail additional economic assumptions. Additionally, we did not attempt to update costs over time; instead, our goal was to standardize them by limiting the collection period to ten years.

It's essential to emphasize that the costs reported in this study are exclusively those directly associated with the harvesting operation. They do not encompass other cost items such as machinery relocation, operation planning, overhead, operator travel, and other administrative expenses. Including these would result in harvesting costs exceeding the ones reported in the study.

Recommendations for future research

Future harvesting systems and equipment must continuously adapt to specific product combinations based on industrial plantation operational parameters (species, rotations, site conditions) and industrial demands. On one end, some systems focus solely on low-cost mass production of fiber/pulpwood, while others prioritize maximizing value recovery, even at the expense of higher costs.

Moreover, local socioeconomic factors and historical sectorial evolution in each region still significantly influence the selection of harvesting systems, machinery, and mechanization levels.

The peer-reviewed literature considered in this study appears to concentrate on large-scale, highly mechanized systems. It is not solely the cost that determines the equipment selection. This aspect would need to be further examined through dedicated studies to identify the most effective solutions in each region. For example, CTL systems might be preferred where slash must be left in the forest to maintain soil fertility or protect the soil from erosion. In contrast, in cases without those constraints, FT systems could be favored.

Plantations being established on more remote sites, such as those dominated by steep terrain and marginal lands, creates a new challenge for many existing systems and machinery. These are often based on local equipment borrowed from other sectors (such as construction and agriculture). Therefore, their adaptation to more rugged and complex terrain requires further investigation to analyze their pros and cons compared to purpose-built equipment.

Finally, this study highlighted the difficulty of obtaining up-to-date and comparable forest harvesting data. Despite the growing amount of information available on the web through numerous scientific publications and technical reports, there is still a need to establish networks of experts who can assist in compiling and scrutinizing the data collected from these studies.

Conclusions

This benchmarking study offers an overview of the most relevant harvesting systems currently applied in industrial roundwood plantations across different global regions. It enables the identification of current productivity and cost levels, along with factors influencing system selection and performance. Additionally, the study suggests literature gaps and future needs for adapting harvesting systems to evolving conditions.

The study emphasizes the necessity for protocols and guidelines in creating, processing, and updating benchmarking datasets. This ensures that up-to-date information on harvesting productivity and costs is readily available to researchers, practitioners, and decision-makers. Such protocols could be structured as a "Logging Watchdog," providing a continuously updated global database.

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Annex I

Table A1. Benchmarking plantation characteristics, harvesting systems, productivity, and costs across the different study regions.

Country (Region)	Plantation characteristics (rotation length, stem volume, removal per hectare, products)	Harvesting system (CTL= cut to length, TL= tree-length, FT= full tree)	Net productivity (m^3 PMH^{-1})	Hourly operational cost (USD SMH^{-1})	Operational cost per unit of product (USD m^{-3})	System cost per unit of product (USD m^{-3})	References
Australia	*Eucalyptus globulus*, *Eucalyptus nitens*, 8–15 years rotations, stem volume 0.1–0.7 m^3, 200–325 m^3 ha^{-1}, pulp logs and pulp chips	*CTL (logs, debarked and loaded)*				17.7–23.4	Strandgard et al. (2019), Acuna et al. (2017), Lambert et al. (2006), Ghaffariyan (2013), Ghaffariyan and Brown (2013), McEwan et al. (2020), Strandgard et al. (2015), Strandgard et al. (2016)
		Tracked harvester (large excavator/ specialized)	8–55	177	5.8–15.0		
		Forwarder	34		5		
		Loader					
		FT (logs, debarked and loaded)				11.5–23.6	
		Feller-buncher (tracked specialized)	65–140	133–198	2.2–3.6		
		Grapple skidder	32–94	98–128	2.6–5.6		
		Processor	5–66	117–147	8.4–15.8		
		Loader	74–96	115	1.7–1.9		
		FT (woodchips A)				12.9–21.9	
		Feller-buncher (tracked specialized)	65–140	133–198	2.2–3.6		
		Grapple skidder	32–94	98–128	2.6–5.6		
		Delimber-debarker-chipper	50–51		8.2		
		FT (woodchips B)				12.9–21.9	
		Feller-buncher (tracked specialized)	65–140	133–198	2.2–3.6		
		Grapple skidder	32–94	98–128	2.6–5.6		
		Flail-delimber-debarker	64		5.2		
		Chipper	64		5.7		

(*Continued*)

Table A1. (Continued).

Country (Region)	Plantation characteristics (rotation length, stem volume, removal per hectare, products)	Harvesting system (CTL= cut to length, TL= tree-length, FT= full tree)	Net productivity (m^3 PMH^{-1})	Hourly operational cost (USD SMH^{-1})	Operational cost per unit of product (USD m^{-3})	System cost per unit of product (USD m^{-3})	References
Australia	*Pinus radiata*, 32–34 years rotation, stem volume 0.6–3.5 m^3, harvest volume 315–470 m^3 ha^{-1}, sawlogs and pulpwood logs	*CTL*				12.6–20.0	Strandgard et al. (2013), Acuna et al. (2011), Ghaffariyan et al. (2015)
		Tracked harvester (large specialized)	50–160	150			
		Forwarder	86	101			
		FT				15.5–19.6	
		Feller-buncher (tracked specialized)	20–206				
		Swing yarder	30–90				
		Processor on excavator					
Brazil	*Eucalyptus* ssp., *E. grandis*, *E. grandis* x *urophylla*, *E. urograndis*, 4–11 years rotation, stem volume 0.1–0.6 m^3, harvest volume 50–440 m^3 ha^{-1}, pulplogs/ debarked pulplogs	*CTL (A)*				4.9–7.5	Moreira da Costa et al. (2017), Carvalho et al. (2018), Bertin (2010), Simoes and Ferres (2010) , Bramucci (2001), Do Nascimento Santos et al. (2018); Nascimento et al. (2011), Simões et al. (2014), Schettino et al. (2015), Miyajima (2019) , Nascimento et al. (2011) , Mac Donagh et al. (2017), de Oliveira Júnior and Seixas (2012), Seixas and Ferreira Batista (2012), Leite et al. (2014), Spinelli et al. (2018), Spinelli and Conrado de Arruda Moura (2019), Spinelli & Moura (2019)
		Tracked harvester (excavator based)	5–42	53–136	1.3–9.7		
		Forwarder	29–44	72–73	1.8–2.5		
		CTL (B)					
		Feller-buncher (tracked excavator based)(felling)	107				
		Processor (tracked excavator based) (processing in stand)	139				
		FT (logs)				2.7–8.8	
		Feller-buncher (tracked specialized)	10–80	81	0.5–2.5		
		Grapple skidder	40–60		0.3–1.8		
		Slasher/grapple processor	38–57		0.3–4.5		
		FT (woodchips)					
		Feller-buncher (tracked specialized)	10–80				
		Grapple skidder	40–60				
		Delimber-Debarker-Chipper	80–112				

(*Continued*)

Table A1. (Continued).

Country (Region)	Plantation characteristics (rotation length, stem volume, removal per hectare, products)	Harvesting system (CTL= cut to length, TL= tree-length, FT= full tree)	Net productivity (m^3 PMH^{-1})	Hourly operational cost (USD SMH^{-1})	Operational cost per unit of product (USD m^{-3})	System cost per unit of product (USD m^{-3})	References
	Pinus ssp, *P. taeda*, age 15–39, stem volume 0.4–1.6 m^3, harvest volume 400–730 m^3 ha^{-1}, sawlogs and pulpwood	*CTL*					Lopes et al. (2007), Lopes et al. (2014), Pereira et al. (2015)
		Tracked harvester (excavator based)	32–34	115	3.4–3.6		
		FT				1.8–2.6 (unprocessed)	
		Feller-buncher (tracked specialized)	85–130	68	0.6–0.9		
		Skidder	46–63	71–82	1.2–1.7		
		CTL					
		Tracked harvester (excavator based)	32–34	115	3.4–3.6		
		FT				1.8–2.6 (unprocessed)	
		Feller-buncher (tracked specialized)	85–130	68	0.6–0.9		
		Skidder	46–63	71–82	1.2–1.7		
China (South East Asia)	*Eucalyptus grandis*, 3–9 years rotation, stem volume 0.1 m^3, harvest volume 58–115 m^3 ha^{-1}, pulpwood	*CTL*	0.4–0.8 (whole system)			1.5–3.0	Engler et al. (2016)
		Motor-manual felling with the chainsaw					
		Manual delimbing by knives					
		Motor-manual bucking by chainsaw					
		Manual extraction by gravity					
		TL					Hoffmann et al. (2015)
		Chainsaw (felling and delimbing)					
		Cable yarder	5.0–6.2	125	33.8–50.2		
		Chainsaw (processing)					

(*Continued*)

Table A1. (Continued).

Country (Region)	Plantation characteristics (rotation length, stem volume, removal per hectare, products)	Harvesting system (CTL= cut to length, TL= tree-length, FT= full tree)	Net productivity (m^3 PMH^{-1})	Hourly operational cost (USD SMH^{-1})	Operational cost per unit of product (USD m^{-3})	System cost per unit of product (USD m^{-3})	References
Thailand (South East Asia)	*Eucalyptus* ssp., 5–10 years rotation, stem volume 0.1 m^3, harvest volume 50–100 m^3 ha^{-1}, pulpwood	*CTL*	2.9–4.6 (whole system)	8.7–14.0		3.5–5.0	Manavakun (2014)
		Brush saw in felling and bucking					
		Manual tools in delimbing and piling					
		Farm tractor in extraction and loading/manual loading					
	Teak, 20–40 years rotation, stem volume 0.86 m^3, harvest volume 130–170 m^3 ha^{-1}, sawed timber	*TL*				8–11	Rianthakool et al. (2018)
		Motor-manual felling with the chainsaw	25–30		1.09		
		Elephant skidding	5–10		1.38		
		Farm tractor	10–25		0.96		
		Skidder	15–20				
	Rubberwood, 25–30 years rotation, stem volume 0.27 m^3, sawed timber	*CTL*					Rianthakool and Sakai (2014)
		Felling with chainsaw	25.1	22.69	0.90		
		Cross cutting with the chainsaw	23.1	22.67	0.98		
Malaysia (South East Asia)	*Acacia mangium*, 10–15 years rotation, stem volume 0.2–1.2 m^3, harvest volume 85–365 m^3 ha^{-1}	*FT*					Engelbrecht et al. (2017)
		Chainsaw					
		Excavator (bunching)					
		Cable yarder	15–133				
		Excavator with grapple					
Philippines (South East Asia)	*Paraserianthes falcata*, 8–10 years rotation, veneer and plywood	*CTL*				13.8	Carandang et al. (2015)
		Chainsaw felling and processing			2.7		
		Extraction with animal, manual, wrecker			11.1		

(*Continued*)

Table A1. (Continued).

Country (Region)	Plantation characteristics (rotation length, stem volume, removal per hectare, products)	Harvesting system (CTL= cut to length, TL= tree-length, FT= full tree)	Net productivity (m^3 PMH^{-1})	Hourly operational cost (USD SMH^{-1})	Operational cost per unit of product (USD m^{-3})	System cost per unit of product (USD m^{-3})	References
Italy (European Poplar)	*Populus* ssp., 10–23 years rotation, stem volume 0.4–1.6 m^3, harvest volume 200–600 m^3 ha^{-1}, production of veneer, sawlogs, pulpwood and woodchips	*CTL (motor-manual)*				18.1–28.1	Spinelli et al. (2008), Spinelli et al. (2010), Spinelli et al. (2011a, 2011b),) Verani et al. (2017)
		Chainsaw	2–9	28	7.0–17.0		
		Farm tractor	15–22		11.1		
		CTL (semi-mechanized)				18.1–28.1	
		Feller-buncher (excavator based) (felling)	12–13	141	7.0–17.0 (incl. proces.)		
		Chainsaw (processing)	8–12	28	11.1		
		Farm tractor					
		CTL mechanized			5.0–13.0	14.7–24.1	
		Harvester (wheeled specialized)	20–60	146	11.1		
		Farm tractor	15–22				
		Forwarder	29–36				
		FT mechanized				20.8	
		Feller-buncher (excavator based)					
		Grapple skidder					
		Processor	14.3				
Spain and Portugal (Iberian Eucalyptus)	*Eucalyptus globulus*, *Eucalyptus* spp., 10–14 years rotation, stem volume 0.1 m^3, harvest volume 90–270 m^3 ha^{-1}, short logs and pulpwood	*CTL (motor-manual)*					CETEMAS-ENCE (2019) Spinelli et al. (2004) Magagnotti et al. (2011), Dias et al. (2007)
		Chainsaw	4				
		Farm tractor	12				
		CTL semi-mechanized				7.7–10.6	
		Chainsaw (felling)	23–32	16	0.6–0.8		
		Harvester (tracked excavator based) (processing)	22–26	71	3.5–3.6		
		Forwarder/Farm tractor and trailer	9–19	47–93	3.0–6.2		
		CTL mechanized				16.3–29.4	
		Harvester (wheeled specialized)	3–33	115			
		Forwarder	9–19	48–93			

(*Continued*)

Table A1. (Continued).

Country (Region)	Plantation characteristics (rotation length, stem volume, removal per hectare, products)	Harvesting system (CTL= cut to length, TL= tree-length, FT= full tree)	Net productivity (m^3 PMH^{-1})	Hourly operational cost (USD SMH^{-1})	Operational cost per unit of product (USD m^{-3})	System cost per unit of product (USD m^{-3})	References
South Africa	*Eucalyptus grandis* x *camaldulensis*, *E. grandis*, 7–12 years rotation, stem volume 0.1–0.5 m^3, harvest volume 118–160 m^3 ha^{-1}, pulpwood	*CTL (debarked)*				7.0–8.0	Ackerman et al. (2018) Norihiro et al. (2018) Hogg et al. (2011)
		Harvester (tracked eexcavator based/ specialized wheeled incl. debarking)	13–20	137	5.3–8.9		
		FT (debarked)				4.8–5.8	
		Feller-buncher (wheeled specialized)			0.8–0.9		
		Grapple Skidder			1.0–1.2		
		Excavator with processor head (delimbing/ debarking and topping)	18–28		1.8–2.9		
		Slasher deck			0.9		
	Pinus radiata, *P. elliottii*, *P. patula*, *P. pinaster*, 20–30 + years rotation, Stem volume 0.3–1 m^3, harvest volume 257–481 m^3 ha^{-1}, sawlogs, plywood, pulpwood	*CTL (no debarking)*				9.0–9.5	Ackerman et al. (2017), Brewer et al. (2018), Williams and Ackerman (2016), Williams and Ackerman (2019), Eggers et al. (2010), Ackerman et al. (2016), Pellegrini et al. (2013), Ackerman et al. (2014)
		Tracked harvester (specialized)	21–101	90–120	2.6		
		Forwarder	28–57	75–110	1.9		
		TL motor-manual (no debarking)				3.6–5.0	
		Chainsaw	10–13	10–25	1.1–1.5		
		Grapple Skidder	9–46	80–100			
		Cable Skidder	20–45	70–80			
		Chainsaw	20–25	10–25			
		Processor	40–50	80–90	5.0–6.3		
		FT mechanized (no debarking)				4.0–4.4 (unprocessed)	
		Feller-buncher (specialized)	80–120	80–90			
		Grapple/Cable Skidder	44–124	70–80			
US	*Pinus taeda*, *P. elliottii*, 14–30 years rotation, Stem volume 0.2–0.6 m^3, Harvest volume 80–223 m^3 ha^{-1}, sawlogs, pulpwood, pulp chips	*FT (logs)*				6.9–8.3	Conrad et al. (2013), Daniel et al. (2019) Baker et al. (2010) Klepac and Mitchell (2016) Klepac and Mitchell (2017) Klepac and Rummer (2000)

(*Continued*)

Table A1. (Continued).

Country (Region)	Plantation characteristics (rotation length, stem volume, removal per hectare, products)	Harvesting system (CTL= cut to length, TL= tree-length, FT= full tree)	Net productivity (m^3 PMH^{-1})	Hourly operational cost (USD SMH^{-1})	Operational cost per unit of product (USD m^{-3})	System cost per unit of product (USD m^{-3})	References
		Feller-buncher (specialized tracked)	82–149				
		Grapple skidder	24–113	55–69	1.6–2.0		
		Delimber/Loader delimber	43–63		1.5–1.9		
		Processor/Processor on excavator	43–94				
		Loader	43–63				
	Eucalyptus camaldulensis, E viminalis, 7–10 years rotation, Stem volume 0.1–0.2 m^3, pulp chips	*FT (pulpchips)*				8.2–12.9	Spinelli et al. (2002)
		Feller-buncher (specialized wheeled/tracked)	24–32	53–94	2.4–4.8		
		Skidder/Loader	49–83	62–69	1.2–1.8		
		Deliber-debarker-chipper	30–38	157–169	4.5–6.3		
	Poplar spp., 6–8 years rotation, Stem volume 0.13 m^3, sawlogs, pulp chips	*FT (pulpchips)*				5.2	Spinelli et al. (2008), Hartsough et al. (2002)
		Feller-buncher	42	82	1.8		
		Forwarder	92	89	0.9		
		Delimber-debarker-chipper	60	175	2.6		
		FT (sawlogs)				17.4	
		Feller-buncher	42	82	1.8		
		Forwarder	92	89	0.9		
		Manual selection	5	75	14.5		
		Processor (on excavator)	17	80	5.3		