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The Influence of Various Silvicultural Treatments and Forest Operations on Tree Species Biodiversity

Francesco Latterini[1] · Piotr S. Mederski[2] · Dirk Jaeger[3] · Rachele Venanzi[4] · Farzam Tavankar[5] · Rodolfo Picchio[4]

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Abstract

Purpose of Review Biodiversity is one of the most important features of forest ecosystems. One of the goals of Sustainable Forest Management is to reduce biodiversity disturbance, which can occur as a consequence of timber harvesting. The aim of this review was to define which silvicultural systems and forest operations can have an influence on forest tree biodiversity by summarising the findings of nearly 60 papers published in the last ten years (2013–2022).

Recent Findings In natural forest ecosystems characterised by a high level of structural complexity, such as uneven-aged tropical forests, selective logging and retention forestry are, in general, suitable forms of intervention that have a limited impact on tree biodiversity. Forest operations, in particular, should be of low intensity and try to simulate as much as possible small-scale natural disturbances. Thinning has proved to be a valid treatment for managing tree biodiversity. However, it is important to shape the magnitude of thinnings according to the management aims. Limited removal is recommended in interventions for maintaining the current structure, and more extensive removal is appropriate in cases when a change in species composition is expected, e.g. in the conversion of planted coniferous stands to uneven-aged mixed or broadleaved stands. In addition, coppicing is suitable for maintaining tree biodiversity due to its effectiveness in fostering the presence of light-demanding tree species. Findings show that it is important to establish the right rotation age, considering that an excessively short period between coppicing interventions can be detrimental to functional biodiversity.

Skid trails and landing sites represent suitable areas for the initial establishment of natural regeneration. However, generally, the level of biodiversity on these sites declines with time as a consequence of soil compaction, thus highlighting the importance of the forest infrastructure network planning.

Summary In uneven-aged tropical forests, selective logging and retention forestry are the most suitable options for maintaining tree biodiversity. Thinning and coppicing help to manage biodiversity, whilst intensive thinning helps to change species composition. Skid trails and landing sites can support natural regeneration. Recommendations and management options were developed, as well as possible future research directions. The authors recommend that future studies should investigate how much tree biodiversity depends on different levels of harvesting technology applied within the same silvicultural treatment.

Keywords Harvesting · Sustainable forest management · Selective logging · Retention forestry · Thinning · Coppicing · Skid trails

Introduction

Forests are crucial ecosystems for maintaining biodiversity [1]. Currently, a substantial area of forest is actively managed and, considering the growing demand for renewable energy and timber, this scenario is unlikely to change in the near future [2••]. In Sustainable Forest Management (SFM), it is therefore vital to consider the issue of biodiversity conservation within the framework of active forestry [3, 4]. Indeed, management is not only able to shape the biological

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✉ Piotr S. Mederski
piotr.mederski@up.poznan.pl

Extended author information available on the last page of the article

diversity of forest ecosystems [5], but also can jeopardise it in the case of poor management [6]. Taking the above into consideration, one of the most important challenges for forest managers is to ensure the conservation of tree diversity whilst fulfilling the traditional objectives of forest management, most notably timber harvesting [7••].

Biodiversity could be regarded as key to life-sustaining ecological services such as nutrient cycling, photosynthesis, decomposition, soil creation, micro-climate regulation, pollution mitigation and maintenance of ecosystem resilience. The presence of more species in an area gives a more complex structure to natural ecosystems, and as a result, these ecosystems are more capable of responding to change [8, 9•, 10, 11]. For instance, plant diversity positively affects the provisioning of useful plant products, erosion control, resistance to other invasive plants and pathogen regulation [12]. Obviously, there is no universal rule indicating that the more species there are, the higher the quality of the ecosystem. However, the maintenance of a suitable level of biodiversity should always be considered as contributing to sustainable forest management.

Forest management, and forest operations in particular, do not always negatively impact the maintenance of biodiversity, nor adversely affect an increase in biodiversity [13•]. In primary forests, it is highly probable that most management activities will generate losses of tree biodiversity. However, in some cases, in actively managed forests over the short and medium term, there is an increase in tree biodiversity [14–17]. It is worth noting that active forest management and the steps taken towards mitigating the consequences of climate change may be positive tools for maintaining and increasing tree biodiversity. For this reason, the introduction of broadleaved tree species to replace coniferous ones can be observed as suitable policy supporting biodiversity [18, 19••].

Logging can result in changes in environmental conditions, such as altered light, humidity and wind speed, thereby putting forest species under stress [20, 21]. Local biodiversity loss due to timber extraction can disrupt the long-term resilience of forests, which may in turn lead to an impoverished delivery of ecosystem services, and also ultimately affect human well-being [22, 23•, 24]. The most evident consequence of forest management in stands is the removal of trees [25]. This change in stand density may also potentially lead to some modification in tree species diversity [26], considering that species composition affects forest structure [27]. The possibility of applying different silvicultural and forest engineering options makes forest management even more complex, leading to variety of ways in which forestry can alter forest biodiversity.

The aim of this review was to investigate the implications of different silvicultural treatments and harvesting systems on the biodiversity of vascular plants in forests, including trees. Additionally, the aim was also to outline the current knowledge on the topic and, finally, to suggest future research directions. In terms of silvicultural treatments, the authors investigated the impact of clear cuts, selection and shelter cutting, as well as thinnings, coppicing and crop tree management on the future biodiversity of tree species. Regarding harvesting options, the authors referred to the infrastructure needed for forest operations (skid trails, strip roads and landing sites), different wood systems, such as the short wood system (SWS), including cut-to-length (CTL) technology, the tree length system (TLS) and whole-tree system (WTS). Different levels of technology and various machine use for forest operations were also considered to have an impact on biodiversity.

It is important to underline that the concept of biodiversity is much more complex than a simple indicator, such as the number of species in a stand per unit of area [28]. Indeed, according to Noss [29], biodiversity can be subdivided into composition, structure and function [29]. Composition is mainly related to species richness, whilst structure refers to features such as the presence or absence of microhabitats or deadwood and tree size distribution. Functional diversity (FD) is a major feature of the ecosystem as it measures the extent of an organism's role in the environment. For instance, tree species that are effective in creating ecological niches or tree roots which fix nitrogen from the air in cooperation with symbiotic soil organisms [2••]. Considering the importance of all these concepts, the authors decided to analyse them separately. The presented work focuses on the implication of forest management on forest tree biodiversity in terms of composition and function, whilst structure will be analysed in a future review.

Methods

A systematic search of the literature was carried out using the Scopus and Web of Science databases applying the keywords: clear cut, clear cutting, shelterwood system, selective logging, retention forestry, thinning, coppice, coppicing, crop tree management, harvesting system, harvesting method, wood system, skid trail, strip road, forest operations, forest management, biodiversity, richness and evenness, and linking them with the Boolean operators AND or OR.

To further increase the number of literature sources, the authors applied the snowball system, which entailed the use of a reference list of recent papers to identify further suitable references, starting from the most recent publications on the topic.

The first screening was carried out by limiting the published research to those findings in the English language, from the last 10 years, 2013–2022. This screening revealed an increasing number of published papers on the topic, thus highlighting researchers' growing interest in the relationship between forest management and biodiversity (Fig. 1).

A further refining process was carried out by reading the title and abstract of each paper and including it in the database only when it fulfilled two of the following criteria: the paper had to refer to the biodiversity of tree species, and not only to herbaceous species, and the paper had to report the biodiversity values of a control treatment on an unharvested area with similar characteristics to the harvested area. Using this process, 56 papers were identified and categorised according to six topics, as suitable and useful for the review. Selective logging proved to be the most investigated category, but a certain amount of attention was also given to coppicing, thinning and to the direct influence of forest operations (Fig. 2). Most of the studies were located in tropical or temperate zones, which also proved to be the areas in which more treatments were investigated (Fig. 2).

Results and Discussion

Before revealing the findings from the literature search, it is worth introducing the issue of the relationship between forestry and biogeography, i.e. that different zones of the world and different climate conditions imply various

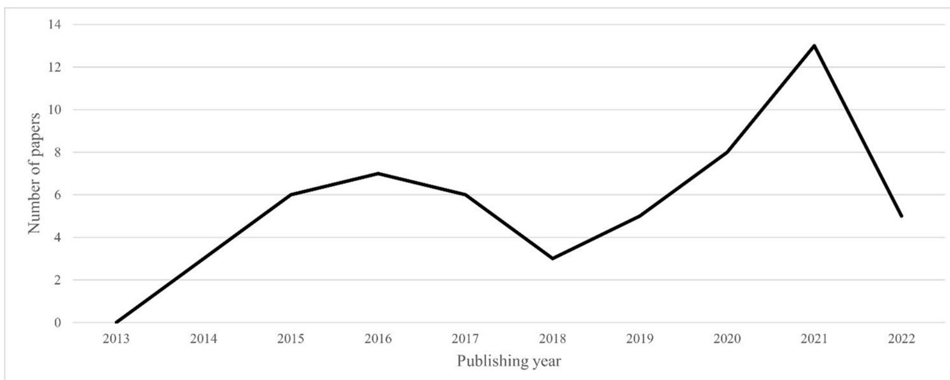

Fig. 1 Relationship between forest management and biodiversity, as a topic explored in published papers from 2013 to 2022. For the year 2022, the number of papers published by May 2022 was multiplied by 2.5

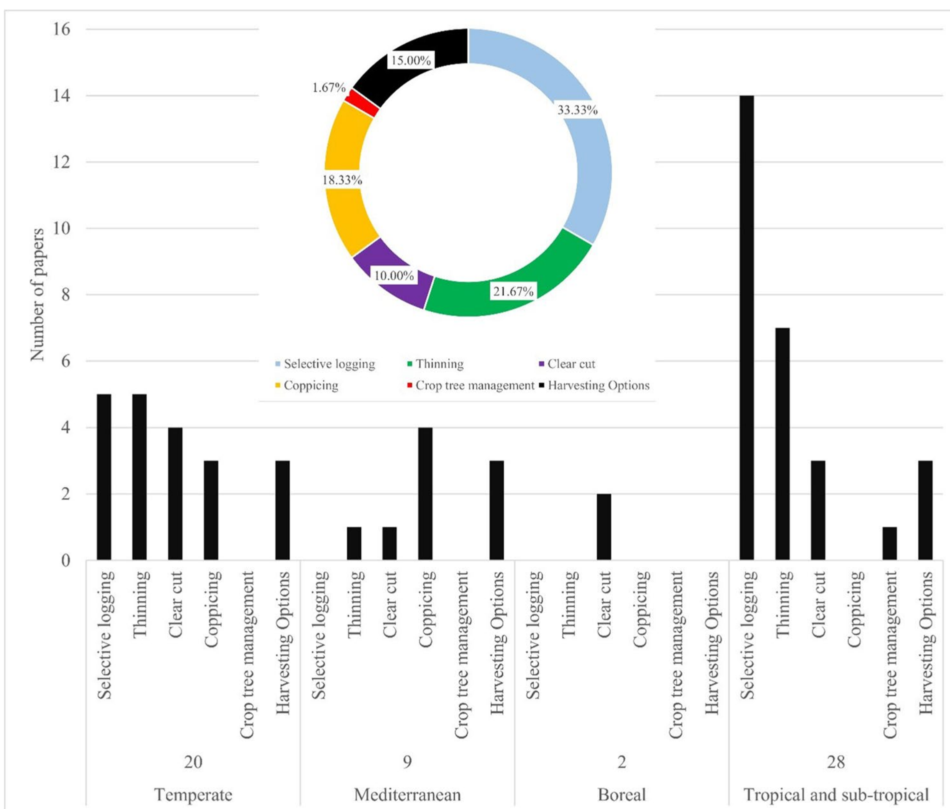

Fig. 2 The distribution of papers per topic (top) and number of papers per topic in represented biogeographical zones (bottom). The total number of papers reported in the figure is not equal to 56 as reported initially, as some of them dealt with two topics simultaneously, such as thinning and clear cut in the same study area

management options, developed as *good practice* over several decades of forest management. In addition to environmental aspects, historical, political and socioeconomic reasons have shaped and generated primary forest management systems [30, 31]. Over recent decades, increased attention to environmental issues on a global scale has given rise to the strengthened concept of SFM [32, 33], which has been extended to Sustainable Forest Operations (SFO) [3].

In tropical forests, selective logging is the most often applied treatment, probably because it is an approach which can, or should, simulate small-scale natural disturbances, thus ensuring the natural regeneration of a complex ecosystem [34, 35]. This approach of SFO evolved from Reduced Impact Logging (RIL), which was developed specifically for tropical forests, but nowadays also used worldwide [36].

In temperate and boreal zones, forestry in the last few years has been shaped by a balance between the paradigm of Continuous Cover Forestry (CCF) and the application of rotation forestry [37–39], both linked to the pure application of SFO [40].

In contrast, in Mediterranean zones, the development of a hybrid forest management system is observed, which is dedicated to high forests with approaches close to CCF, or coppice forests, where silvicultural techniques are constantly evolving (tree silviculture, groups of stands and systemic approaches) [41]. Moreover, in small-scale forestry, coppice management has considerable importance, and after a period of abandonment in the previous century, it has started to occupy a crucial role again in Mediterranean forestry, mostly for the production of fuelwood as a renewable energy source [41–43]. Forest operations in the most sensitive areas were carried out by adapting the RIL guidelines to specific scenarios, and planning and implementing forest operations to sustain or enhance forest services and functions [44, 45]. This was shaped further into the paradigm of SFO.

In general, biodiversity conservation and, specifically, tree biodiversity is crucial for forestry, but the management goals have to be formed by taking into consideration the biogeographical context. There is no one model of biodiversity which is universal throughout the world; for example, in planted stands in boreal conditions, it is not possible to reach and maintain a level of biodiversity and structural complexity that is typical for tropical uneven-aged forests. However, forestry can be adjusted in order to make sure that planted stands are not monocultural, ensuring a certain amount of biodiversity and also a share of natural regeneration, by, for instance introducing the shelterwood system, or converting, when suitable, pure stands into mixed ones [46, 47•, 48].

Influence of Silvicultural Treatment on Forest Biodiversity

Selective Logging

There have been a substantial number of studies on selective logging that have evaluated the influence of silvicultural treatment on forest tree biodiversity. The majority of these studies had been located in tropical or subtropical zones, but research on this topic have also been carried out in a temperate climate. Selective logging is considered to be one of the less impactful treatments, considering that it mimics small-scale natural disturbances, such as the collapse and decomposition of a large tree, to induce natural regeneration [49, 50]. However, the results obtained from the literature search on the influence of this treatment on forest tree biodiversity are rather diverse, particularly when a further variable is introduced into the evaluation, that is, the recovery time needed after logging to fully restore the biodiversity level to pre-intervention values.

The majority of the analysed studies highlighted no difference or just a slight decrease in vascular plant richness and evenness between forest stands harvested via selective logging and control areas with unharvested stands [51–54]. Furthermore, several studies highlighted the influence of selective logging on tree biodiversity and the magnitude of the intervention, with limited biomass removal (removal of approximately 3 trees per hectare equal to a harvest volume of approximately 20 m^3 per hectare) generally leading to a lower impact on biodiversity indices [55–57]. When applying group selection cutting, opening size did not show any effect on species richness in regeneration. However, smaller openings of 6–20 m in diameter (single tree selection) were more effective in achieving a regeneration with a higher density and richer species composition. In particular, when openings were larger than 46 m in diameter (mainly for group selection), they were unsuccessful, and further human intervention, such as thinning of the regenerating vegetation and herbivore protection, were needed to ensure successful regeneration [58]. On the other hand, some changes in functional diversity after selective logging have been detected, such as a shift from a deciduous to evergreen phenology [59] or an increased number of vines [60].

As anticipated above, there is even more contrast when dealing with the issue of the time needed after selective logging to restore the biodiversity level. Identified recovery time ranged from five years [61] to more than 40 years [62]; some studies also reported increasing species richness in selectively logged stands after 27 years [63].

Another study carried out in Central Amazonia reported increased regeneration growth, up to three years after selective logging, but an increased mortality rate of seedlings and saplings in logged areas up to 11 years after intervention.

It was speculated that, over time, the habitat becomes less suitable for species regeneration in selectively logged stands [64]. On the other hand, in studies carried out with the goal of comparing the effects on biodiversity of selective logging and other treatments, mainly clear cutting, use of the CCF technique was more successful in maintaining biodiversity [65]. The same was also confirmed in terms of functional biodiversity, with a higher number of shade-tolerant species found in selectively logged rather than clear cut stands, 40 years after intervention in a tropical rain forest [66]. Finally, illegal harvesting and repeated selective logging were found to be detrimental to tree biodiversity [67, 68], highlighting once more the importance of forest management planning and monitoring [69–71].

Thinning and Crop Tree Management

The results presented in the literature regarding the effects of thinning treatments on forest tree biodiversity are much more consistent than those found for selective logging. Indeed, thinning proved to be an effective tool for the positive management of tree biodiversity, mostly in planted stands [72, 73]. The main aspect investigated in the literature was the effect of different magnitudes of thinning intervention. In general, lower intensity thinning proved to be more effective in preserving biodiversity [74]. However, this statement should not be taken as dogma. Indeed, it is crucial to ensure biodiversity conservation when shaping a thinning pattern, according to the kind of stand and to the management goal.

In planted coniferous stands where conversion is planned in order to replace softwood species with native hardwoods, thinning is a powerful tool for the quick promotion of natural regeneration and increased tree biodiversity [75–77]. The magnitude of intervention can also be substantial, where up to 60% of pre-intervention biomass can be removed on one occasion for conversion purposes [78–80]. Furthermore, thinning in the coniferous forests of the Pacific Northwest in the USA led to increased richness, which also remained stable 17 years after the intervention and with the negligible appearance of invasive species [81]. This highlights, therefore, that thinning does not trigger biological invasions. However, this conclusion needs further investigation in different kinds of forests.

In more complex stands, such as tropical rain forests, in which the management goal should rather be conservation of the *status quo*, lower biomass removal during thinning is suggested since excessive thinning can have detrimental effects not only on functional diversity, but also on tree species composition [82]. Indeed, thinning with intensity of about 33% of biomass removal proved to favour late-successional species, whilst more intensive biomass removal led to the co-dominance of all successional states [83].

Concerning crop tree management, only one paper dealing with the effects of this treatment on tree biodiversity was found in the selected period. This study referred to a *Pinus massoniana* Lamb. plantation in subtropical China and the main results highlighted how crop tree management could increase the Shannon–Wiener biodiversity index of the shrub layer. Obviously, considering the increasing attention towards this silvicultural treatment [84, 85], much more effort should be devoted to investigating the effects of crop tree management on vascular plant biodiversity.

Clear Cutting and Coppicing With Standards

Turning now to clear cutting and coppicing with standards, we leave the framework of retention forestry, which is generally considered less impactful [86]. However, as found for the other investigated treatments, large-size interference in the forest cover does not necessarily lead to a significant negative impact on tree biodiversity, although this depends on management goals.

In sensitive ecosystems such as riparian forests, clear cutting proved to be a strong driver changing functional diversity, triggering ruderal invasive species [87]. Therefore, clear cutting should be limited in such stands in favour of retention forestry as much as possible [88]. On the other hand, there are situations in which clear cutting can act as a shock treatment to induce regeneration or increase the biodiversity of abandoned or degraded stands [89]. For instance, clear cutting can be beneficial in favouring native hardwood colonisation in coniferous plantations [90, 91], and in maintaining the richness and evenness of open environments such as savannas, also in the medium term [92]. Furthermore, gap clear cutting can promote natural regeneration in closed-canopy temperate oak-dominated forests [93] and limit the presence in the seedling pool of strongly competitive species such as beech (*Fagus sylvatica* L.) and initiate the presence of different species, such as maple (*Acer* spp.) and ash (*Fraxinus* spp.), instead.

In contrast, coppicing with standards is an effective management option for sustaining tree biodiversity in the long term [94, 95], although coppice aging and abandonment can lead to general landscape and habitat simplification [96]. In comparison to beech high forest, coppice stands present a higher share of light-demanding species [14, 97, 98, 99•]. However, it is worth highlighting that proper forest management and planning is vital in coppice forests. Indeed, an excessive short rotation (10–15 years) resulted in a considerable change in functional diversity in black alder (*Alnus glutinosa* (L.) Gaertn.) coppice forests in Northern Italy, with a substantial increase in non-native and ruderal species, notwithstanding a higher richness and Shannon–Wiener biodiversity index [100]. Therefore, planning of the rotation, taking into account the edaphic features of the stand, is crucial for the long-term sustainability of coppice [41].

Influence of Forest Operations on Tree Biodiversity

Forest Infrastructure

The forest infrastructure network, including skid trails, strip roads, secondary roads and landing sites, is essential for effective forest management [101–104]. However, these elements of infrastructure, most of all the ones specifically established during forest operations such as skid trails, strip roads and often landing sites, too, are parts of the forest in which there is a significant level of soil disturbance caused by machine passes [13•, 105]. Therefore, it is expected that the presence of these elements within forests can somehow shape tree biodiversity. In the last 10 years, the influence of the infrastructure relating to forest operations on tree biodiversity was investigated in six papers. The results of these studies are rather consistent.

Skid trails proved to be sites in which there is generally an equal or even higher species richness in comparison to unharvested, control areas. On the other hand, these zones also represented a marked change in functional diversity, with a significant increase in the presence of light-demanding and pioneer species [15, 106, 107]. A major aspect being considered is the degree of disturbance to the soil on skid trails and landing sites. Higher traffic intensity, causing higher soil compaction [108], can lead to a decrease in the number and diversity of seedlings [16, 109]. Furthermore, a study carried out in the Amazon forest revealed that, after eight years, tree richness returned to the pre-harvest condition on skid trails, but not on landing sites and secondary roads, due to the major compaction on these sites linked to a higher number of machine passes [110]. A study conducted in the temperate zone in Europe suggested that, in the short term, the richness of both heliophilous and mesophilous species increased on skid trails, but the abundance of these decreased in the medium term (> 12 years) [111]. These results demonstrate the importance of skid trail network planning [112–114]. The accurate design of a skid trail network will firstly limit the disturbed area of the forest by reducing skidding and winching distances. Secondly, it will prevent any damage to the soil and the stand during timber extraction from the forest. Therefore, more precision in the design of skid trails will reduce damage caused to the remaining trees in the forest [112], reduce soil compaction [113, 114] and reduce the edge effects of skid trails, which in turn will increase the regeneration capacity of forest trees and preserve tree biodiversity. Indeed, although initially triggering light-demanding species regeneration, in the long term these zones have harsher conditions for the proper development of seedlings when growing in areas of substantial soil compaction [115, 116].

Applying best management practices to decrease soil compaction and the amount of forest soil disturbed by machinery during ground-based operations is therefore crucial for sustainable forest management, as well as for safeguarding tree biodiversity [40, 117]. The planning of forest operations, via the application of best management practices [40] and modern technology, can increase the overall sustainability of logging [118]. Therefore, modern technology (usually CTL technology) is the way to develop sustainable forest operations, merging the environmental, economic and social needs of forestry [3].

Wood Systems and Technological Level of Mechanisation

Regarding the implications of forest operations for biodiversity, the authors referred to the terms and definitions differentiating wood systems and levels of mechanisation (Fig. 3).

In the recently published literature, substantial attention to the implications of silvicultural treatments for biodiversity is noticeable, whilst forest engineering is underrepresented. Only three studies have been detected that deal with the effects of the different applications of forest operations on tree biodiversity. Different machinery can cause different levels of disturbance to forest soil, and thus differentially affect tree species regeneration [108, 116].

Concerning wood systems, Venanzi et al. (2019) analysed the influence of WTS, TLS and SWS on the Shannon–Wiener biodiversity index and evenness after coppicing in a Mediterranean turkey oak stand [99•]. The results obtained indicated that the Shannon–Wiener biodiversity index did not differ from the control values for the three systems six months after the intervention. However, 16 and 36 months afterwards, there was a decrease for all three systems, which resulted in a full recovery for TLS and WTS after five years, whilst for SWS the difference from the values in the control area was still significant after five years. In contrast, the evenness of species (i.e. the distribution of individuals amongst the various species in the stand) was still lower than in the unharvested control areas in all the three applied systems [99•].

In a study carried out in secondary Atlantic forests in Brazil [119•], two motor-manual timber harvesting techniques were analysed. The harvesting methods differed mostly in the amount of training received by the chainsaw operators, local experience and timber extraction devices. Besides productivity assessment [119•] and analysis of

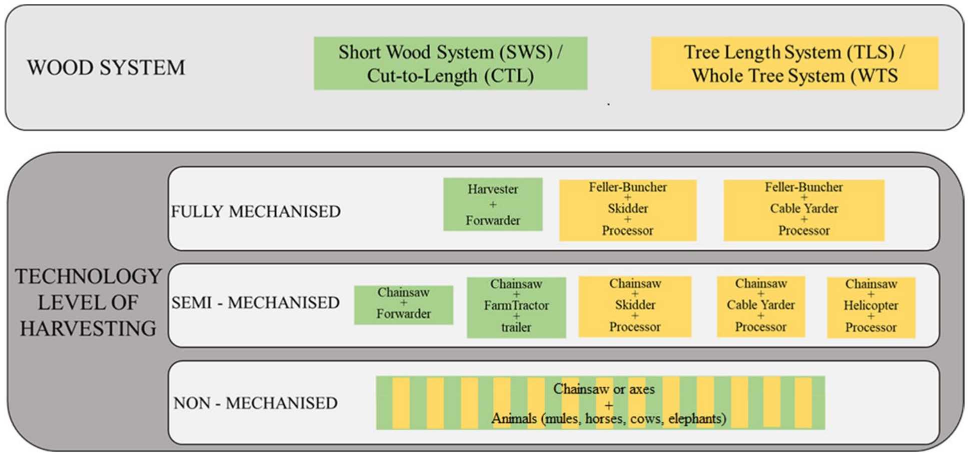

Fig. 3 Wood systems and related technology levels of harvesting. The same colour of wood system and machinery indicates the possibility of applying that machinery for that wood system. For example, SWS/CTL is applicable in (1) fully mechanised technology with harvester and forwarder; (2) semi-mechanised level with chainsaw and forwarder or chainsaw and farm tractor with trailer; and (3) non-mechanised level with chainsaw and animals used for timber extraction (please note that this technology level runs for the two systems)

felling and extraction damage to remaining trees [120], species composition was investigated two years after intervention [121•]. The results of the latter showed (amongst trees with a diameter at breast height > 5 cm) an increase in palm trees and secondary species, irrespective of applied harvesting technique. However, with respect to tree regeneration and the number and intensity of damaged trees remaining, the harvesting technique including additional extraction tools, such as a snatch block or a skidding cone, showed significantly better results [121•]. This, therefore, highlights the importance of applying best management practices and mitigation strategies for the sustainability of forest operations.

Focusing on the influence of different extraction systems, a recent case study [17] compared extraction by horse, a forestry-fitted farm tractor equipped with a winch, and a medium-gravity cable yarder in the context of tree diversity after strip clear cutting in black pine (*Pinus nigra* Arn.) forest in Central Italy. Interestingly, all three systems showed higher species evenness in comparison to the unharvested control stand, whilst winching also led to an increase in the Shannon–Wiener biodiversity index. It seems, therefore, that for this kind of intervention, the disturbance that occurred after timber winching with the removal of a substantial amount of pine litter initiates the establishment of seedlings and the consequent level of biodiversity of tree species [17].

The influence of the operational part of forestry interventions on tree biodiversity should, however, be investigated further. The influence of various applications of forest operations on forest biodiversity is not only limited to implications in natural regeneration. Indeed, different wood systems and different level of harvesting technology can cause varying levels of damage to the residual stand [13•]. Considering that the regenerative ability after logging damage varies amongst the various tree species [122], this damage could be a further influencing factor for biodiversity. It might, therefore, also be interesting to test this hypothesis in medium- and long-term studies.

Summary and Future Research Directions

In complex forest stands, such as uneven-aged tropical forests, selective logging and retention forestry are the most suitable options for maintaining tree biodiversity — interventions should be minimal and mimic as much as possible small-scale natural disturbances. Thinning is a useful option for managing tree biodiversity. The magnitude of thinning should be shaped according to the management goals, i.e. light removal in interventions aimed at keeping the current stand structure, whilst a more intensive removal is recommended when managers want to induce or facilitate a change in species composition (a typical example is the conversion of planted coniferous stands into uneven-aged mixed or broadleaved stands).

Coppicing is a suitable option for maintaining tree biodiversity by triggering the presence of light-demanding tree species. Attention should be paid to the establishment of a proper rotation age, considering that an excessively short time between coppicing interventions can be detrimental to functional biodiversity.

Finally, skid trails and landing sites can represent suitable zones for the initial establishment of natural regeneration, however in these areas it is common to observe changes in functional diversity, with higher presence of light-demanding and pioneer species. Therefore, the planning of the forest infrastructure network, that is in fact dependant on machines used, is crucial for the sustainability of forest operations, considering that these can have a substantial impact on biodiversity.

Considering the above remarks, it can be stated that future research should cover a comparison of different silvicultural treatments in the same study area. There is also a lack of studies that evaluate tree biodiversity after logging in the long term. In the future, studies should cover the impact of the technological level of forest operations on stand biodiversity, possibly on the whole forest ecosystem.

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Compliance with Ethical Standards

Conflict of Interest The authors declare that they have no conflict of interest.

Human and Animal Rights and Informed Consent This article does not contain any studies with human or animal subjects performed by any of the authors.

Disclaimer The views and opinions in this manuscript are those of the authors. They do not purport to reflect the official policies of the European Union or the European Commission.

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Authors and Affiliations

Francesco Latterini[1] · Piotr S. Mederski[2] · Dirk Jaeger[3] · Rachele Venanzi[4] · Farzam Tavankar[5] · Rodolfo Picchio[4]

Francesco Latterini
latterini@man.poznan.pl

Dirk Jaeger
dirk.jaeger@uni-goettingen.de

Rachele Venanzi
venanzi@unitus.it

Farzam Tavankar
fa.tavankar@iau.ac.ir

Rodolfo Picchio
r.picchio@unitus.it

[1] Institute of Dendrology, Polish Academy of Sciences, Parkowa 5, 62-035 Kórnik, Poland

[2] Faculty of Forestry and Wood Technology, Department of Forest Utilisation, Poznań University of Life Sciences, Wojska Polskiego 71A, 60-625 Poznań, Poland

[3] Faculty of Forest Sciences and Forest Ecology, Department of Forest Work Science and Engineering, University of Göttingen, Büsgenweg 4, 37077 Göttingen, Germany

[4] Department of Agriculture and Forest Sciences, University of Tuscia, Via San Camillo de Lellis, 01100 Viterbo, Italy

[5] Department of Forestry, Islamic Azad University, Khalkhal Branch, Khalkhal 56817-31367, Iran