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Original Article

Field estimation of fallen deadwood volume under different management approaches in two European protected forested areas

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Abstract

Fallen deadwood is essential for biodiversity and nutrient cycling in forest ecosystems. In modern forest management, there is growing interest in developing accurate and efficient methods for field estimation of deadwood volume due to its many benefits (e.g. carbon storage, habitat creation, erosion control). The most common methods for deadwood inventories are fixed-area sampling (FAS) and line-intersect sampling (LIS) methods. While the estimations of deadwood volume by LIS generally show results comparable to FAS estimations, active management (e.g. production forestry clearcutting, logging, and thinning activities) can impair LIS accuracy by changing local deadwood patterns. Yet, the comparison of LIS and FAS methods has typically focused on production forests where deadwood is limited and deadwood volumes are comparably low. In this study, we assessed fallen deadwood volume in two large national parks—one being a more actively managed landscape (including, e.g., selective thinning for maintaining cultural–historical values and enhancing recreational opportunities) with overall lower levels of fallen deadwood, and the other having a strict non-intervention approach with higher levels of deadwood. No significant differences between average FAS and LIS estimations of deadwood volumes were detected. Additional experimentations using simulated data under varied stand conditions confirmed these results. Although line-intersect sampling showed a slight overestimation and some variability at the individual plot level, it remains an efficient, time-saving field sampling method providing comparable results to the more laborious fixed-area sampling. Line-intersect sampling may be especially suitable for rapid field inventories where relative changes in deadwood volume rather than absolute deadwood volumes are of large interest. Due to its practicality, flexibility, and relative accuracy, line-intersect sampling may gain wider use in natural resource management to inform national park managers, foresters, and ecologists.

Keywords: coarse woody debris; sampling methods; fixed-area sampling; line-intersect sampling; temperate mixed forest; forest management

Introduction

Monitoring deadwood volumes in forest national parks is vital since deadwood amount influences forest recreational and biodiversity values, as well as fire risk (Montes and Cañellas 2006, Tomppo et al. 2010). Deadwood also plays a crucial role for many forest ecosystem functions (Heilmann-Clausen and Christensen 2005, Bani et al. 2018, Shannon et al. 2022). As a fundamental resource for saproxylic species such as beetles and fungi, deadwood plays an important role in shaping the composition, structure, and diversity of these communities (Lassauce et al. 2011, Haeler et al. 2021). For instance, many ecological studies identified thresholds for the amount of fallen deadwood necessary to promote the presence of saproxylic species, including endangered species (see Müller and Bütler 2010). With its proven relevance for biodiversity, deadwood is becoming an important management consideration for national parks, as well as policymakers and private companies aiming to increase the sustainability of their operations (Deal 2007, Mazziotta et al. 2023).

Traditionally, dead trees and logs were and are still removed from managed stands for various reasons, such as ensuring safety (e.g. preventing forest fires and ensuring hikers' security), harvesting wood for timber production or firewood, or attempting to manage pest outbreaks (Montes and Cañellas 2006). In parks and forests with high recreational use, forest managers tended to remove deadwood because it was associated with mismanagement and was considered aesthetically unappealing, especially in highly managed landscapes (Arnberger et al. 2018, Vítková et al. 2018). As a result, forests in which deadwood is actively removed are characterized by lower amounts of deadwood and fewer fallen deadwood logs remaining in the stand as compared to natural forests with a strict non-intervention approach (Fridman and Walheim 2000, Siitonen et al. 2000, Gibb et al. 2005, Böhl and Brändli 2007, Lombardi et al. 2008, Vandekerkhove et al. 2009, Paletto et al. 2014, Puletti et al. 2019). With a better understanding of its associated functions, deadwood perception, however, evolved in the past decades. For instance, a survey conducted in the Bavarian Forest National Park (Germany) demonstrated that

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deadwood now contributes to the park's recreational value by adding structural diversity (Sacher et al. 2022). This change in perception is also apparent with a shift toward more nature- or biodiversity-oriented management, a strategy that became more prevalent within natural reserves and forest national parks in Europe (Bujoczek et al. 2021).

Due to its importance for biodiversity and recreational values, accurate assessment of fallen deadwood volume became increasingly relevant. Various sampling methods have been developed to measure fallen deadwood volume in forests, among which fixed-area sampling (FAS) and line-intersect sampling (LIS) are the preferred methods (Ståhl et al. 2001, Rondeux and Sanchez 2010, Kershaw et al. 2016). Fixed-area sampling is an area-based method that requires the measurements of all fallen logs within the sampled area. It is a method prone to non-detection errors in high deadwood-density areas because it is easy to overlook a log in those conditions (Jordan et al. 2004). It is also a time-consuming method as the mathematical equations used to calculate individual volumes of logs require multiple measurements (Fraver et al. 2007). Despite some disadvantages, FAS remains a popular and accurate method (Gove and van Duesen 2011). While FAS estimates are based on all pieces of fallen deadwood, line-intersect sampling only considers fallen logs intersecting with the transect line. Primarily developed for forest fuel inventories in countries prone to fires (e.g. USA and Canada), its use was later extended to other purposes such as biodiversity and carbon pool assessments (Brown 1974, Woodall and Monleon 2008, Tomppo et al. 2010). Line-intersect sampling is more efficient and practical in the field than fixed-area sampling, especially in high deadwood-density areas (Jordan et al. 2004, Fraver et al. 2007).

Line-intersect sampling offers numerous advantages over FAS but is sensitive to local deadwood conditions, unlike FAS measurements, which remain independent. Specifically, silvicultural activities can alter the abundance, distribution, and orientation of fallen deadwood logs, potentially impacting LIS measurements (Bell et al. 1996, Woldendorp et al. 2004, Andini et al. 2017). Scarcity of logs at a given site, e.g., influences LIS accuracy, which tends to increase with longer transect lines since the probability of encountering a log is greater (de Vries 1986, Kaiser 1983). Thus, in highly managed areas, where logs are scarce, transect length is an important variable to be adapted for achieving an acceptable accuracy. In those conditions, FAS could be preferred over line-intersect sampling as optimal transect lengths may reach hundreds of meters and may not be easily implemented in the field, especially in the context of multipurpose assessments (Mckenzie et al. 2000, Woldendorp et al. 2004, Miehs et al. 2010, Ligot et al. 2012, Fraver et al. 2018). Although more relevant to commercial and production forests than for forests managed primarily for nature conservation and recreation, uniform orientation of logs due to harvesting practices may occur, resulting in overestimation or underestimation of deadwood volumes if one or more transect lines are parallel or perpendicular to the logs (Bell et al. 1996, Woldendorp et al. 2004, Andini et al. 2017).

Ecological and forest inventories often conduct simultaneous measurements using plots, with deadwood inventories being only one of the measured variables (Kershaw et al. 2016, Fraver et al. 2018). Deadwood inventory methods would preferably align with the general sampling designs in these cases for efficiency and comparability (Cochran 1977, Ritter and Saborowski 2014). These ecological and forest inventories generally cover parks and forests exhibiting diverse local deadwood conditions and volumes influenced by different management strategies. These strategies can range from strict non-intervention to clearcutting, selective logging, or thinning to achieve various objectives spanning from maintaining ecosystem functioning to sustaining local economies (Dudley 2008, van Beeck Calkoen et al. 2020). Previous studies have primarily focused on comparing the accuracy of LIS relative to FAS in timber-production forests (Jordan et al. 2004, Woldendorp et al. 2004, Teissier et al. 2009, Ligot et al. 2012), which typically have limited amounts of deadwood. The corresponding results may not be directly transferrable to the special situation of forests with biodiversity, socio-cultural, and recreational values as main management objectives as they generally undergo less intense management and have a higher amount of deadwood (Duncker et al. 2012). Consequently, the applicability of LIS in temperate European forests with a primary emphasis on preserving natural ecosystems and facilitating recreational activities remains largely unexplored (but see de Meo et al. 2017). To address this gap, we compared fallen deadwood volumes estimated with LIS and FAS methods in two protected European temperate forested areas with differing management strategies (selective thinning for historical–cultural, recreational, and biodiversity purposes vs. strict non-intervention) and amended our analysis with some experimentations based on simulated data covering a wider range of management scenarios.

Materials and Methods

Study sites

The study was carried out in two protected European temperate forested areas in Germany and The Netherlands, where 20 and 28 plots were sampled, respectively (Figure 1). This study was part of a more extensive ecological field campaign where multiple variables were measured in the sampled plots. The Bavarian Forest National Park (referred to as 'Bavarian NP' hereafter) lies in the southeast of Germany along the border with the Czech Republic and is part of the Bohemian Forest landscape. With a range of elevation between 600 and 1453 m over a total area of 250 km^2, the Bavarian NP is influenced by temperate and continental climates (Heurich et al. 2010). The Bavarian NP is predominated by European beech (*Fagus sylvatica*) at lower altitudes and Norway spruce (*Picea abies*) at higher altitudes (Cailleret et al. 2014). Since its establishment in 1970, the Bavarian NP has adopted a nature-oriented management. Initially focusing on reducing human disturbance through passive management, the park transitioned to a full non-intervention strategy a decade later, thereby strictly refraining from any human intervention in 75% of the park designated as a natural zone (van der Knaap et al. 2019). Within this designated non-intervention zone, active logging management for economic purposes was abandoned in old-growth and mature stands. In the remaining 25% of the park's surface, designated as a management zone, active conservation measures are implemented, and some limited-scale preventive logging for bark beetle management has been permitted adjacent to neighboring commercially managed forests (Müller et al. 2010).

The Veluwe NP includes three connected national parks and domain forest in the Veluwe area, located in the central part of The Netherlands (Het Nationaal Park De Hoge Veluwe, Het Nationaal Park Veluwezoom, and Royal Estate Het Loo). The Veluwe NP was formally established in the early 1900s to protect Dutch landscapes and progressively shifted from private to public nature reserves in the late 1900s (Het Loo Royal Estate 2022, Het Nationaal Park De Hoge Veluwe 2015). With an elevation of around 40 m with slight variation in elevation, the Veluwe NP is influenced by a temperate maritime climate and comprises a mix of forests, grasslands, and heathlands over an area of 90 000 ha, dominated

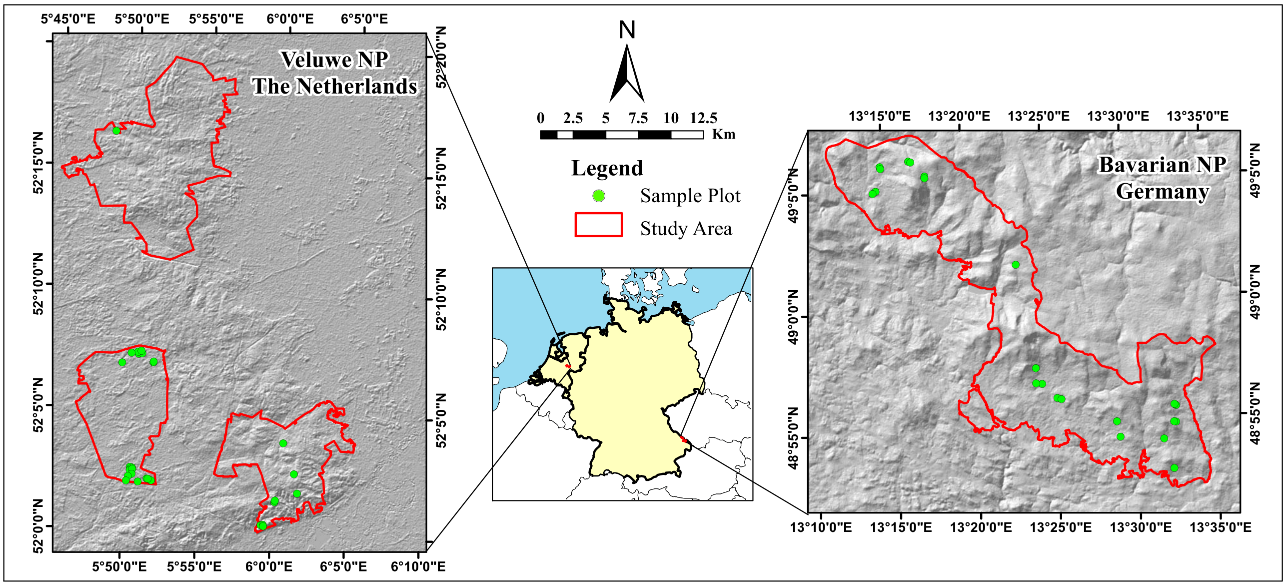

Figure 1. Location of the study areas in The Netherlands and Germany and location of sample plots within each study area.

by Scots pine (*Pinus sylvestris*), Norway spruce (*P. abies*), English oak (*Quercus robur*), silver birch (*Betula pendula*), and European beech (*F. sylvatica*) (Mol et al. 2003, Hein 2011, de Hoop et al. 2022). The Veluwe region consists of multiple parks, which all promote and ensure a balance between the historical–cultural, recreational, and biodiversity values. Management strategies of the three parks covered in this study consistently aim to increase the amount of deadwood but vary in their level of intervention within and between parks. Specifically, active management is permitted for achieving more natural and varied forest composition and structure, maintaining traditionally more open woodland landscapes (Nationaal Park Veluwezoom en IJsseluiterwaarden 2014, Het Nationaal Park De Hoge Veluwe 2015, Kroondomein Het Loo 2022), enhancing landscape aesthetics and improving recreational opportunities (Nationaal Park Veluwezoom en IJsseluiterwaarden 2014, Het Nationaal Park De Hoge Veluwe 2015, Kroondomein Het Loo 2022), exotic tree eradication (Het Nationaal Park De Hoge Veluwe 2015, Kroondomein Het Loo 2022), and supporting small-scale sustainable logging for financial and societal goals (Kroondomein Het Loo 2022).

Sampling design, deadwood measurements, and deadwood volume calculation

Deadwood measurements were collected in 20 and 28 plots located in the Bavarian NP and the Veluwe NP, respectively (Figure 1), using a stratified sampling strategy across coniferous and deciduous stands. We inventoried fallen deadwood logs using FAS (square plot inventory) and LIS. As this study focuses on coarse woody debris (longer decay turnover period compared to fine woody debris), we considered fallen deadwood logs with a minimum diameter d of 10 cm (IPCC 2003; Rondeux et al. 2012). In an effort to gauge the potential cost and time saving associated with LIS in comparison to FAS, the number of logs per plot was recorded. Subsequently, a Wilcoxon signed-rank test was conducted to evaluate the LIS efficiency by comparing the recorded number of logs per plot for each sampling method.

For the fixed-area sampling inventory, we followed the 'chainsaw method' (Gove and van Duesen 2011). This method only considers fallen deadwood found strictly within the plot's boundaries. Only logs with a mid-length diameter ≥10 cm were considered. For every log crossing the plot's boundaries, only the portion of the log inside the plot was considered and measured. For each log, the log diameter at mid-length and the total length of the log located within the plot's boundaries were measured. While most trees lose their tops before falling, a small proportion of fallen tree deadwood still retains tops. Since this will disproportionally influence their diameter at mid-length, the thinnest section of the tree below the diameter threshold (10 cm), generally the top section, was disregarded in those cases, and the remaining part of the tree was measured as described above. Huber's formula (Huber 1839) was used to determine the total deadwood volume of each plot:

$$V = \sum \left(\frac{\pi d^2 L}{4} \right) / 0.09$$

where V is the area-based volume of the plot ($m^3\ ha^{-1}$), d is the diameter at mid-length of the log (m), and L is the total length of the log (m).

The LIS inventory took place within each plot along two transect lines (42.4 m each) perpendicular to each other and placed in northeast–southwest and northwest–southeast directions (Figure 2). Fixed rather than random transect lines were used for efficiency and practicality in the field and to increase the reproducibility of results (following Böhl and Brändli 2007). The sampling order of the transects was determined arbitrarily. Only fallen deadwood logs crossed by a fixed transect line were considered, and their diameter at the intersection with the transect line was recorded. If a log crossed both transect lines, it was only recorded once upon the first encounter, except if it was smaller than the diameter threshold. In those cases, the larger intersecting diameter was recorded. The total deadwood volume estimated with LIS was calculated with de Vries' formula (van Wagner 1968, de Vries 1986):

$$V = \pi^2 \sum \left(\frac{d^2}{8L} \right) * 10\,000$$

where V is the area-based volume of the plot ($m^3\ ha^{-1}$), d is the diameter of the deadwood log at the point of intersection with the transect line (m), and L is the total length of the transects

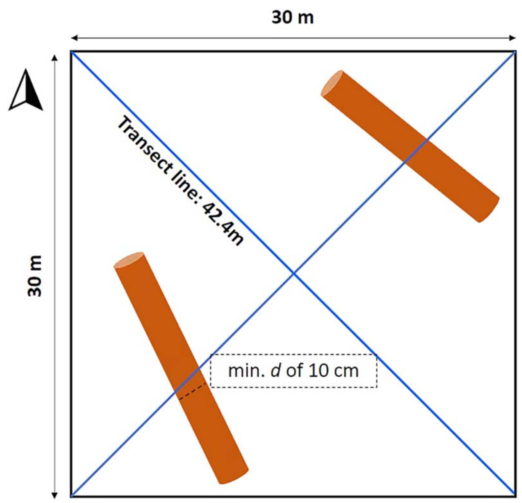

Figure 2. An illustration of the sampling design used to measure fallen deadwood logs. The fixed-area sampling (FAS) measurements were done within the boundaries of the 30 × 30 m square plot, while the line-intersect sampling (LIS) measurements were carried out along the two fixed transect lines (blue lines). Red cylinders represent fallen logs.

within the plot (two transects lines of 42.4 m each). As FAS provides a complete inventory of all fallen deadwood logs within the sampled area, the LIS measurements were compared relative to FAS measurements (Woldendorp et al. 2004, Teissier et al. 2009).

Data simulation and processing

In addition to the field study, a forest simulation model was used to compare the effectiveness of FAS and LIS across a broader range of fallen deadwood scenarios. The Forest Vegetation Simulator (FVS) (https://www.fs.usda.gov/fvs/) was used to simulate forest stands in both non-human interventions and actively managed settings (Herbert et al. 2023). This forest simulation model facilitates the emulation of forest stands by considering natural succession, disturbances, and management responses. In simpler terms, the FVS model can mimic stands with diverse tree species compositions and simulate a range of management and disturbance scenarios (Crookston and Dixon 2005). For this investigation, we utilized the inventory data within the FVS model, specifically focusing on data from temperate forests in the USA, given that the U.S. Forest Service developed this simulator. We consider the selected inventory datasets to be also representative of temperate European forests. Management actions were subsequently applied to simulate non-human intervention and actively managed forest stands. Non-human intervention stands were simulated using a natural growth model over a 100-year period (referred to as 'US Simulation 1' hereafter). Conversely, for actively managed stands (referred to as 'US Simulation 2' hereafter), basic thinning actions were implemented, modifying the thinning events for deadwood trees based on factors such as insect or disease epidemics, climatic events, senescence of older trees, or other causes. At the end of each simulation, all standing trees were removed, and the graphical representations of the fallen deadwood were exported for further analysis. Subsequently, the simulated plot stands were imported into ImageJ software (Schneider et al. 2012) for scale addition (similar to the field plot size) and manual measurement of the length and diameter of deadwood logs within each plot as described for fieldwork deadwood measurements (see Supplementary material 2 for details and information about the simulation process and setup using the VFS model).

Statistical analysis

All analyses were conducted in R version 4.3.2 (https://www.R-project.org/). The non-parametric Wilcoxon signed-rank tests were used to compare deadwood volume estimated by FAS and LIS methods plot per plot for each dataset individually. Spearman's correlation tests and linear regression models were performed between the deadwood volume of both methods to investigate the strength and accuracy of the relationship for fieldwork (Bavarian NP and Veluwe NP) and simulated (US Simulation 1 and US Simulation 2) datasets separately. Linear regression models were also conducted between FAS and LIS estimates per forest type to determine regression coefficients. This was done for Bavarian NP and Veluwe NP only, as this information was not available at the plot level for simulated datasets. A Wilcoxon rank-sum test between FAS measurements of Bavarian NP and Veluwe NP was also performed to determine differences in deadwood volume stocks.

Results

The time-saving potential of LIS was first assessed by recording and comparing the number of logs per plot between sampling methods. A significant decrease of approximately three in the number of logs measured was observed, indicating a likely reduction in time (Table 1; Wilcoxon signed-ranked test: $V = 9690$, $N = 128$, $P < .001$). In addition, a comparison of deadwood stocks between the two study sites showed that Bavarian NP (strict non-intervention) had four times more deadwood than Veluwe NP (selective thinning) (Wilcoxon rank-sum test: $W = 425$, $N = 48$, $P = .002$; Table 1; see Table S1 for FAS and LIS estimates per plot). The observed range of deadwood volume was larger for the Bavarian NP than the Veluwe NP (Table 1). Both forests exhibited minimum deadwood volumes as low as ~3 m^3 ha^{-1}. Although both study areas exhibited high deadwood volumes, the variability among plots (represented by the standard deviation) was smaller for the Veluwe NP (Table 1). Seventy percent of the plots measured in the Veluwe NP were under 30 m^3 ha^{-1}, while this proportion was only 30% for Bavarian NP (Table S1).

When comparing FAS and LIS estimations, no significant differences were observed for both Veluwe NP (Wilcoxon signed-rank test: $V = 266$, $N = 28$, $P = .16$) and Bavarian NP (Wilcoxon signed-rank test: $V = 128$, $N = 20$, $P = .41$) (Figure 3). When analyzing FAS and LIS estimates per plot, Spearman's correlation test revealed a strong and positive relationship ($P < .001$, rho >.80). A linear regression slope of 1.07 indicated a slight overestimation of LIS estimates, likely due to two deciduous plots in Bavarian NP (21BP51 and 21BP55), which had the highest deadwood volumes (Table S1, Figure 4). There was also an underestimation ranging between 50 and 90 m^3 ha^{-1} observed in three coniferous and one deciduous plot in Bavarian NP (21BP29, 21BP22, 21BP23, and 21BP45) and three coniferous plots in Veluwe NP (21HV03, 21HV04, and 21HV34), indicating significant variability at the individual plot level (Table S1, Figure 4). Finally, we noticed forest-type-dependent variation when examining the relationship between FAS and LIS estimates per forest type (Table S2).

Simulation analyses of two datasets (representing different management strategies: non-human intervention and thinning) allowed us to compare LIS relative to FAS across a broader range of forest stands and deadwood conditions. Both analyses confirmed (i) Wilcoxon signed-rank tests showed no significant differences

Table 1. The distribution and mean ± standard deviation (SD) of fallen deadwood volume (m^3 ha^{-1}) estimated with the fixed-area sampling (FAS) and line-intersect sampling (LIS) methods, along with the mean number of logs recorded ± SD, are indicated for Veluwe NP ($N = 28$) and Bavarian NP ($N = 20$). Results of the two simulated datasets (US Simulation 1, $N = 50$ and US Simulation 2, $N = 50$) are also included.

	FAS			LIS		
	Mean ± SD	**Range**	**Logs**	**Mean ± SD**	**Range**	**Logs**
Veluwe NP	29.35 ± 34.98	3.41–168.73	19.5 ± 11.1	21.74 ± 24.30	0.00–95.59	4.2 ± 3.6
Bavarian NP	127.66 ± 151.47	3.32–547.58	6.25 ± 5.1	122.92 ± 174.44	1.57–617.28	7.6 ± 4.2
US Simulation 1	72.90 ± 55.85	7.50–352.46	39.2 ± 23.4	85.04 ± 79.24	6.67–480.79	9.0 ± 6.1
US Simulation 2	45.51 ± 30.05	12.20–140.98	10.5 ± 7.8	58.79 ± 62.63	0.00–306.24	3.6 ± 2.6

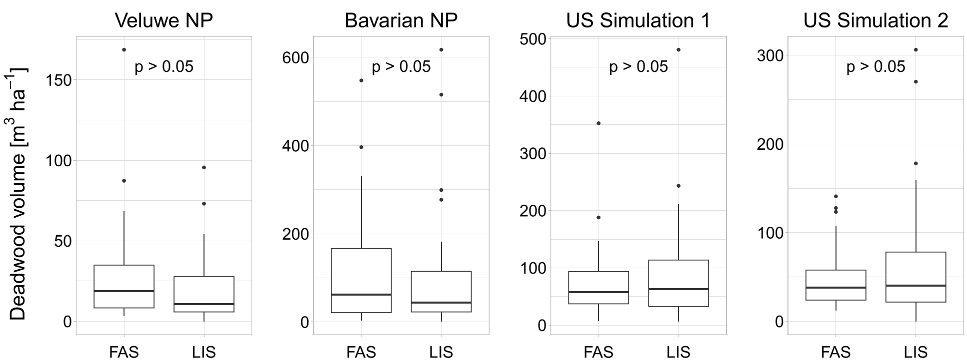

Figure 3. Boxplot of the fallen deadwood volumes (m^3 ha^{-1}) estimated with the fixed-area sampling (FAS) and the line-intersect sampling (LIS) methods for Veluwe NP, Bavarian NP, US Simulation 1, and US Simulation 2. No significant differences between FAS and LIS measurements were found for all datasets.

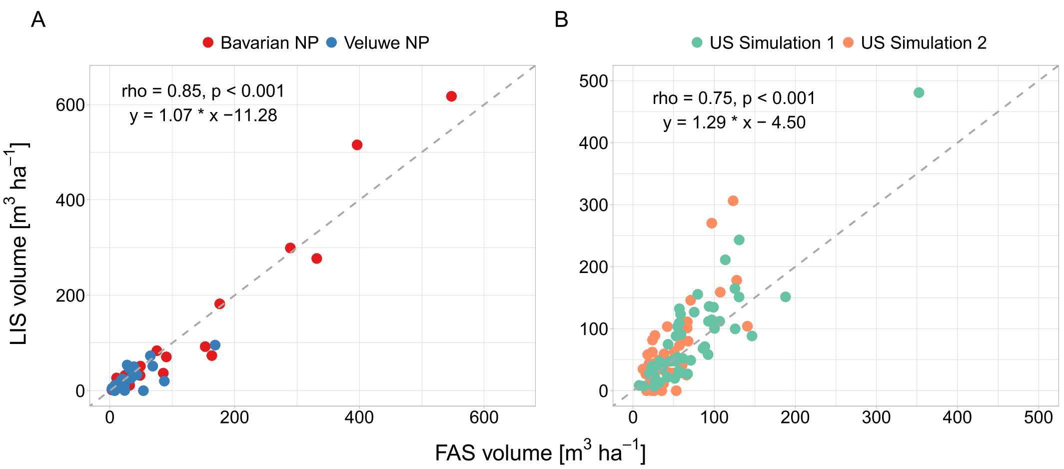

Figure 4. Estimated FAS versus LIS deadwood volumes (m^3 ha^{-1}) for (**A**) Veluwe NP and Bavarian NP, and (**B**) US Simulation 1 and US Simulation 2. Results of Spearman's correlation tests and linear regression equations between LIS and FAS measurements are indicated. The lines correspond to $y = x$.

between FAS and LIS estimates for both simulated datasets (US Simulation 1: $W = 479$, $N = 50$, $P = .13$; US Simulation 2: $W = 481$, $N = 50$, $P = .13$; Figure 3), (ii) a strong and positive correlation between FAS and LIS estimates at the plot level ($P < .001$, rho = .75), and (iii) the linear regression slope indicated an overestimation of LIS estimates compared to FAS estimates, likely driven by plots with the highest deadwood volumes (M1, M36_b, U23, and U25; Table S1 and Figure 4).

Discussion

Harvesting dead trees for timber and aesthetic purposes in actively managed forests usually results in low deadwood stocks, negatively affecting forest biodiversity in managed forests (Green and Peterken 1997, Montes and Cañellas 2006, Lombardi et al. 2008). Thus, European natural reserves have increasingly adopted biodiversity-oriented management strategies to promote and protect biodiversity, e.g. by implementing non-intervention strategies (Dudley 2008, Heurich et al. 2010). In this context, accurately assessing and monitoring deadwood stock has become crucial within these protected areas. Recognized as a biodiversity indicator, deadwood plays a crucial role in promoting and ensuring, e.g., the diversity of saproxylic species (Bani et al. 2018). Consequently, one approach for these protected nature areas to achieve their biodiversity goals is to increase the overall deadwood stock (Dudley 2008). However, the management strategies of these protected nature areas vary widely per country, ranging from strict non-intervention to selective logging and clearcutting (Duncker et al. 2012, van Beeck Calkoen et al. 2020), aligning with the specific economic, recreational, cultural, and ecological goals of each 2000 Natura forest domain and national park. These differences in management strategies affect deadwood volume and distribution and may cause bias in sample-based measurement methods such as LIS (Woldendorp et al. 2004; Andini et al. 2017). Our study shows that FAS and LIS methods yielded similar results for fallen deadwood volume estimation in the studied forests. We confirmed the effectiveness and applicability of LIS under diverse local deadwood conditions in protected forest national parks with differing low-intervention management strategies primarily aimed at enhancing ecological values. Furthermore, LIS showed a 3-fold reduction in the number of logs measured compared to FAS. A direct comparison of the time spent on log measurement was unfortunately not conducted, but assuming that the time to measure an individual log is on average constant, the notably fewer logs sampled with the LIS method greatly reduce the sampling effort.

While multiple aspects of FAS and LIS methods have been studied extensively, most of these studies remain restricted to specific and uniform deadwood conditions. To our knowledge, de Meo et al. (2017) is the only study comparing FAS and LIS methods in forests prioritizing both biodiversity and recreational values with differing deadwood management, thereby including broader conditions and volumes. Although both our findings and those of de Meo et al. (2017) indicated an overestimation of LIS estimates in comparison to FAS estimates, their study reported a smaller overestimation (4%) compared to ours (29%). This difference could be explained by the differing diameter thresholds of 5 cm (de Meo et al. 2017) and 10 cm (our study, following Böhl and Brändli 2007, Teissier et al. 2009). By using a diameter of 10 cm, our study aligns with the definition of coarse woody debris proposed for deadwood data harmonization across Europe and follows the Good Practice Guidance for Land Use, Land-Use Change and Forestry (IPCC 2003, Rondeux et al. 2012).

In this study, the LIS design successfully combined the efficiency of transect lines with a fixed field plot. This flexible LIS approach can be adopted by similar studies requiring simultaneous measurements, such as ecological and forest inventory metrics (Kershaw et al. 2016, Fraver et al. 2018). The relatively small sample size (a total of 48 plots) may be a limitation of this study. However, the additional experimentations with the simulated data confirm our results and support the applicability of LIS across various deadwood conditions and volumes. Such variations in local deadwood patterns are commonly encountered in European temperate forest areas primarily managed for nature protection with low- to no-intervention management approaches. Specifically, the addition of simulated data expanded the range of deadwood volumes captured with the fieldwork data while encompassing a broader spectrum of local deadwood conditions resulting from different intensities of simulated selective thinning. Furthermore, the variety in simulated stands that included multiple tree species and disturbance scenarios (e.g. insect or disease epidemics, climatic events, senescence of older trees) allowed us to test the effectiveness of the current LIS design in many potential situations that could be found in protected areas.

The simulated datasets further emphasized the tendency of LIS to overestimate deadwood volumes compared to FAS estimates. This consistent overestimation in our study may indicate that the used transect length might have been insufficient. The more pronounced overestimation of the simulated data likely reflects that. As de Vries' formula only relies on the log's diameter where it intersects the transect line, the LIS method is particularly affected by this parameter and has been shown to consistently generate higher volumes than Huber's formula (Herrero et al. 2016). This discrepancy becomes tangible when comparing the fallen logs measured in the field, which were, on average, smaller (15.0 ± 12.0 cm) than the ones produced by the simulations (23.5 ± 8.0 cm). While increasing the total length of the transect lines can help reduce the overestimation, it may not always be possible during multipurpose assessments where other target variables also have to be sampled.

Although the current LIS design is suitable and efficient for the fieldwork conditions encountered, it comes with some limitations. Firstly, logs should be recorded only once, even when multiple transects were crossed, potentially impacting the efficiency of the current LIS design in high deadwood-density areas with a significant number of logs. In such cases, the likelihood of logs intersecting multiple transects rises, posing a challenge to ensure logs are recorded only once during the fieldwork. One approach to address this could involve initiating the transect lines a few meters away from the center of the plot because this area likely encounters the highest incidence of multiple intersections (Böhl and Brändli 2007). As for all transect-based methods, LIS is sensitive to log clusters and large logs, which, if overlooked by the transects, can significantly influence LIS estimations (Woldendorp et al. 2004). For example, two plots in Veluwe NP (21HV03 and 21HV04) showed large differences between FAS and LIS measurements because none of the transect lines intersected with the large pieces of fallen deadwood present in the plot. Where this type of log distribution occurs widely in a study area, this limitation can be alleviated by adopting another transect layout, such as the 'Y' shape used by National Forest Inventories in Switzerland and the USA (Böhl and Brändli 2007, Woodall and Monleon 2008). Alternatively, one could create a straight line at random and extend it by turning 90 degrees for each new segment until achieving the desired total length of the transect (Woldendorp et al. 2004). Alternative LIS designs may offer improvements to the current layout, but their applicability will depend on study and site-specific conditions. The advantage of LIS is that it allows for the flexibility of tailoring these designs to the study's needs.

Conclusion

The implementation of biodiversity-orientated management strategies by European natural reserves has resulted in the integration of deadwood assessment in multipurpose assessment inventories. Consequently, there is an increasing need to accurately monitor and assess deadwood stock in these protected areas, which has been overlooked in previous comparisons of the two sampling methods. Drawing on both empirical field and simulated data, this study supports the reliability and applicability of LIS for assessing deadwood stock and studying ecological patterns across varying local deadwood conditions in European forest national parks with strict non-intervention to moderate intensity management strategies. The outcome of this study is, thus, relevant to practitioners and researchers focusing on—but not restricted to—biodiversity assessment for management, protection, and conservation, where full-inventory methods are not an optimal choice due to practical or time constraints.

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Supplementary data

Supplementary data are available at *Forestry* online.

Conflict of interest. None declared.

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Data availability

Data available on request.

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