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Tree stumps — an important but undervalued dead wood pool

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Abstract

Key message: Dead wood in forests is an important resource due to its role for nutrient cycles, carbon budgets, and biodiversity, among other. While standing and downed dead wood are typically monitored in National Forest Inventories (NFI), stumps have not received comparable attention. Based on the detailed stump inventory in the current Swiss NFI, this study demonstrates the important contribution of stumps to the dead wood pool.

Context: Dead wood (DW) in forests is an important resource due to its role for nutrient cycles, carbon budgets, and biodiversity, among other. NFIs provide representative DW estimates focusing primarily on standing and downed DW. Little is known on stumps as a DW pool.

Aims: The aim of this study is to obtain an accurate assessment of the stump volume and biomass in the Swiss NFI to identify its significance for the DW pool, to evaluate the development over the last 30 years, and to examine the need for additional measurements for improving estimates compared to commonly applied assumptions for stump height such as a constant stump height or a fraction of tree height.

Methods: The current NFI includes a detailed stump inventory to improve accuracy and completeness of the above-ground DW pool estimate. Based on available data, stump volume estimates were derived at different accuracies to evaluate the contribution to the total DW pool over time.

Results: Based on the extended stump inventory in the NFI5, the contribution of stumps to the total DW pool is approximately 25%. The effect of simplifying assumptions or limited measurements to estimate stump volume can result in a significant underestimation of up to 2/3 of the more accurate and comprehensive assessment of this pool.

Conclusion: This study demonstrates that stumps can be a significant proportion of DW in forests, which should be accounted for in order to improve accuracy and completeness of NFI estimates and derived data such as C stocks for greenhouse gas reporting.

Keywords: Volume, Biomass, Carbon, Biodiversity, Protection forest, National Forest Inventory, Harvest

1 Introduction

Dead wood in forests is recognized as an important resource providing several ecological functions and services including biodiversity and nutrient cycling (Harmon et al. 1986). Dead wood can be present in various dimensions from coarse to fine woody debris, in different stages of decomposition, be standing or downed, or consist of stumps (Harmon et al. 1986; Woodall et al. 2009). Today, information on dead wood is collected in many forest monitoring schemes, albeit at different details (Puletti et al. 2019; Woodall et al. 2009). Nationally representative estimates on dead wood are typically derived from the National Forest Inventories (NFI), which are based on a large number of sample plots systematically distributed across a whole country (Lawrence et al. 2010).

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As countries have developed individual methods to collect dead wood data, there are harmonization needs (Rondeux et al. 2012). In NFIs, the available information on dead wood ranges from volume estimates to data on biomass or carbon, which consider the effect of decreasing wood density with advancing decay (Woodall et al. 2009). Assessing the decay stage of dead wood and the associated wood density is important to obtain accurate biomass and also carbon estimates (Fraver et al. 2013). Since the speed of dead wood decomposition depends on tree species and dimension (Tuomi et al. 2011), and position, i.e., standing or downed (Hararuk et al. 2020), the availability of such information further contributes to the accuracy of estimates.

Standing dead trees in NFIs are typically defined as dead trees with a height larger than 1.30 m (i.e., with existing measurement of the diameter at breast height (DBH); Rondeux et al. 2012). The standing upright part of trees above ground surface that remains after cutting is considered as stump (Lanz et al. 2010). However, stumps are often defined inconsistently (Merganičová et al. 2012), for example, with regard to the diameter, and are subsumed under either standing or downed dead wood (Crecente-Campo et al. 2016). The lack of unambiguous definitions and the confinement to case studies, for example, to production forests (Niese 2013) or to a small subsample (Teissier du Cros and Lopez 2009), hamper an evaluation of the stump pool at larger scales.

NFIs present a source of nationally representative data. However, Woodall et al. (2009) reported that stump data are collected in only 60% of the cases where an NFI collects dead wood data ($n = 30$ of a total of 66 countries included). Furthermore, the collected data differ by dimensional thresholds and detail (e.g., measured dimensions, reidentification, and remeasurement) limiting the comparability between NFIs. Also, stump data are rarely transparently reported in the dead wood volume or biomass estimates of NFIs, although basic measurements may exist (Rondeux et al. 2012). Nationally representative and comparable estimates are however important for international reporting obligations (Gschwantner et al. 2022). Based on national data from Spain (Alberdi et al. 2020) and Germany (Schnell and Hennig 2019), stumps account for approximately 5% and 25%, respectively, of the total dead wood volume in these countries.

In addition to information on stumps and their contribution to the state of the dead wood pool, repeated measurements are important to evaluate the temporal dynamics of stump biomass and carbon. Still rooted, upright stumps can be assumed to remain in this position over a long period and decay thus with slower rates than downed dead wood (Hararuk et al. 2020). This can have implications on the carbon and nutrient fluxes from stumps to the litter and soil C pools or to the atmosphere (Oberle et al. 2018).

Despite the collected information in NFIs and the potentially significant (e.g., data from Germany; Schnell and Hennig 2019) contribution to the total dead wood pool, little published qualitative and quantitative information exists on stumps at the national scale. For example, in the reports on the State of Europe's Forests, stumps are not considered (Forest Europe 2020). Knowledge of the stump pool is also important to understand their role for, among other, biodiversity (Jonsell and Schroeder 2014; Persson 2012), forest regeneration (Bace et al. 2011; Motta et al. 2006), and as an indicator of naturalness (Kunttu et al. 2015). Furthermore, stumps have recently also received attention due to their potential for forest bioenergy production (e.g., Kaarakka et al. 2018; Persson 2012). Volume or biomass estimates from such studies are however limited to clear-cut conditions and are thus not representative at national scales. In Switzerland as well as in other mountainous regions, stumps can also add to the stability of slopes and can provide protection against debris slides or avalanches (Fuhr et al. 2015).

The comparatively poor information available on stumps has been discussed in the context of international greenhouse gas reporting requirements (e.g., Dunger et al. 2012; Petersson and Melin 2010), but it also applies to data needs to evaluate and monitor forest biodiversity criteria (cf. Kunttu et al. 2015). In the Swiss NFI, the collected information on stumps has increased since the first data on the height of stumps were collected in the third NFI measuring cycle (NFI3, 2004–2006). In addition to stump height, the top diameter was measured in the fourth NFI measuring cycle (NFI4, 2009–2017). Only in the fifth measuring cycle (NFI5), which started in 2018, a stump inventory with particular attention to the comprehensive and accurate collection of stump data was implemented. The stump inventory also improved completeness as it was not limited to stumps of trees that were harvested since the previous inventory. However, the contribution of measured, rooted stumps to the dead wood pool is, similar to other NFIs, not considered in the reported volume of this pool (e.g., in the report on results of the NFI4; Brändli et al. 2020). Since the Swiss NFI covers a range of forests with different management priorities including production, protection, conservation, or recreation (Brändli et al. 2020), the collected stump data can assumed to be representative for a range of forest conditions. Our objective is to obtain an accurate assessment of stumps as a dead wood resource. The main aim is to identify the need for appropriate measurements by quantifying the effect of differences in measurement detail on the accuracy of the pool size. To this end, we evaluate the development of the stump pool over the last 30 years since the second NFI measuring cycle (NFI2, 1993–1995)

to identify the significance of stumps as a dead wood pool. The data also allow us to examine the effect of stump height assumptions applied by some NFIs for growing stock estimation such as a constant stump height of typically 30 cm or a fraction of tree height such as 1% (Gschwantner et al. 2009). Such information will be valuable to optimize stump measurements for accuracy, which is relevant for harmonization efforts (Gschwantner et al. 2019; McRoberts et al. 2009; Rondeux et al. 2012; Woodall et al. 2009) as well as for greenhouse gas reporting (Dunger et al. 2012). Due to additional protective function of stumps in Swiss forests, we compare stump attributes between regular and protection forests hypothesizing that stump dimensions in protection forests are larger than in regular forests.

2 Methods

The Swiss NFI (Brändli and Hägeli 2019) is currently in its fifth measuring cycle (NFI5), and methods have evolved significantly over time from the first inventory (NFI1) in 1983 to 1985, the NFI2 (1993–1995), the NFI3 (2004–2006), the NFI4 (2009–2017), and the current, ongoing NFI5 (2018–2026). With the NFI4, the inventory approach changed from a periodic to a continuous survey, where over nine consecutive years each year a nationally representative subsample of approximately 650 plots is visited. Hence, each sample plot is visited every 9 years. In a complete measuring cycle, approximately 6300 permanent plots located on a 1.4 km grid and which are classified as accessible forest are visited. The Swiss NFI defines five production regions (Jura, Plateau, Pre-Alps, Alps, and Southern Alps) which represent comparably homogeneous forest type and management conditions (Glossary in Fischer and Traub 2019; Fraefel et al. 2021).

2.1 Dead wood data

In the field surveys, living and dead trees are measured and described in detail on two concentric circles of 200 m^2 and 500 m^2 including standing and downed stems (see Table 1 for an overview of available measurements) with diameter at breast height (DBH) $\geq$ 12 cm and $\geq$ 36 cm, respectively (tally trees; Lanz et al. 2019). In the case of NFI1, the definition of dead wood, especially concerning the downed dead stems, was slightly different to the subsequent measuring cycles since stems in advanced decay stages were not included. Whether living or dead, all tally trees are measured repeatedly until they disappear from the plot. In the case of dead stems, the decay process can thus be traced over several NFI cycles (cf. Hararuk et al. 2020). Additionally, downed tree elements including stems (including tally trees) and branches with diameter greater than 7 cm are sampled along three transect lines 10 m in length since the NFI3 (henceforth LIS-DW for "line-intersect sampling"). To better understand dead wood decomposition, the decay stage is measured on dead tally trees since the NFI3 and since the 3rd year of the NFI4 also on LIS-DW. The stage of dead wood decomposition is based on the five stages raw wood, solid dead wood, rotten wood, mold wood, and duff wood as defined in Hunter Jr. (1990).

A further dead wood element considered in the Swiss NFI are stumps, which are defined as "the aboveground base part of the stem that would remain after cutting the tree with a height <1.3 m (i.e. DBH) aboveground" (Glossary in Fischer and Traub 2019). Since the NFI3 measurements on some stumps were conducted with increasing detail. In NFI3 and NFI4 however, the focus was on collecting ancillary information such as tree age to complement data on cut or broken tally trees. So, the sample of stumps was not yet representative for the complete population of stumps. In the NFI3, a single height measurement was taken on the side facing upslope of stumps of which the stem was found and identified on the 200 m^2 and 500 m^2 sampling circles (Keller 2011). In the NFI4, sampling was intensified to include also the

Table 1 Available measurements of dead wood elements and temporally consistent stump volume models throughout five Swiss National Forest Inventories (NFI1 to NFI5)

Dead wood element	NFI1	NFI2	NFI3[f]	NFI4[f]	NFI5[f]
Standing dead tally tree[a] > = 1.3-m height	Y	Y	Y	Y	Y
Downed dead tally tree[a]	Y	Y	Y	Y	Y
Lying dead wood — line intersects sampling[b]	N	N	Y	Y	Y
Stump					
- *Model 1* — fresh stumps of harvested tally trees with assumed diameter[c] and height (30 cm)	N	y	y	y	y
- *Model 2* — stumps of former[d] tally trees with assumed diameter[c] and measured upslope height	N	N	y	y	y
- *Model 3* — stumps of former tally trees with measured top diameter upslope height	N	N	N	y	y
- *Model 4* — all stump[e] with two heights and diameters	N	N	N	N	y

[a] Tally tree: measured tree $\geq$ 12 cm DBH in 0.02 ha and $\geq$ 36 cm DBH in 0.05 ha circle. [b] Line intersects sampling (LIS) using three transect lines 10 m in length as described in Lanz et al. (2019) and in Böhl and Brändli (2007). [c] Top diameter corresponding to the DBH measured in the previous inventory. [d] The downed stem must still be present on the plot, and DBH mark must be identifiable. [e] Fresh and old stumps with top diameter > 7 cm in small circle, > 20 cm in large circle. [f] Top diameter and diameter at half the downslope height and upslope and downslope height

diameter of stumps measured at the top and the decay stage. Furthermore, the sampled stump population was expanded to all stumps of trees, which were present in the previous inventory (Keller 2013). For the NFI5, a distinct stump inventory was implemented to finally have a fully representative and complete sample of stumps. In addition to stumps from tally trees that died or were cut since the previous measuring cycle (i.e., NFI4), all stumps are with a top diameter ≥ 7 cm found on an inner circle of 50 m^2 and with a top diameter ≥ 20 cm on the 200 m^2 circle used also for tally trees with a DBH ≥ 12 cm. Observations on all stumps included two height and diameter measurements (i.e., heights on the upslope (smallest) and downslope (tallest) facing sides and diameters at the top and at half the downslope height; Fig. 1), the percentage of missing volume in case of existing cavities (e.g., due to heart rot), the decay stage, and any existing seedling or sapling regeneration on the stump as well as the information on decomposition stage and species type (Düggelin et al. 2020).

2.2 Volume, biomass, and carbon stock estimates
For estimating the stem wood (i.e., from the tree base to the tree top) of standing and downed dead trees, volume functions using DBH (incidentally measured on the upslope facing side by convention) as the explaining variable are used (Herold et al. 2019). Consistent with the approaches made in other countries (Gschwantner et al. 2009), for the volume of the merchantable part of the stem, a general stump height of 30 cm is assumed (Rohner et al. 2019). The volume of LIS-DW is estimated based on the approach by Gregoire and Valentine (2007) using three transect lines 10 m in length eventually intersecting lying dead wood pieces

as described in Lanz et al. (2019) and in Böhl and Brändli (2007). Volumes are converted to biomass based on wood densities specific to species-type and the five decomposition stages (Didion et al. 2014), and biomass is converted to C by species type-specific C concentrations (Didion et al. 2019).

The accuracy of the volume estimation for stumps depends on the detail of the available measurements and attributes, as well as on the completeness of the assessed stump population. To examine this aspect despite lack of detailed measurements in the past, simplified but temporally consistent estimates were derived since the NFI2. This was ensured by considering only tally trees that were harvested since the previous inventory and assuming a cylindric volume based on a top diameter corresponding to the DBH from the previous inventory and a height of 30 cm (model 1 in Table 1). With the additional measurement details and inventorying of stumps of former tally trees since the NFI3, i.e., in addition to harvested trees, the accuracy of the stump volume estimates and the completeness of the population can then be improved; in the NFI3, the assumed stump height could be replaced with the single stump height measured upslope (model 2 in Table 1). In the NFI4, the assumed top diameter could be replaced with the measured top diameter and used in combination with the single height measurement (model 3 in Table 1). With the NFI5, two diameter (at the top and half the downslope height, Fig. 1) and two height (downslope and upslope, Fig. 1) measurements became available for all stumps found on the sample plots. In addition to a simplified estimate assuming a cylindric shape (as done for models 1 to 3), the measurements in NFI5 allow a more complex calculation (model 4). The volume V of a stump is approximated by the shape of
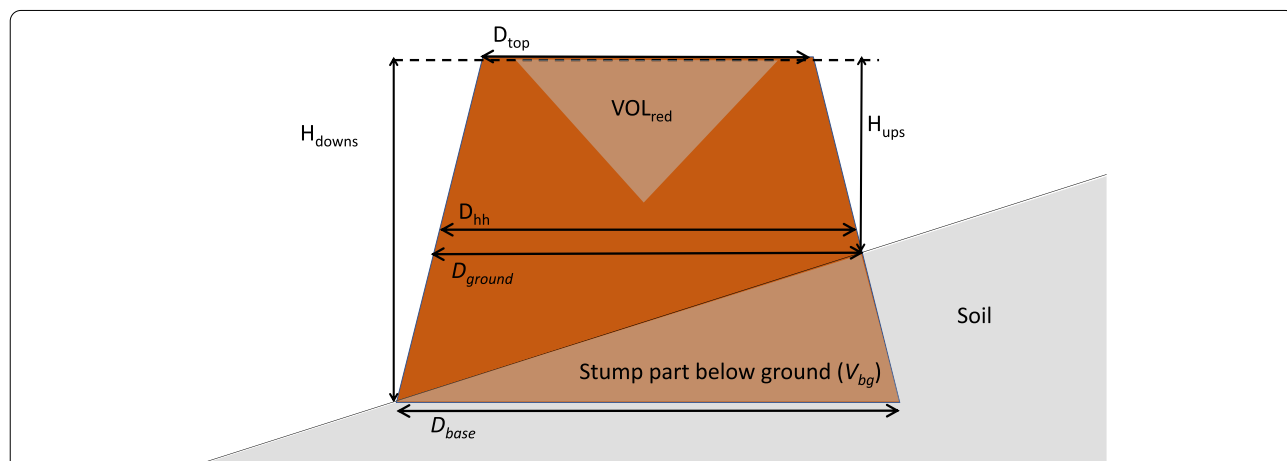
Fig. 1 Measurements on stumps in the NFI5: D_{top}, diameter at the top of the stump; D_{hh}, diameter at half of the maximum height, i.e., in case of uneven soil surfaces, the height on the side facing downslope; H_{downs}, on uneven surface the maximum height; H_{ups}, on uneven surfaces the minimum height (on even surfaces $H_{downs} = H_{ups}$); VOL_{red}, estimated % missing volume due to cavities or in cases of uneven upper stump parts. Derived variables: D_g, diameter at upslope ground level; D_{base}, diameter at the base of the stump; and V_{bg}, volume of the stump that is below ground

a truncated cone (or frustum of a cone) using the two height and two diameter measurements (Eq. 1).

$$V = \frac{1}{3}\pi \times H_{downs} \times \left(R_{base}^2 + R_{base} \times R_{top} + R_{top}^2 \right) \tag{1}$$

where H_{downs} is the height downslope, R_{base} is the radius at the base of the stump (derived from the two diameter measurements at the top and at half the height downslope), and R_{top} is the radius at the top of the stump.

The cone shape was adopted in favor of a more complex shape such as a neiloid because the irregular shape of the lower part of trees results in poorer model fits (Kublin et al. 2013). Furthermore, the accuracy of complex taper equations would remain low as additional measurements along the stem (i.e., tree DBH and height) are not always available, particularly in the case of older stumps. Cavities and irregularities of the stump shape are however accounted in the estimate of the remaining volume, which is used to better approximate the real stump volume by reducing the volume of the truncated cone accordingly. The estimated stump volume may be further reduced to account for the volume fraction (V_{bg}) of the hypothetical cone-shaped stump that is below ground in uneven terrain (Fig. 1 and Eq. 2):

$$V_{bg} = 0.5 \times \left[\frac{1}{3}\pi \times H_{bg} \times \left(R_{base}^2 + R_{base} \times R_{ground} + R_{ground}^2 \right) \right] \tag{2}$$

where H_{bg} is the upslope height from the base of the cone to the ground surface (i.e., the difference between upslope and downslope height) and R_{ground} is the radius at the upslope ground level. V_{bg} is thus assumed to correspond to half the volume of a truncated cone with the height from the cone base to the upslope ground level (Fig. 1).

In addition to the detailed measurements of stumps in the NFI5, the population of stumps that already existed as stumps in the NFI4 is known, and their volume can be estimated. This enhances the completeness of information on the stump pool, similar to the standing and downed dead trees that are tracked as long as they can be identified over several NFIs.

2.3 Analysis

All data were retrieved from the NFI database. To ensure consistent and comparable estimates over time, only sample plots common to all five inventories, i.e., $n = 5318$ for the completed NFIs 1 to 4 and $n = 2386$ for the first 4 years of the NFI5, were used (Didion and Abegg 2022). Due to changes in the sampling of stumps in different inventories, comparability of nationally representative stump volume between individual NFIs was hampered. Thus, to obtain comparable populations of stumps, only stumps from former tally trees with an observed saw-cut could be considered for the analysis of changes in the stump volume over

time. Additional information such as second height and diameter measurements or older and broken stumps was used to demonstrate the need for detailed measurements to ensure accuracy and completeness.

The data were processed with R (Version 4.0.3; R Core Team 2020) using the packages "data.table" (Dowle and Srinivasan 2020), "ggplot2" (Wickham 2016), "ggpubr" (Kassambara 2020), and ggpattern (FC et al. 2022). Besides graphical means (boxplots) to examine and analyze the data, we used *t*-tests, analysis of variance (ANOVA), and Tukey HSD post hoc tests. Nonparametric Kruskal-Wallis rank-sum and pairwise Wilcox tests were used when the data did not meet the assumptions for parametric ANOVA.

3 Results
3.1 Stumps

Figure 2 shows estimates of stump volume since the NFI2 based on a simplified cylindric volume calculated using a top diameter corresponding to the DBH of the tally tree from the previous inventory and a height of 30 cm. For comparability of the population, we considered only stumps from former tally trees with an observed saw-cut below a height of 1.30 m since the previous inventory. For consistency over time, the upscaled estimates based on the common sample plots were used. Thus, for the stump volume estimate for the NFI2, 5477 tally trees on 1513 sample plots from the NFI1 were considered, for the NFI3 7522 tally trees on 1823 plots from the NFI2, for the NFI4 6430 tally trees on 1509 plots from the NFI3, and for the NFI5 2664 on 684 plots tally trees from the NFI4 (i.e., a lower number of stumps on ca. one 4/9 of the plots because data from only the first 4 years of the NFI5 were available). The increase in the number of tally trees with a saw-cut, the number of affected sample plots, and the volume from NFI2 to NFI3 are the result of the increased harvest after the large-scale damages caused by the storms Vivian (1990) and Lothar (1999). As the harvest rate remained high, also due to bark beetle damage (Bundesamt für Umwelt (BAFU) 2020), stump volume further increased in the NFI4. The decline after the NFI4 corresponds to the slight reduction in harvest rates in the years between the NFIs 4 and 5 (BAFU 2020).

On sample plots visited in both the NFI4 and the first 4 years of the NFI5, 1642 stumps existed in the NFI5 which had an observed saw-cut and originated from tally trees measured in the NFI4. Based on the measurements of these stumps in the NFI5 stump inventory (i.e., within the smaller 200 m^2 circle only), Fig. 3a demonstrates the effect of increasing measuring detail on the accuracy of nationally representative stump volume. The stump volume estimate based on model 2 is moderately higher than in model 1, although the mean of the stump height measured upslope (25.8 cm) is less than the assumed height of 30 cm in the
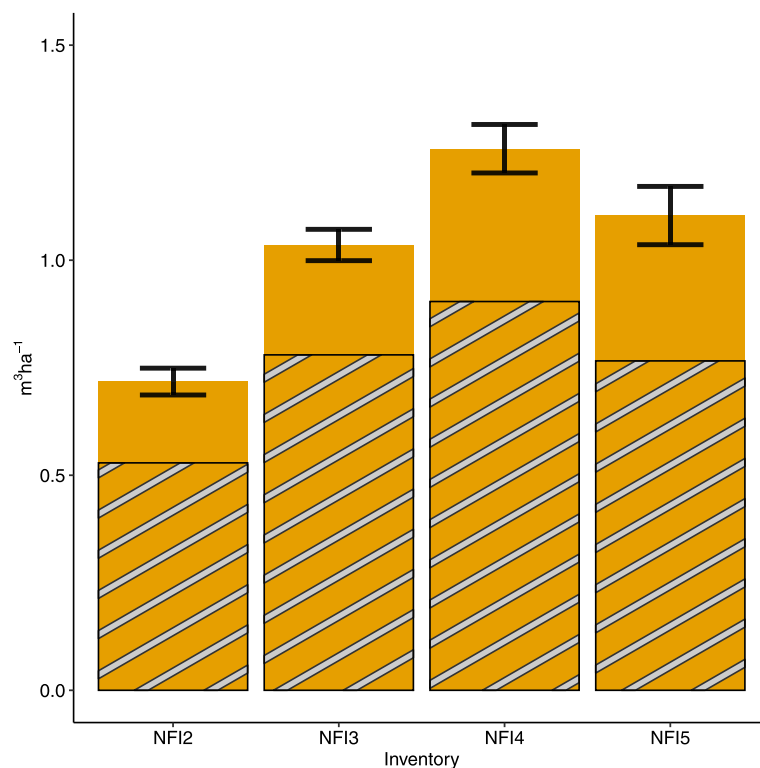
Fig. 2 Simplified cylindric volume (assumption stump height = 30 cm, top diameter = DBH from previous inventory) for stumps that resulted from harvested conifer (dashed) and broadleaf tally trees (i.e., a saw-cut was observed). The error bars indicate one standard error of the total volume of stumps of conifer and broadleaf tree species. The data are based on sample plots common to all five NFIs. The data were standardized based on the time period between the measurements of the sample plots in the NFIs 4 and 5 to account for biases due to different interval times between two consecutive NFIs, i.e., on average 10.1 years between NFIs 1 and 2, 10.8 years between NFIs 2 and 3, 8.8 years between NFIs 3 and 4, and 8.7 years between NFIs 4 and 5

simple model 1. This is due to approximately ¼ of stumps with heights between 30 and 129 cm. The standard error in the estimate based on model 2 increased due to the variability introduced by using a measured stump height rather than a constant. In the estimate based on model 3, using a measured stump top diameter rather than the DBH of the tree from the previous inventory results in a statistically significant ($p < 0.001$) increase of the stump volume estimate. The most accurate model 4, which is based on two stump height measurements, two diameter measurements, and an estimate of missing volume due to cavities and damage (cf. Fig. 1), results in an approximately doubling of the volume estimate based on model 3. Figure 3b shows the nationally representative mean stump volume based on model 4 as in Fig. 3a but including also older stumps, i.e., which existed even before the NFI4 ($n = 7263$) and stumps that appeared between NFI4 and NFI5 but for other reasons than harvest, particularly natural mortality ($n = 187$). The volume of older stumps (9.9 ± 0.3 m^3 ha^{-1} mean $\pm$SE) is approximately three times higher than that of fresh stumps (3.6 ± 0.4 m^3 ha^{-1}). Based on the nationally representative mean stump volume in the NFI5 (Fig. 3b), Table 2 presents

biomass and C stocks based on measured decay stage and corresponding wood densities and C contents.

The difference in the values for NFI5 stumps calculated based on a single height measurement only (model 3 in Fig. 3a) and on down- and upslope diameters (model 4) demonstrates that a significant part of a stump on the downslope side is above the soil surface and thus exposed. The data on stump height based on all 9564 stumps measured in the first 4 years of the NFI5 indicate a high variability and a skewed distribution (Fig. 4a). The height measured on the upslope facing side has a mean of 25.7 $\pm$ 23.3 (SD) and on the downslope facing side of 50.7 $\pm$ 34.9 cm. For the 1642 stumps that originated from harvested tally trees since the NFI4, the means on the values were similar to all stumps and are 25.6 $\pm$ 22.4 cm and 49.1 $\pm$ 37.3 cm, respectively. Differences in stump up- and downslope heights are not restricted to mountainous areas. Also, on stumps in the NFI5 originating from harvested trees since the NFI4 ($n = 416$) located in the Plateau production region below 600 m, statistically significant ($p < 0.01$) differences between downslope and upslope height were found. The height difference is independent
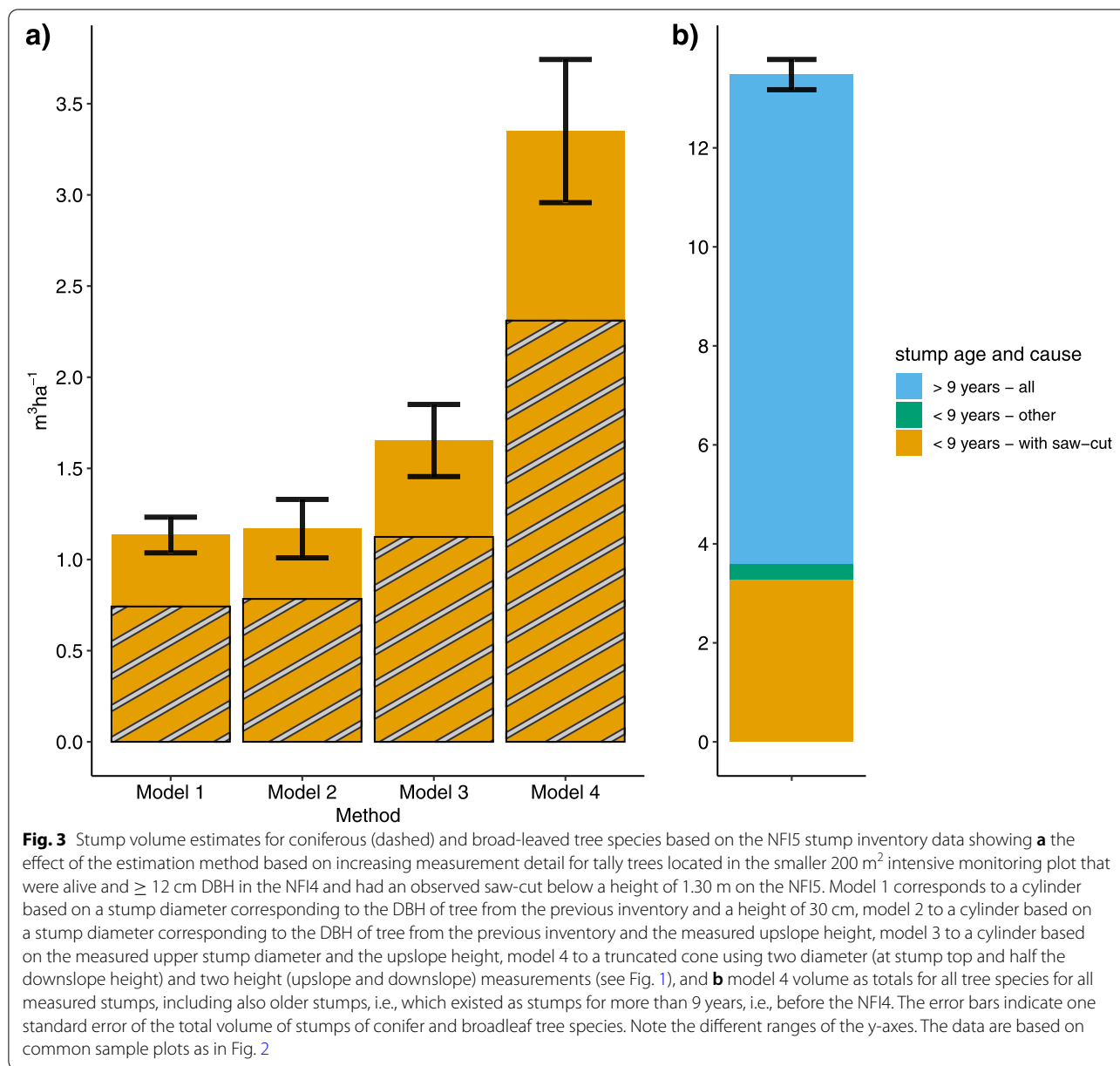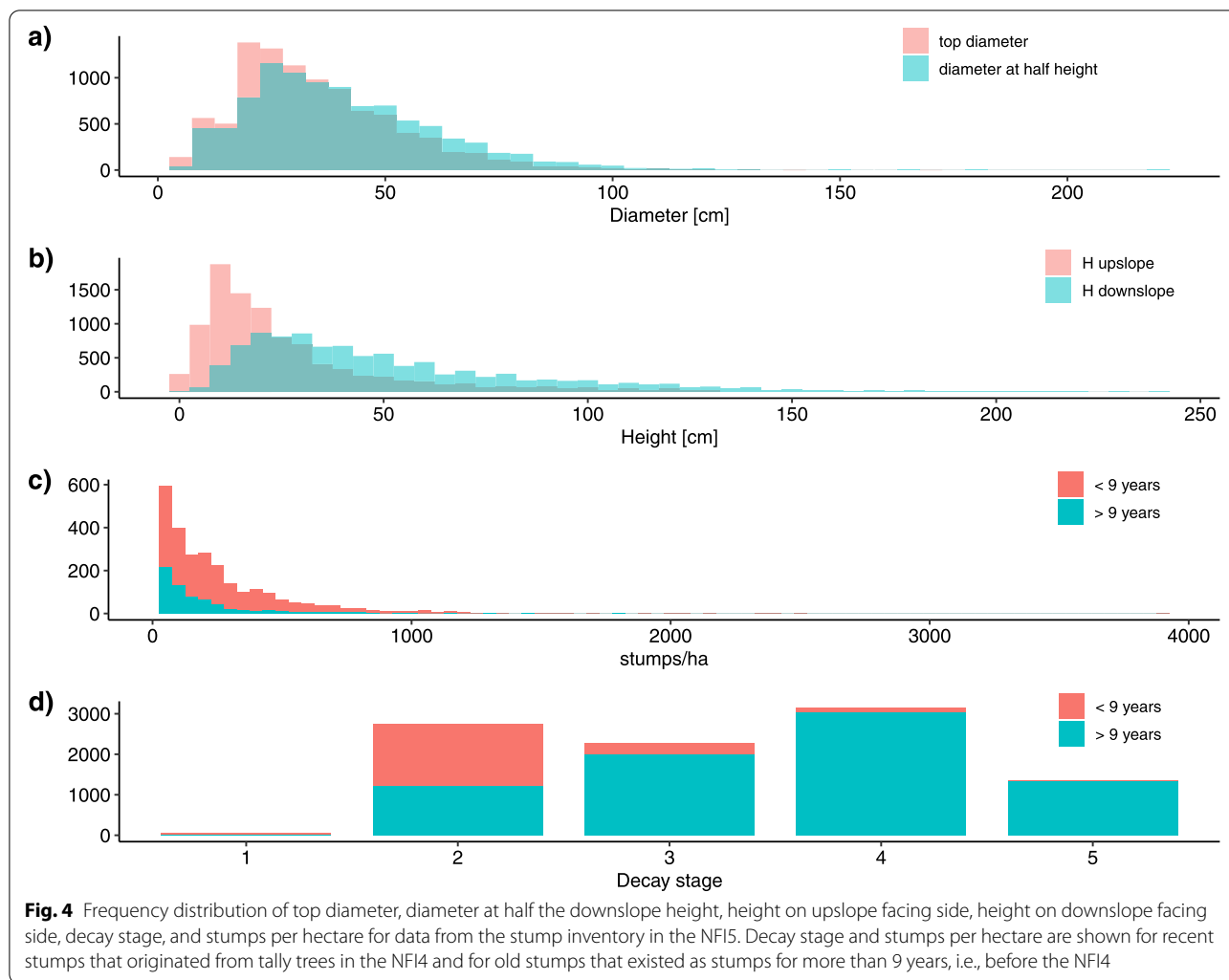
Fig. 3 Stump volume estimates for coniferous (dashed) and broad-leaved tree species based on the NFI5 stump inventory data showing **a** the effect of the estimation method based on increasing measurement detail for tally trees located in the smaller 200 m^2 intensive monitoring plot that were alive and $\geq$ 12 cm DBH in the NFI4 and had an observed saw-cut below a height of 1.30 m on the NFI5. Model 1 corresponds to a cylinder based on a stump diameter corresponding to the DBH of tree from the previous inventory and a height of 30 cm, model 2 to a cylinder based on a stump diameter corresponding to the DBH of tree from the previous inventory and the measured upslope height, model 3 to a cylinder based on the measured upper stump diameter and the upslope height, model 4 to a truncated cone using two diameter (at stump top and half the downslope height) and two height (upslope and downslope) measurements (see Fig. 1), and **b** model 4 volume as totals for all tree species for all measured stumps, including also older stumps, i.e., which existed as stumps for more than 9 years, i.e., before the NFI4. The error bars indicate one standard error of the total volume of stumps of conifer and broadleaf tree species. Note the different ranges of the y-axes. The data are based on common sample plots as in Fig. 2

Table 2 Mean $\pm$ SE of the volume, biomass, and C stocks based on the NFI5 stump inventory including all measured stumps, cf. Fig. 3b. The data are based on sample plots in the NFI that are common to all five NFIs

Species type	Volume (m^3 ha^{-1})		Biomass (t ha^{-1})		C (t ha^{-1})	
	Mean	SE	Mean	SE	Mean	SE
Conifer	9.80	$\pm$ 0.37	3.14	$\pm$ 0.12	1.55	$\pm$ 0.06
Broadleaf	2.42	$\pm$ 0.21	0.94	$\pm$ 0.09	0.45	$\pm$ 0.05
Undetermined	1.26	$\pm$ 0.14	0.36	$\pm$ 0.04	0.18	$\pm$ 0.02
Total	13.48	$\pm$ 0.31	4.44	$\pm$ 0.11	2.17	$\pm$ 0.05

Fig. 4 Frequency distribution of top diameter, diameter at half the downslope height, height on upslope facing side, height on downslope facing side, decay stage, and stumps per hectare for data from the stump inventory in the NFI5. Decay stage and stumps per hectare are shown for recent stumps that originated from tally trees in the NFI4 and for old stumps that existed as stumps for more than 9 years, i.e., before the NFI4

of the tree species type within an elevation class of a forest region (Figure 6 in Appendix) but is correlated with the slope of the sample plot ($p < 0.001$, Figure 7 in Appendix). The effect of the slope is most pronounced for slopes more than 40%, and it decreases with sample plot elevation. The mean stump height difference on even terrain with slopes less than 10% is 6.8 cm on sample plots below 600 m, 8.6 cm on plots between 601 and 1200 m, and 19.3 cm on plots above 1200 m. The means for the diameters measured at the stump top and at half the downslope facing side (Fig. 4b) were 34.6 ± 17.7 cm for the top diameter and 40.6 ± 20.8 cm for the diameter at half the height. We did not find a correlation between stump height and tree height based on stumps of trees with measured heights in the previous inventory (Figure 8 in Appendix).

The total of 9564 stumps measured in the first 4 years of the NFI5 were found on 2109 (77%) of the total of 2744 sample plots visited including plots that were non-forest in previous NFIs. On 50% of the sample plots, stump density

per hectare was less than 273 (Fig. 4c). One-thousand nine-hundred thirty-seven or 20% or of all stumps were tally trees in the NFI4, including 1711 (87%) that were still living at that time. The origin of the stumps resulting from living tally trees in the NFI4 was primarily human intervention, i.e., a visible saw-cut was observed (1684 or 98%). For 27 (2%) stumps, natural mortality was identified. In the NFI5 inventory, 7627 (i.e., 9564–1937) old stumps that existed as stumps already 9 years previously in the NFI4 were found. Within these 9 years on average, 215 (1937 stumps/9 years) or approximately 6 ha^{-1} yr^{-1} new stumps emerged annually. Assuming a constant rate of new stumps annually, it would take approximately 35 years (7627 old stumps/215 new stumps per year) to build up the sample of 7627 old stumps. Hence, the oldest stumps may be as old as 35 years and likely considerably older considering that approximately 43% of all stumps in NFI5 consisted of still fresh, solid wood, or rotten (i.e., decay stages 1 to 3; Fig. 4d) indicating no or only slight decay (Puletti et al. 2019).

In protection forests, the mean upslope height was 30.9 $\pm$ 27.0 (SD) cm compared to 22.7 $\pm$ 20.3 cm in regular forests, and the downslope heights were 65.1 $\pm$ 37.8 cm and 42.3 $\pm$ 30.2 cm, respectively (Figure 9 in Appendix). The differences were statistically significant ($p < 0.001$). Stump density was slightly but not statistically significantly higher in protection forests with means of 427 $\pm$ 463 stumps/ha compared to *407 $\pm$ 360 stumps/ha in regular forests.*

3.2 Dead wood pools

The comprehensive monitoring of stumps, including methodological aspects such as two height measurements, and completeness by monitoring also older stumps, is important to obtain accurate and also balanced estimates of all pools, i.e., standing and downed dead wood, and stumps. This aspect is demonstrated by comparing the size of different dead wood pools available in a particular measuring cycles of the Swiss NFI (Fig. 5). Data on LIS-DW and stumps had not been collected in NFI1 and NFI2. Furthermore, for NFI1, no stump information could be derived as no previous information was available. And only NFI5 has complete information on stumps, resulting in a contribution of stumps of 23.2% to the dead wood pool.
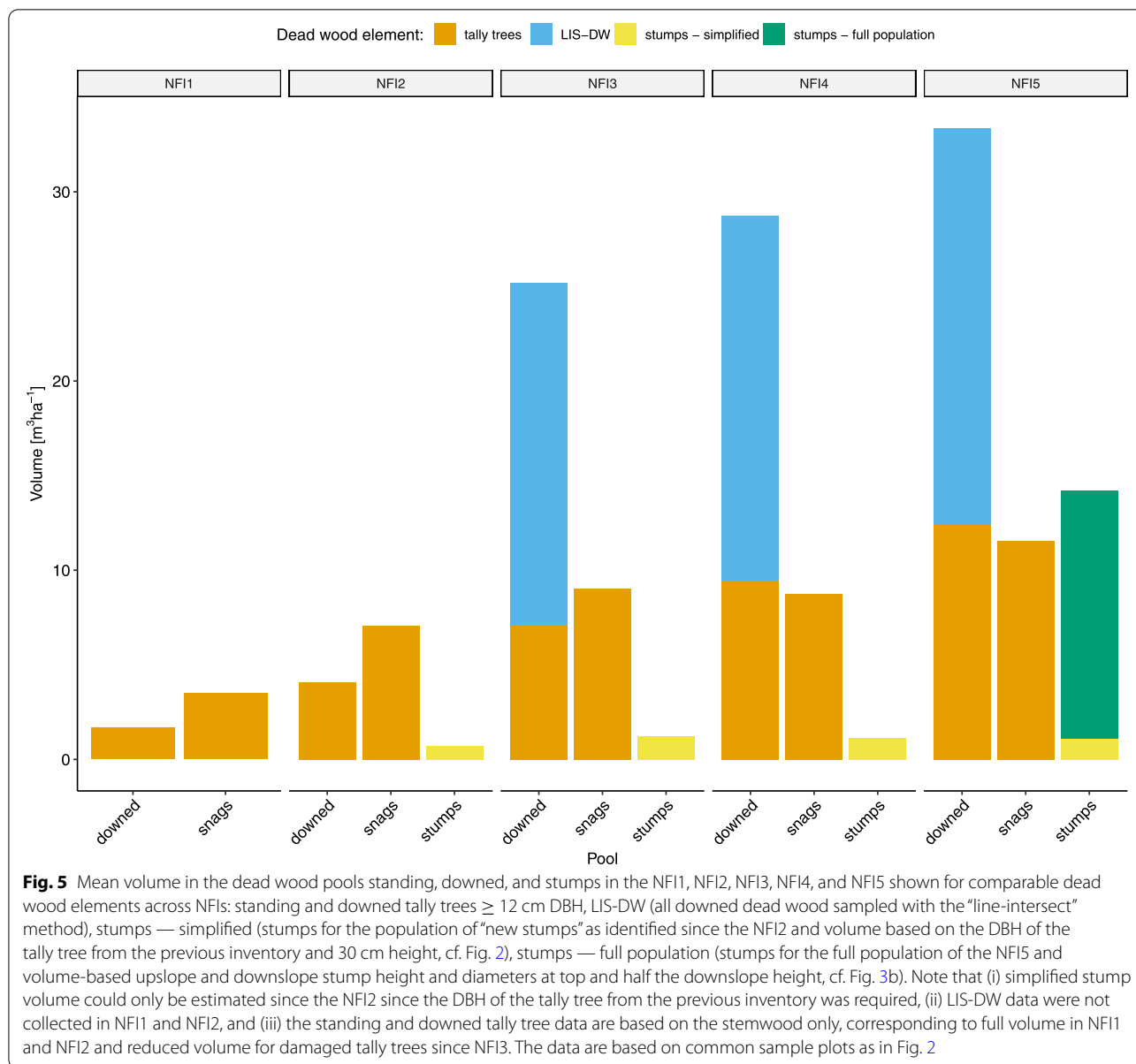
4 Discussion

In managed forests, harvested trees are the main source of stumps. Depending on harvest rate and management intensity, a large number of stumps can remain in the forest. Using a simplifying assumption of a stump height of 30 cm (Gschwantner et al. 2009) and a stump top diameter corresponding to the DBH of the tree from the preceding NFI, the stump population originating from "newly" harvested trees was estimated based on four Swiss NFIs ranging over almost 30 years (Fig. 2). Based on this simplified assessment, which underestimates the true stump pool, the mean national stump volume in Swiss forests is approximately 1 m^3 ha^{-1}, which would correspond to between approximately 5 to 25% of the dead wood volume estimated for different European forest categories (Table 9 in Rondeux et al. 2012). The true dead wood pool can however be significantly larger, because the diameter of stumps is greater than the tree DBH, and height may be higher than 30 cm. The effect of available data on stump dimensions (Fig. 3a) demonstrates that the stump pool is significantly underestimated without specific measurements (model 1) and also with a single height measurement (model 2) and diameter (model 3) measurement. The full aboveground stump volume is represented accurately only with a second height and diameter measurement. Model 4 provides the most accurate and complete estimates based on the additional measurements of two heights, two diameters, and the estimated remaining volume to account for the complex

shapes, cavities, and topography. The irregular and complex shapes of the lower part of the stem are difficult to capture geometrically, and simplifications are required. Fraver et al. (2007) found that the truncated cone used here provides a reasonable alternative to more complex shapes such as a frustum of a neiloid. Also, the use of taper equations to estimate a stump diameter is not always an option as additional measurements along the stem are not available, for example, in the case of older stumps. Advanced techniques such as terrestrial laser scanning may become an alternative (e.g., Novotny et al. 2021). To establish a baseline for the stump pool, it is important to also collect information on older stumps in addition to stumps that originated from harvested trees since the preceding inventory as they account for approximately 3 times more volume than recent stumps (Fig. 3b). Once a baseline is established, stumps need to be sampled repeatedly to estimate changes of the stump pool. As demonstrated based on the comprehensive stump inventory in the Swiss NFI5, stumps decay slowly. The estimated minimum residence time of 35 years corresponds to residence times of standing dead trees in similar forest types reported in Hararuk et al. (2020), i.e., both appear to decay at a similar rate. As discussed by Seedre et al. (2012), the comparability of decay rates between stumps and standing dead trees is limited, and in our case, the age of the older stumps is not known. The progression of the decay process through the five stages is similar to the dynamic found by Niese (2013) for stumps in Austria.

The results based on the stump inventory in the NFI5 demonstrate the importance of stumps as an important dead wood pool. The estimated contribution of 23% to the total dead wood pool (Fig. 5) in the entire Swiss forest agrees well with the approximately 25% based on data from the German NFI (Fig. 1 in Schnell and Hennig 2019) but is less than the estimated contribution of 33% in Austrian production forests (Niese 2013). The total dead wood pool in Swiss forests is however larger than in Germany and other neighboring countries (Forest Europe 2020). The effect of the increasingly comprehensive and accurate estimation of all dead wood pools following the collection of additional detail is significant (Fig. 5) and demonstrates the need for more complete inventories (Russell et al. 2015). The lacking information on stumps in previous NFIs limits the assessment of the historic contribution of the stump pool. However, due to the traditional practice of removing downed dead wood from the forest (Gimmi et al. 2013), dead wood pools were low, and thus, it can be assumed that historically, the contribution of stumps to the total dead wood pool was even higher than as found in the NFI5.

The survey by Woodall et al. (2009) indicated that stumps have received little attention in NFIs, i.e., only 60% of 30 NFIs where dead wood data were collected also monitored stumps in one or the other way. This was

Fig. 5 Mean volume in the dead wood pools standing, downed, and stumps in the NFI1, NFI2, NFI3, NFI4, and NFI5 shown for comparable dead wood elements across NFIs: standing and downed tally trees ≥ 12 cm DBH, LIS-DW (all downed dead wood sampled with the "line-intersect" method), stumps — simplified (stumps for the population of "new stumps" as identified since the NFI2 and volume based on the DBH of the tally tree from the previous inventory and 30 cm height, cf. Fig. 2), stumps — full population (stumps for the full population of the NFI5 and volume-based upslope and downslope stump height and diameters at top and half the downslope height, cf. Fig. 3b). Note that (i) simplified stump volume could only be estimated since the NFI2 since the DBH of the tally tree from the previous inventory was required, (ii) LIS-DW data were not collected in NFI1 and NFI2, and (iii) the standing and downed tally tree data are based on the stemwood only, corresponding to full volume in NFI1 and NFI2 and reduced volume for damaged tally trees since NFI3. The data are based on common sample plots as in Fig. 2

corroborated in a questionnaire among European NFIs in 2014 by A. Lanz in preparation of the stump inventory for the Swiss NFI5 (document available in the data repository). In the meanwhile, this number may have increased. We found only few published studies with estimates of the stump pool. The nationally representative estimates from Spain (Alberdi et al. 2020) and Germany (Schnell and Hennig 2019) suggest a large range, i.e., 1% and 25% of the dead wood pool. This may be due to differences in the minimum thresholds to identify dead wood elements and to the estimation of volume. Also, forest types and management are not comparable between the two countries. The case study by Teissier du Cros and Lopez (2009) based on 31 plots of

the French NFI suggests a contribution of stump volume to total dead wood volume of 5%. Petersson and Melin (2010) estimated the total biomass of stumps systems (i.e., including roots > 2 mm diameter) of trees that were harvested or died between two inventories at the national scale in Sweden. Their estimates ranged from 224 Mt in 1990 to 270 Mt in 2003, which corresponds to approximately 8 to 10 t ha^{-1} based on the reported forest area of 28 Mio ha. The corresponding estimate for Switzerland based on stumps originating from trees harvested between the NFI4 and the NFI5 is approximately 16 t ha^{-1}, although the values from Sweden and Switzerland are not fully comparable due to different methodologies, forest management practices,

and forest types. Other studies (e.g., Jonsell and Schroeder 2014; Kaarakka et al. 2018) are not comparable as they are based on clear-cut systems. In Switzerland, harvesting of stumps is not economic due to the difficult terrain (Mohr et al. 2019) and the prohibition of clear cuts. Thus, using stumps as source for bioenergy as, for example, in Scandinavia (Persson and Egnell 2018) is not practiced. Also, important ecological services such as biodiversity, protection, soil functions, and C storage are compromised by harvesting of stump systems (Ranius et al. 2018; Walmsley and Godbold 2009).

Not surprisingly, stump volume, biomass, and C mass estimates depend strongly on the used height and diameter measurements. Our results demonstrate that it is important to use two height and diameter measurements to avoid underestimating the stump pool. Taking differential height measurements applies particularly to uneven terrain, where large parts of a stump are located below the theoretical stump base resulting from an assumed even surface implied by only the upslope height measurement (which also serves as basis for "breast height" in DBH measurements), while additional diameter measurements are important to account for the stronger tapering of the lower stem (Kublin et al. 2013). Our results for stump height were consistent with our hypothesis that stumps are higher in protection forests than in regular forests. However, the heights of 30.9 ± 27.0 (SD) upslope and 65.1 ±37.8 cm downslope may not be sufficient to provide protection, particularly against rock falls (Fuhr et al. 2015).

4.1 Implications and recommendation

As rooted stumps are typically not included in the inventoried dead wood pool, except in Germany (Table 4 in Rondeux et al. 2012), a potentially large part of dead wood is not accounted in forest inventories and, hence, neither in reports based on forest inventories such as greenhouse gas inventories. A consequence of this is that also the associated belowground part of the stump is not further considered. It would hence be important to include stumps in National Forest Inventories as identified by Rondeux et al. (2012). Regarding the belowground part of stumps as well as of whole trees, it is important to consider the potential overlap resulting from the application of allometries to estimate the belowground part. For example, the functions developed for Norway spruce (Wirth et al. 2004) and European beech (Wutzler et al. 2008), which are widely applied, are based on meta-studies which consider root systems with and without aboveground parts.

Based on our findings, it would be important to include field measurements of stump height and diameter for an accurate estimation of stump volume and biomass. Assumptions for stump height that are made in NFIs using either constant values such as 30 cm or a value relative to tree height (Gschwantner et al. 2009) can lead to considerable bias in estimates of stump volume and biomass. It should also be considered that heights of stumps that remain after harvesting can be homogenous and specific to a particular forest management practice, while the height of stumps of trees that died of natural causes can be highly variable. This is demonstrated by our data, which also show that stump height is not correlated with tree height. Additional information on decay stage at different locations of the stump complemented by the identification of the presence of heart rot (Wunder et al. 2013) would improve the accuracy of derived biomass and carbon stock estimates and provide an information on forest health and stability (Knüsel et al. 2015).

The experience gained in the first 4 years of the intensive stump monitoring in the NFI5 shows that the effort required for the additional stump measurements is reasonable considering the improved accuracy and completeness, complementing information on wood resources, carbon stock, and forest biodiversity. As demonstrated, the comprehensive stump and dead wood assessment in the Swiss NFI improves completeness and accuracy of the aboveground woody dead wood pool estimates. However, limitations in reporting still exist as, for example, trees < 12 cm DBH and other vegetation are not considered. Depending on national circumstances, the required effort for collecting additional stump measurements may even be lower, for example, if a second stump height is deemed unnecessary in cases of more homogenous conditions regarding, among other, forest management and topography than in Switzerland. It remains to be seen, however, if already measured stumps can be reidentified in subsequent inventories as especially smaller stumps may become hidden under ground vegetation. Considering the longevity of stumps and the contribution to the total volume of the stump pool, resampling is however deemed worthwhile.

5 Conclusion

National Forest Inventories are the primary source of information on forest conditions. Country-specific developments result in the use of different methodologies and the collection of different forest attributes, which can limit the comparability of estimates. Unfortunately, stumps are often not included in NFIs. This study demonstrates that stumps can be a significant proportion of dead wood in forests, which should be accounted for in order to improve accuracy and completeness of NFI estimates and derived data such as C stocks for greenhouse gas reporting. The study further highlights that in order to obtain nationally representative and accurate estimates of stump volume, comprehensive (re-)sampling of fresh and old individuals and their dimensions is required.

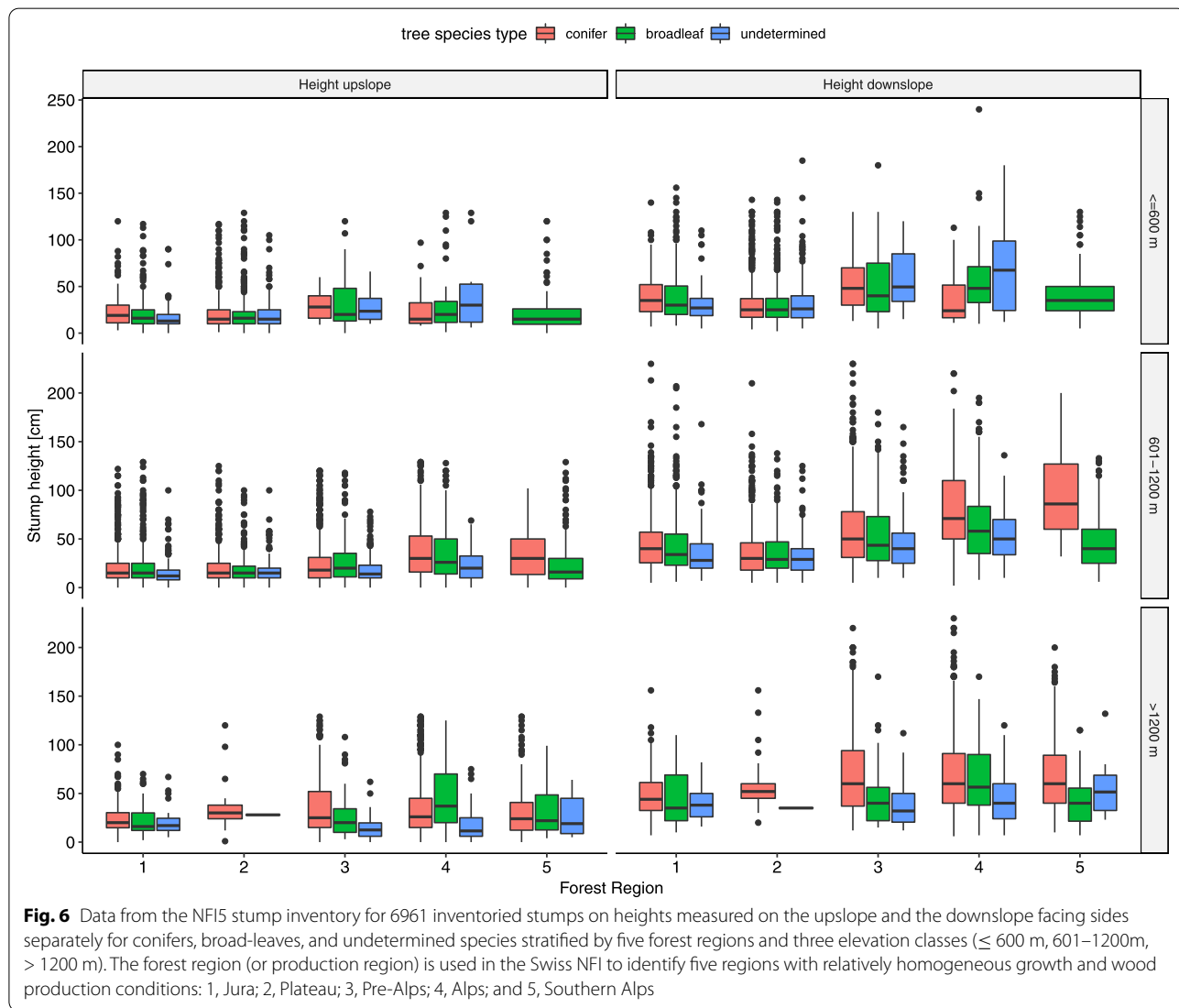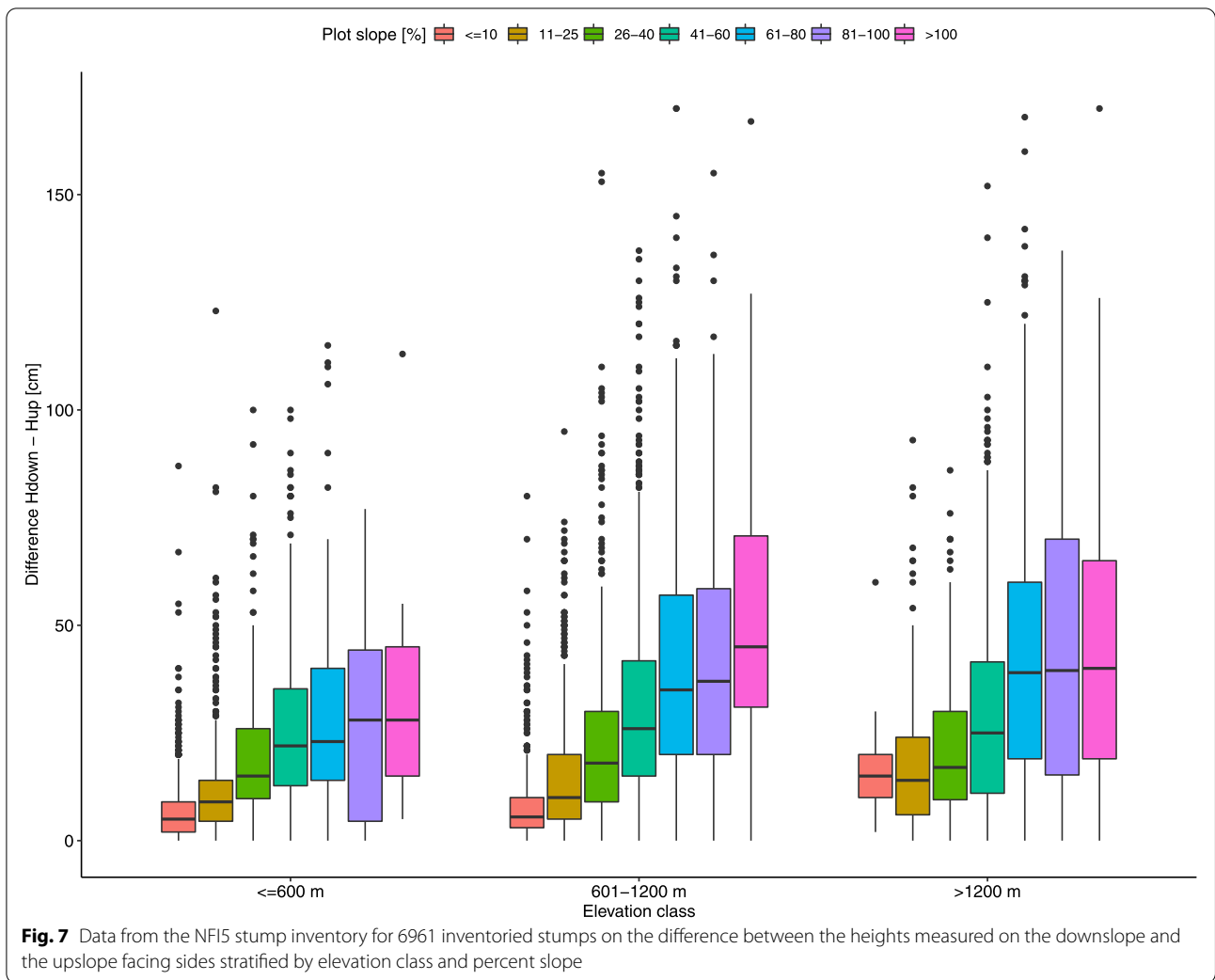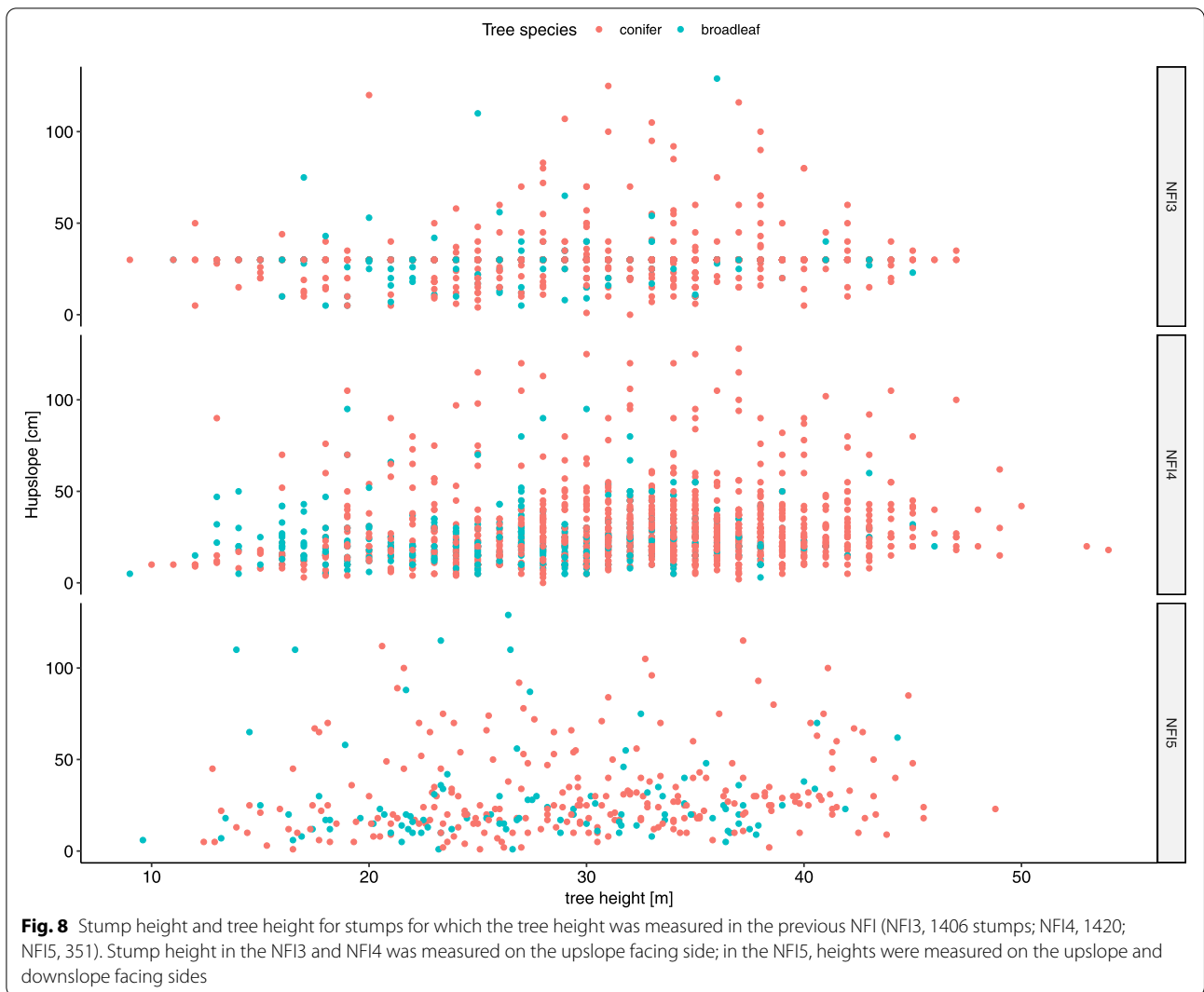# Appendix
Figs. 6,7,8 and 9

Fig. 6 Data from the NFI5 stump inventory for 6961 inventoried stumps on heights measured on the upslope and the downslope facing sides separately for conifers, broad-leaves, and undetermined species stratified by five forest regions and three elevation classes ($\leq$ 600 m, 601–1200m, > 1200 m). The forest region (or production region) is used in the Swiss NFI to identify five regions with relatively homogeneous growth and wood production conditions: 1, Jura; 2, Plateau; 3, Pre-Alps; 4, Alps; and 5, Southern Alps

Fig. 7 Data from the NFI5 stump inventory for 6961 inventoried stumps on the difference between the heights measured on the downslope and the upslope facing sides stratified by elevation class and percent slope

Fig. 8 Stump height and tree height for stumps for which the tree height was measured in the previous NFI (NFI3, 1406 stumps; NFI4, 1420; NFI5, 351). Stump height in the NFI3 and NFI4 was measured on the upslope facing side; in the NFI5, heights were measured on the upslope and downslope facing sides

Fig. 9 Boxplots for stump height measured up- and downslope and diameter at the top and at half the downslope height in regular and protection forests

Code availability

Not applicable.

Authors' contributions

Conceptualization, MD and MA; methodology, MD and MA; formal analysis and investigation, MD; writing — original draft preparation, MD; writing — review and editing, MD and MA; funding acquisition, not applicable; resources, MD and MA; supervision, not applicable. The authors read and approved the final manuscript.

Availability of data and materials

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request and are available at https://doi.org/10.16904/envidat.304.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

All authors gave their informed consent to this publication and its content.

Competing interests

The authors declare that they have no competing interests.

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