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Deadwood Mapping in Davos:

Assessment and Analysis of Deadwood through Field Work and Remote Sensing Techniques

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Abbreviations

ALS	-	Airborne Laser Scanning (LiDAR mounted on aircraft)
CHF	-	Swiss Francs
CIR	-	Colour-Infrared Images
DBH	-	Diameter at Breast Height
DSM	-	Digital Surface Model
i.i.d.	-	independent and identically distributed
IQR	-	Interquartile Range
LeiNa	-	Leistungsnachweis Wald (Forest Performance Record)
LFI	-	Landesforstinventar (Swiss National Forest Inventory)
LiDAR	-	Light Detection and Ranging
m a.s.l.	-	meters above sea level
NRMSE	-	Normalized Root Mean Squared Error
OHM	-	Object Height Model
PA	-	Plate Area
PH	-	Protective Height
SD	-	Standard Deviation

Abstract

Deadwood plays an important role in mountainous protection forests and for ecosystem services as it increases terrain roughness and prevents soil erosion. It is also an indicator for biodiversity because many saproxylic species rely on its abundance. However, field surveys, especially in areas that are difficult to access, are time and cost intensive which is why remote sensing techniques are an interesting approach for mapping deadwood. In this thesis, it was investigated how deadwood occurrence is related to certain forest and terrain variables, using a combination of field surveys and GIS analysis in the Dischma valley near Davos, canton Grisons. Furthermore, the protective height and plate area of uprooted trees which are beneficial for the protection function were measured and statistical predictions about said aspects using the diameter at breast height were made. Finally, an analysis of possibilities, difficulties and limits of deadwood detection with LiDAR (Light Detection and Ranging) and orthophotos in subalpine coniferous forest was carried out. The main methods were direct manual point cloud processing and half-automated deadwood map creation. The products of these steps were then compared to each other and to the field survey. There is a high overall deadwood volume of 99 m^3/ha in the study area but only a weak correlation between this amount and different levels of forest/terrain variables such as the stand density, the exposure and the elevation. The diameter at breast height proved to be a stable predictor for the protective height as well as the plate area of uprooted trees. The remote sensing analysis showed that LiDAR data can only be used for the detection of lying deadwood with certain limitations. Shrub lines and other forest floor cover, canopy density and inhomogeneity were found to be the most interfering and limiting factors. In the processing of LiDAR point clouds, the quality of the object height model influenced the results the most. Light-intensity, echo-width and number of returns all turned out to be useful parameters as well.

1 Introduction

1.1 Background and State of the Art

Deadwood plays an important role in mountainous protection forests. It increases terrain roughness and soil stability which protects from rockfalls, prevents soil erosion as well as the formation of avalanches [1]. Furthermore, in some cases the forest regeneration on coarse wood debris makes up over fifty percent of the total regeneration in mountainous areas and is therefore important for securing the protective effect in the long term [1]. Overall, the protection value of Swiss forests is estimated to amount to 4 billion CHF per year [2], which shows that deadwood also is of economic interest. Moreover, the richness in species of taxa such as saproxylic beetles, bryophytes, lichens and fungi [3] as well as small mammals and birds [4] positively correlates with the amount of deadwood in forests. But deadwood also has some negative management aspects as it hinders workers and may enhance fire risk [5]. The above-mentioned costs and benefits underline the relevance of deadwood mapping.

However, using field surveys for inventorying deadwood, especially in areas that are difficult to access, is time and cost intensive [6], [7]. Remote sensing techniques and analysis tools are useful for the assessment of deadwood as they allow a more efficient inventory than field work if implemented correctly [6], [8]. Results from several studies summarized in the review of Marchi et al. (2018) [4] show that there are already promising methods for identifying deadwood from Airborne Laser Scanning (ALS) data, mostly from deciduous forests in leaf-off season. Nevertheless, there is a wide range in the accuracy, ranging from 25% to up to 90% and only few studies were conducted in subalpine coniferous forests where about 75% of the Swiss protection forests are located.

1.2 Objectives and Research Questions

This bachelor thesis aims to gather and investigate data on the amount and distribution of deadwood in Davos with the focus on the Dischma valley. Moreover, dimensions relevant to the protection function of the deadwood are examined. This thesis therefore provides the local forest management and researchers with information they can use for their work. The findings of this study are also relevant for subalpine coniferous forests generally. For example can the correlation between the diameter at breast height (DBH) and the size of a root plate of a dead tree allow predictions whether living trees will still have a protection value after a windthrow according to their DBH. The integration of Light Detection and Ranging (LiDAR) as well as orthophotos aims to identify difficulties, limits and possibilities of deadwood detection with these technologies in subalpine coniferous forests.

The research questions are the following:

1. What is the estimated amount of deadwood per hectare in the study area?
2. How is the occurrence of deadwood related to topographical variables (elevation, exposure, slope inclination), forest structural variables (stand density) and forestry interventions?
3. How is the protective height and the area of root plates correlated to the diameter at breast height of the belonging upper part?
    a. What are the predicted protective heights and plate sizes in the study area?
4. What are the possibilities, difficulties and limits in detecting lying deadwood with LiDAR and orthophotos in subalpine coniferous forests?
    a. Which are the most important properties/parameters of LiDAR datasets for the detection of lying deadwood?
    b. What are the ideal ranges of said parameters for the detection of lying deadwood?

2 Materials and Methods

2.1 Study Area

The Dischma valley is located south-eastern of the city Davos in Grisons (CH). Its deepest point lies at 1550 metres above sea level (m a.s.l.) and the upper tree line is located between 2000 and 2200 m a.s.l., depending on exposure, forestry interventions and natural disturbances. The two valley sides are mainly southwest, respectively northeast exposed. The slope inclination is often above 40% in the forested area with hollows and crests as well as a few plateaus where the inclination is lower or higher [9].

Most forests are even-aged high forests that can be classified as small to medium size timber stands with a range from very low to very high density. There are also a few plenter forests as well as stands in early development stages [10]. Most of the area is designated protection forest [11].

Site Variables

The characteristics of the study area were summarized in site variables which were then attributed to each survey transect. This enabled the comparison of the site variables and the respective amounts of deadwood.

Exposure

The exposure is divided into the two intercardinal directions the valley sides are facing which is *north-east* and *southwest*.

Elevation Level

There were three elevation levels chosen. 1700 m a.s.l. represents the *subalpine* level, 1850 m a.s.l. the *upper subalpin*e level and 2000 m a.s.l the *tree line* elevation level and were classified according to maps from the Bundesamt für Landestopographie swisstopo and the Bundesamt für Umwelt BAFU (2020) [12].

Inclination

The steepness of the terrain was graded in five classes. *Low* ranges from 0% to 18%, *medium* from 18% to 36%, *high* from 36% to 54% and *very high* from 54% to 90%. The inclination map was created by Mark Schaer through map material of the Bundesamt für Landestopographie swisstopo (2020) [9].

Stand Density

The stand density was approximated by the crown closure and was graded as in the paper *Anleitung zur Waldbestandeskartierung mit der Checkliste BK2010.2* [13]. The three stand density classes are *open*, *intermediate* and *dense* with respective crown closures of about 60%, 80% and 90%.

Interventions

This variable describes whether there were forest management interventions on a patch or not. Since 2006 there exists a data base called LeiNa (Leistungsnachweis Wald) for Grisons where foresters register their forest management interventions. However, LeiNa was reworked in 2016 and older entries than 2010 are rare.

2.2 Field Survey

Many methods described in this chapter were adapted from the paper *Erhebungsmethode für liegendes Totholz in Kernflächen von Naturwaldreservaten* [14]. However, in their study a full survey on permanent plots was carried out, whereas in this thesis a sample inventory was made. This, as well as additional parameters that are included in this thesis allowed only a partial adaption of their methods.

Height measurements were done with a folding rule (2.00 metres) and a Haglöff Vertex III and Transponder T3. Diameters were measured with callipers (80 centimetres) or a DBH measurement tape. For length measurements the folding rule as well as a length measurement tape (10.00 metres) were used. GPS locations were determined with the GNSS receiver Stonex S800.

Inventory Plots

The 18 inventory plots were chosen randomly in order to deliver unbiased results. Nevertheless, they also had to cover sufficient topographical and forest structural variables as well as contain representative amounts of deadwood pieces. For that reason, an equal number of plots were chosen for each valley side and each elevation level.

In order to keep the risk and added effort of working in steep and difficult terrain within a limit, the inventory strips had a small width of 4 metres and the length was variably chosen in the field. The ending and the starting point of each plot were referenced with the Stonex S800. At least 10 pieces per plot had to be inventoried so that the chance of big pieces falsely representing a plot was minimized. The inventory stripes ideally followed contour lines. But as this was difficult to keep track of in the field, another approach was chosen. Instead of contour lines an azimuth was to be followed until the end of the plot. The initial direction was to result in a path with minimal height differences and was not to be biased with regards to visible deadwood ahead. The plots were then characterized by the site variables and notes from the field.

Deadwood was inventoried as follows. If a piece was completely within the plot it was recorded as a whole. For pieces that crossed the border, only the parts inside the plot were measured. Root plates were an exception to this. As the number of root plates in the plots were too little to make statistically relevant statements, additional root plates outside the plots were included. These additional uprooted trees had to be visible from the line segment that was being inventoried so that the site variables could still be attributed to them. In a test run of the field work, the number of recorded root plates was increased from one to six in a plot due to this method. A disadvantage of this method was, that the root plates could not be used for the volume calculation per area. However, because of the rarity and the high soil content, their impact on the deadwood volume per area was estimated to be rather low. The definition of different kinds of deadwood is given in the *Form Distinction* chapter.

Parameters

This chapter gives an overview of all deadwood parameters that were measured in the field as can be seen in table 1. Further, it covers certain requirements that pieces had to fulfil to be included in the survey. Lastly, thorough explanations of more complex parameters are given.

Parameters that included length or height measurements were rounded to 0.05 metres and those including diameter measurements were rounded to 0.01 metres. All measurements were recorded in metres to minimize the risk of unit confusion in the field and when digitalizing the field sheet.

Table 1: Explanation of the field work parameters. The first column contains the parameter's names as well as examples. In the second column the corresponding explanations are given.

Parameter	Explanation
Patch number [1], [2], [3]	A unique number was given to each plot.
ID [1], [2], [R.1], [3], [R.2]	Each individual piece of deadwood per plot had its unique identification number. Root plates were marked by adding "R" in front of the number and were counted separately from the other pieces.
Tree species [Sp], [La]	An abbreviation of the species' names.
Degree of decay [1], [2], [3], [4], [5]	The degree of decay was represented as a number between 1 and 5 in the manner described in the *Degree of Decay* chapter.
Form distinction [lying], [standing], [snag], [stump], [root plate]	Each piece was registered in only one of the five categories on the left. Root plates and their belonging upper part were therefore inventoried as different pieces even when they were connected. The distinction was made according to the belonging chapter *Form Distinction*.
Length or height [5.00], [7.45], [10.70]	Length: measured for lying deadwood Height: measured for standing trees, snags and stumps The pieces were measured to where they still met the minimal dimensions. Additionally, the starting point for the height measurement was the lowest downhill facing point above ground.

Protective height [1.00], [0.75], [2.20]	The protective height (ger.: Wirkhöhe) is a special variable that was measured only for root plates. The measurement was done from the lowest uphill facing point.
Diameter [0.10], [0.53], [0.61]	This section contains various subsections and the pieces were measured differently according to their deadwood type as described in the *Diameter* chapter.
Number of seedlings per piece	The absolute number of seedlings was counted for each piece of deadwood. Seedlings were defined as living young trees less than 1.5 metres in height. This year's germinants were not counted either.

Minimal Dimensions

The deadwood pieces had to fulfil certain minimal dimensions to be inventoried. Below that threshold the volume was considered negligible compared to pieces that are larger. A piece had to have a minimal diameter of at least 7 centimetres on a length of 1 metre. Alternatively, if the piece was shorter it was still inventoried if it had a minimal diameter of 14 centimetres on a length of minimum 0.5 metres. Deadwood shorter than 0.5 metres was neglected entirely.

Form Distinction

Deadwood occurs in different forms. Generally, a distinction is made between standing dead trees and lying deadwood as well as snags, stumps and root plates. Yet, the fine distinction between these categories varies from study to study [5]. The form distinction is important because not every parameter can be measured for every category. For example, it is possible to measure the diameter of lying pieces at the thinnest and thickest part whereas this is not possible for standing trees. Therefore, the formulas used for the volume estimations vary between the different forms.

Robin et al. (2009) [14] distinguish lying and standing deadwood mainly by their pitch angle. The pitch angle is normally measured relatively to the horizontal line. Pieces with an angle of 45° and higher are classified as standing, below 45° as lying deadwood. However, this method is not suitable for terrain with high inclination values. For example, lying trees would actually be classified as standing in areas where the terrain is inclined steeper than 45°. This can be seen in the following figure on the left. If the pitch angle is measured relatively to the ground instead and the same threshold of 45° is taken, some actually standing trees would be considered as lying. This case is illustrated on the right.

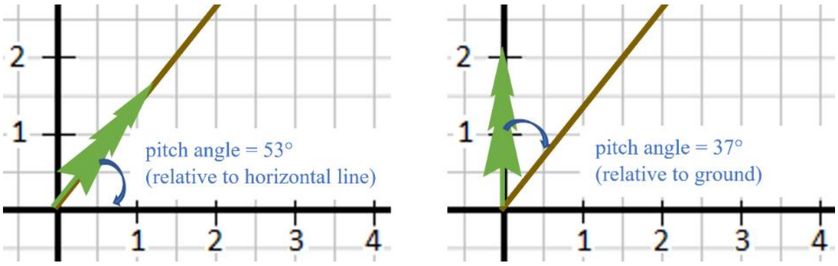


*Figure 1: Problem with distinguishing deadwood by the pitch angle: **left** would be considered standing when the pitch angle is measured relative to the horizontal but is actually lying on the ground; **right** would be considered lying when the pitch angle is measured relative to the ground but is actually standing.*

In order to eliminate this problem, the distinction in this survey was based on qualitative and practical aspects rather than quantitative ones. This decision was made due to a test run of the field survey in an open forest as well as in a very dense forest, where it was not a problem to distinguish lying from standing dead trees in either of the forests. However, some standing trees were heavily tilted and too high to be measured with a measuring tape. They were measured with the Vertex height measuring device, but remarks were made in the notes section as the Vertex only accurately measures more or less upright trees. Through the remarks, the number of these trees could be tracked and if necessary mitigation measures could be taken such as the exclusion of plots with too many heavily tilted trees.

Snags and stumps are a special form of standing dead trees where the top is missing for any reason. Snags are only distinguishable from stumps by their height. Pieces of which the top diameter was measurable were considered stumps and pieces of which this was not possible were classified snags. Following figure shows what the different pieces look like.

Figure 2: Different deadwood categories. From left to right: standing, snag, stump, lying [5].

A root plate results from an uprooted fallen tree. Root plates are often still connected to the upper part of the tree. The plate ends where the roots merge into the trunk and the upper part begins. The root plate and the upper part were inventoried separately. The upper part was inventoried as lying deadwood if inside the plot and the measurements were to be done accordingly.

Degree of Decay

The degree of decay was categorized according to the method used in the LFI, the Swiss National Forest Inventory [15]. A pocketknife is used to test the resistance of the deadwood pieces. The test is to be done at least 4 times per piece. For the categories, the German names were used, as the English language does not differentiate between as many stages of wood decay. There are 5 categories which were tested in the order of the table from top to bottom:

Table 2: Measurement of the degree of decay according to the method used in the LFI [15].

Code Number	Name	Definition
1	Frischholz	The wood is sap-bearing.
2	Totholz	The wood is hard but not sap-bearing. The knife's blade hardly penetrates the wood in fibre direction.
3	Morschholz	Less resistant. The blade penetrates in fibre direction but not crosswise.
4	Moderholz	Soft. The blade penetrates in every direction.
5	Mulmholz	Very soft, the wood is already loose or powdery and hardly coherent.

Diameter

This parameter was measured differently for each kind of deadwood. For standing dead trees and snags, the diameter at breast height was measured with a DBH measurement tape or callipers. Breast height was defined as 1.3 metres above ground. For stumps the diameter was recorded at the cutting or breaking point. Lying deadwood pieces were inventoried with callipers. For both the small and the thick end of a piece a measurement was done. Again, the minimal requirements had to be fulfilled and the measurement were done where no deformations of the trunk appeared. For root plates the maximal vertical diameter of the plate itself as well as the DBH of the upper part was measured.

2.3 Volume Calculations and Statistical Analysis

Volume calculations

The volume of standing dead trees and snags was calculated with the following formula [16]:

$$V_{standing\,\&\,snag}[m^3] = \pi * f * h * (\frac{DBH}{2})^2$$

Where *f* is the shape-coefficient, *h* the tree's height and *DBH* the diameter at breast height. The chosen shape-coefficient for standing trees was 0.4. For snags it was 0.6 because of the lesser decrease in volume per height. The lying deadwood pieces and root plates were calculated with the formula of a truncated cone [14]:

$$V_{lying}[m^3] = \frac{l * \pi}{12} * (D^2 + D * d + d^2)$$

Where *l* describes the length of a piece, *D* the larger diameter and *d* the smaller one. A stump's form resembles a cylinder and was therefore calculated with the cylinder volume formula [16]:

$$V_{stump}[m^3] = \pi * h * (\frac{ST_{up}}{2})^2$$

Where *h* is the stump's height and ST_{up} the diameter at the cutting or breaking point.

The area of the plots was estimated by measuring the geodesic distance between the starting and ending point with the Esri ArcGIS Pro 2.4.0. *near* tool and multiplying this by the width of 4 metres. The volume per m^2 was calculated by dividing the volume sum of the patch by its area. From that, the volume per hectare was derived.

Statistical Analysis

The data collected in the field was analysed with RStudio (Version 1.1.456). Each site variable was examined for significant impact on the amount of deadwood through analysis of variance models. Further, median values and the interquartile range (IQR) were calculated to provide an overview of the data. The models were visualised with boxplots.

Two linear models each were fitted for the relation between the DBH and the protective height (PH) as well as between the DBH and the area of root plates (PA). The tested models were a linear regression with non-transformed variables and a log-log transformed regression. They were visualised in scatterplots with regression lines and 95% confidence intervals. With an analysis of variance table (ANOVA) the fit of the models was compared. The model assumptions were tested through Tukey-Anscombe and normal Q-Q Plots. Predictions of the PH and the PA on the basis of the DBH were then conducted for the best fitting models. The quality of the predictions was quantified with the root mean squared error which was normalized by the *maxmin* method to get the normalized root mean squared error (NRMSE).

2.4 Remote Sensing Analysis

For the LiDAR point cloud analysis and editing the three open source software programmes Displaz (Version 0.4.0), CloudCompare (Version 2.10.2 Zephyrus) and RStudio (Version 1.1.456) were used. The full wave form point clouds were recorded with the sensor LMS-Q 780 by the MILAN Geoservice GmbH in August 2015. Except for the boundary tiles, each point cloud tile covered 1 km^2 and the points were divided into the two classes *ground* points and *not ground* points. The average point density was 15 points per m^2 but was varying between different tiles. The values of the light-intensity and the echo-width parameters were not normalized, which means they did not have meaningful SI units. To ensure the comparability to other studies a descriptive evaluation is made as described further on in the chapter.

For each of the 18 plots that had lying deadwood or uprooted trees with diameters bigger than 30 centimetres according to the fieldwork, the point clouds were visualized and inspected with Displaz and CloudCompare. This was done in order to see whether the stems were visible in the unprocessed clouds and what parameters impact their visibility the most. Afterwards, the clouds were processed with CloudCompare.

The first step was the creation of a 2.5D digital surface model (DSM) by projecting the ground classified points on the XY plane with a Delaunay algorithm. Then the distance of the DSM to the point cloud was calculated, which resulted in an object height model (OHM). This height model was saved as an attribute of the point cloud, so it could be used as a filter. These three steps can be seen in the following figure.

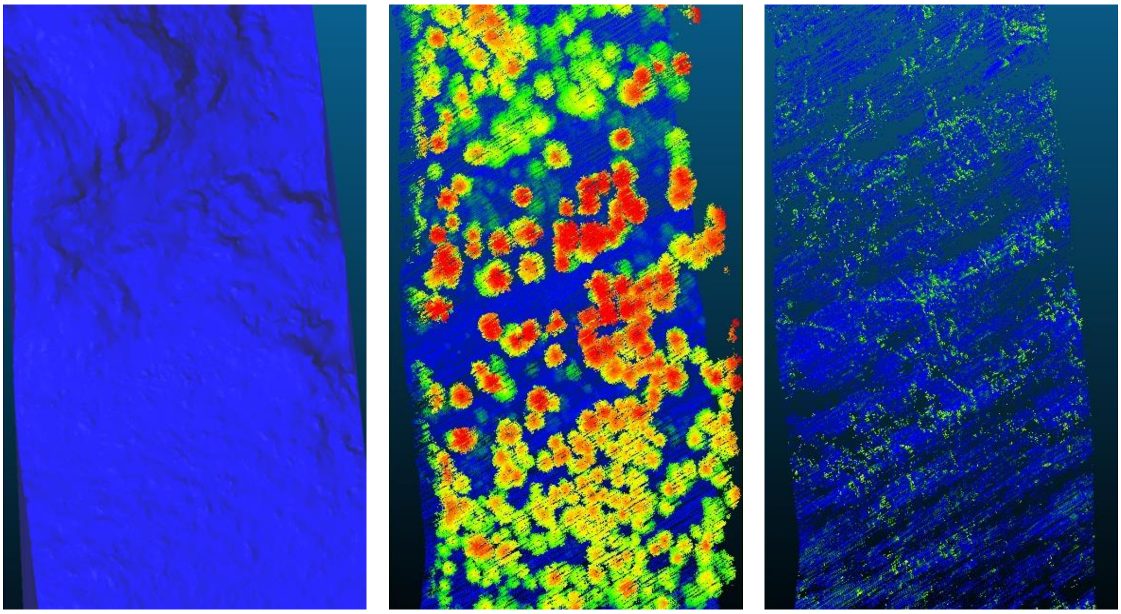


Figure 3: Digital surface model (left), object height model unfiltered (middle) and object height model filtered (right).

The second step was the processing of the cloud by removing points that did not represent lying deadwood. The ideal filter range was thereby defined as the range in which points lied after the filtering. Outside this range, the points were filtered out. The best fitting filter values for each parameter were exploratory determined and were not the same for every point cloud. The ideal ranges of each filter were written down for later steps in the process.

First, the height was adjusted to remove the tree canopy. Next, points were removed according to their echo-width and the light-intensity values. Yet finer distinction was done by filtering the number of returns and removing ground points. For the non-normalized echo-width and light-intensity parameters, the exploratory determined ideal range of the filters as well as the overall range of the parameters were noted and compared. This way, a descriptive evaluation could be made by describing for example at what percentage of a parameters overall range the ideal filter lies. However, there were a few outlier points, which heavily distorted the maximum of the overall range. To minimize this distortion, the maximal value was defined at the value below which 99% of the points were.

The determined ideal filter values were then used in RStudio for an automated interpretation of the data by creating shapefiles that contained the location and approximate length of stems. The used scripts were adapted from scripts written by Weber and Bardet (2019). The first step was the creation of a filtered object height model raster with the previously determined ideal values. Next, the filtered OHM was vectorised and entities with a surface larger than 10 m^2 were removed from the file. Lastly, lines representing potential pieces of lying deadwood were created by Delaunay triangulation as well as by skeletonization.

The CloudCompare and the RStudio products were then compared with each other, with Orthophotos (swissimage, 25 cm Resolution, RGB LV03 LN02) from the years 2015 and 2017 and the field survey data. This was done with the GIS software application Esri ArcGIS Pro 2.4.0.

3 Results

3.1 Field Survey

Site Variables

On the 18 surveyed plots, 243 pieces of deadwood were inventoried of which 52 were root plates. With the exclusion of root plates, the mean volume per hectare in the Dischma amounted to 99 m^3/ha with the median being lower at 78 m^3/ha. The standard deviation from the mean was 66 m^3/ha with the maximum and minimum values being 296 m^3/ha, respectively 24 m^3/ha. The interquartile range was 40 m^3/ha.

The boxplots in figure 4 display how the deadwood volume varies according to different site variables and among different groups per site variable. The p-value is based on a F-test and indicates whether there are significant differences in the deadwood volume among the groups of a site variable. Overall, there was no F-test for each of the five examined independent variables that showed a significant p-value below 0.05. Therefore, the correlation between the deadwood volume per hectare and different levels of the variables is weak. There were also a few outliers, which can be seen in the boxplots. Nonetheless, the difference between the stand density groups (fig. 4a) had the highest impact on the deadwood volume per hectare with a p-value of 0.209. Corresponding median values were 60 m^3/ha in dense stands, 63 m^3/ha in intermediate stands and 87 m^3/ha in open stands with the respective IQR of 26 m^3/ha, 41 m^3/ha and 54 m^3/ha.

The northeast exposed valley side (fig. 4b) showed higher amounts of deadwood than the southwest facing side with a median of 87 m^3/ha compared to 63 m^3/ha at a p-value of 0.35. The belonging IQR amounted to 48 m^3/ha for northeast exposure and 53 m^3/ha for southwest exposure. Elevation, inclination and whether there were interventions were found to impact the deadwood volume in a more ambiguous way and no evident trends could be seen. The degree of decay was not included as the sample size turned out to be too small for the analysis of a variable with more than 3 levels.

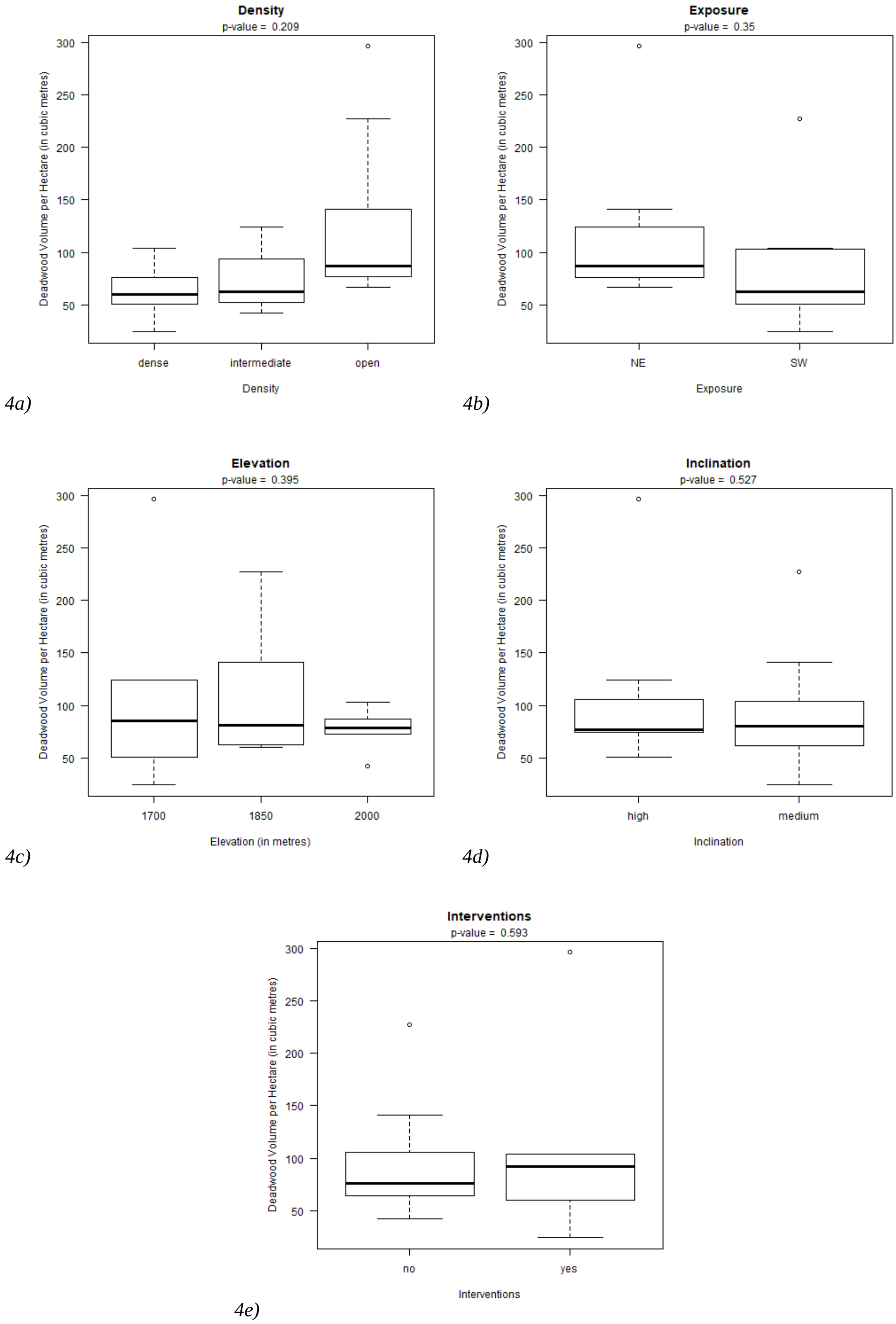


Figure 4: Boxplots displaying how the abundance of deadwood varies according to different site variables. The p-value is based on a F-test and indicates whether there are significant differences in the deadwood volume among the groups of a site variable.

Root Plates

The regression between the protective height and the DBH as well as the regression between the plate area and the DBH both showed significant positive correlation. Linear regression models resulted in p-values smaller than 0.001 with log-log models providing the best fit. Figure 5 shows the 4 fitted models. On the left the linear regressions of the PH against the DBH are displayed (fig. 5a & 5c), on the right the linear regressions of the PA against the DBH (fig. 5b & 5d). The upper plots are linear regressions with non-transformed variables (fig. 5a & 5b), in the lower ones both variables were logarithmised (fig. 5c & 5d). In blue the 95% confidence intervals are drawn. The intervals show a wider plausible range of the mathematical expectation for values near the lower and the higher end than for values in the mid-range. Additionally, it can be seen that the error variance is smaller in the log-log models. An ANOVA model comparison between the non-transformed and the logarithmic models showed that the logarithmic models fit the data significantly better at p-values of smaller than 0.001. The PH against DBH linear log-log model's multiple R-squared was 0.5044 on 50 degrees of freedom. For the PA against DBH linear log-log model the multiple R-squared was 0.6607 on 50 degrees of freedom.

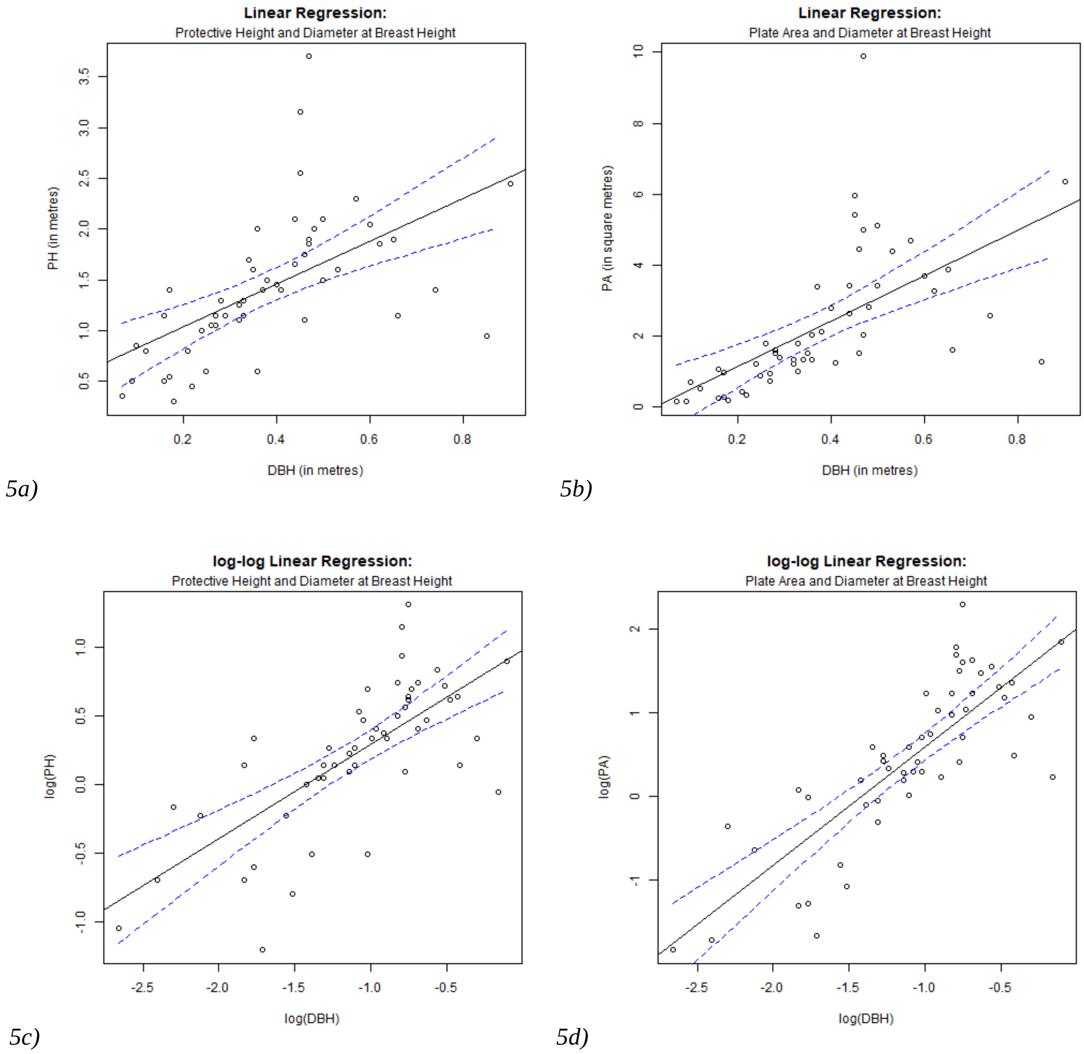
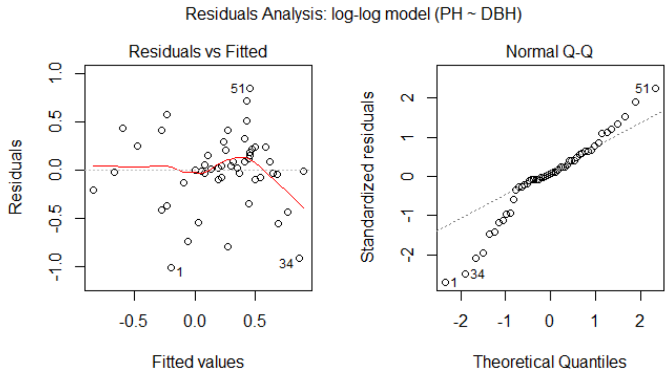
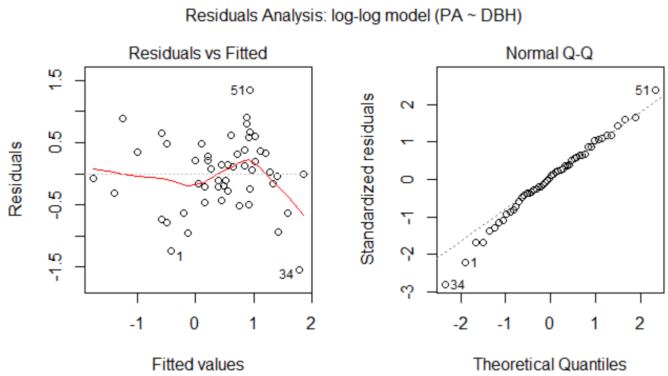


Figure 5: Linear regressions with 95% confidence intervals (blue).

The residual analysis of the linear log-log models can be seen in the next figures. Figure 6a shows the PH against DBH log-log model, figure 6b the PA against DBH model. In the Tukey-Anscombe plots the residuals are evenly distributed around 0 for both models except at the upper ends, where they deviate from the horizontal line. This trend is stronger for the model between PA and DBH. Overall, the i.i.d. and the linearity assumption were considered to be fulfilled. The normal Q-Q plot shows a heavy-tailed deviation from the normal distribution for the PH against DBH model. For the model between PA and DBH the normal distribution assumption was met. Overall compared to other models, the linear logarithmic models provided the best fit and the smallest deviance from the model assumptions.



6a)



6b)

Figure 6: Residual analysis of the linear log-log models.

Predictions, which can be seen in figure 7, were therefore made based on the linear logarithmic models. The NRMSE of the PH prediction was 16.2%. For the PA prediction the NRMSE was 16.7%. Both, the protective height as well as the plate area increase with a larger DBH. The height increase is strong for DBH values below 30 cm, but the curve starts to flatten for DBH values higher than 30 cm. This trend is reversed for the area. In small to medium timber stands (DBH = 24 cm – 52 cm), which represented 15 out of 18 survey plots in the study area, the predicted protective height of a plate was between 1.00 m and 1.70 m whereas the predicted area was between 1.00 m^2 and 3.00 m^2.

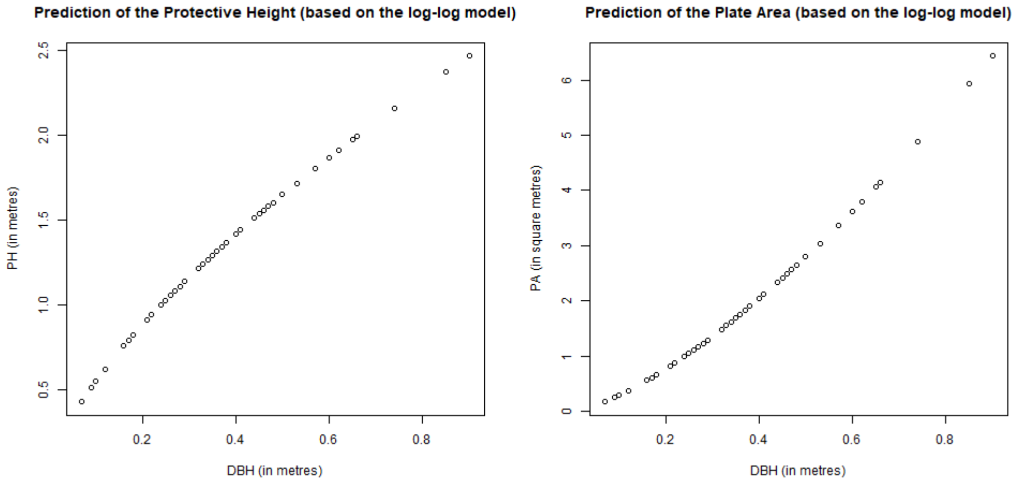


Figure 7: Predictions of the PH and the PA based on the DBH and the linear logarithmic models.

3.2 Remote Sensing Analysis

In the unprocessed LiDAR point clouds there was no deadwood visible on any of the surveyed plots. In total, results from processed point clouds were derived from 11 out of 18 patches. On the remaining patches, the analysis was unsuccessful, and no deadwood was found. In the processed clouds, the filter influencing visibility of deadwood the most was the object height model as it enabled a view beneath the tree canopy. The echo-width and the number of returns helped to increase the distinguishability of deadwood from other structures such as brushes or low tree canopy. To generally remove noise from the cloud, the light-intensity and the removal of the ground points proved to be the most effective. However, an increased noise removal often led to a decrease in distinguishability between different structures as the outlines and forms of the structures became blurry because of the overall reduced point density.

The ranges of the object height, the light-intensity and the echo-width are listed in table 3. The range of the light-intensity was not exactly the same in all files, which is why the standard deviation (SD) is given. Moreover, the exploratory determined mean ideal ranges of the filters with the respective standard deviations for the upper and lower ends are shown. For the non-standardized light-intensity and echo-width, no SI units could be defined. The object height model's mean ideal filter range is in metres above ground level.

Most deadwood could be seen between 0.25 m and 1.75 m above ground level at a standard deviation of 0.1 m for the lower and 0.9 m for the upper end. The ideal filter range for the light-intensity was between 46 and 262 at standard deviations of 34 and 73. Compared to the complete range, the best noise removal was achieved when filtering out light-intensity values below 10% and above 54% of the maximal value. The overall echo-width ranged from 0 to 255, the respective ideal filter from 41 to 69 at standard deviations of 8 and 13. Thus, the best distinguishability of deadwood from other structures was established when filtering out echo-width values below 16% and above 27% of the maximal value. Additionally, the distinguishability was further increased when the number of returns was set to 2 or 3.

Table 3: Range of the point cloud parameters and mean ideal range of filters with standard deviations for the upper and lower ends. The light-intensity and the echo-width are represented by non-normalized values and do therefore not have any SI units.

Object Height Model		Light-Intensity		Echo-Width	
Range:		Range:		Range:	
Min	Max	Min	Max	Min	Max
Ground level	Tree tops	0	483	0	255
0 m		SD	SD		
		0	64		
Mean ideal filter range:		Mean ideal filter range:		Mean ideal filter range:	
Min	Max	Min	Max	Min	Max
0.25 m	1.75 m	46	262	41	69
SD	SD	SD	SD	SD	SD
0.1 m	0.9 m	34	73	8	13

Figure 8 displays processed point clouds on a surface model mesh to show difficulties regarding noise and deadwood visibility. On 11 out of the 18 surveyed plots there was lying deadwood visible after the processing of the clouds, but sometimes there were only few pieces or there was much noise from non-deadwood points left in the processed cloud. In figure 8a, a larger sector is shown than in figure 8b with no deadwood apparent but two areas with a lot of noise visible. Marked with a green 1, there is a debris flow track, which was identified as such during the field survey. The debris flow track resembles lying deadwood. In figure 8b, at least 3 pieces of lying deadwood can be seen which are marked and numbered in black. There are two areas with a lot of noise on the right as well. These large noise areas were also observed in other point clouds and often correlated with steep, rocky terrain, hollows and crests as well as dense shrubs. In the stands with very dense crown closure there was often no data from beneath the canopy available and/or a lot of noise in the filtered point clouds. Large single trees in open forests could often be seen as in ring-shaped structures in the point clouds (fig. 9c). Generally, lying trunks with a higher DBH were detected more often than thinner ones.

8a) 8b)

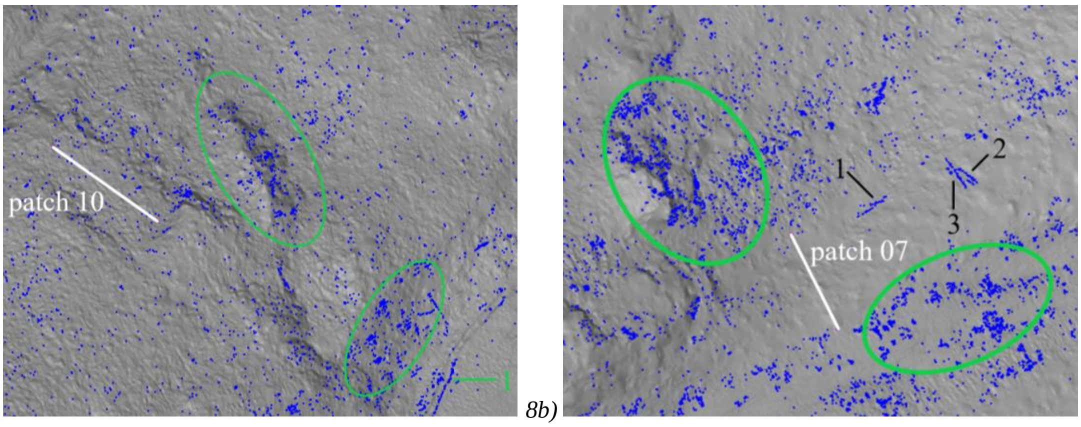
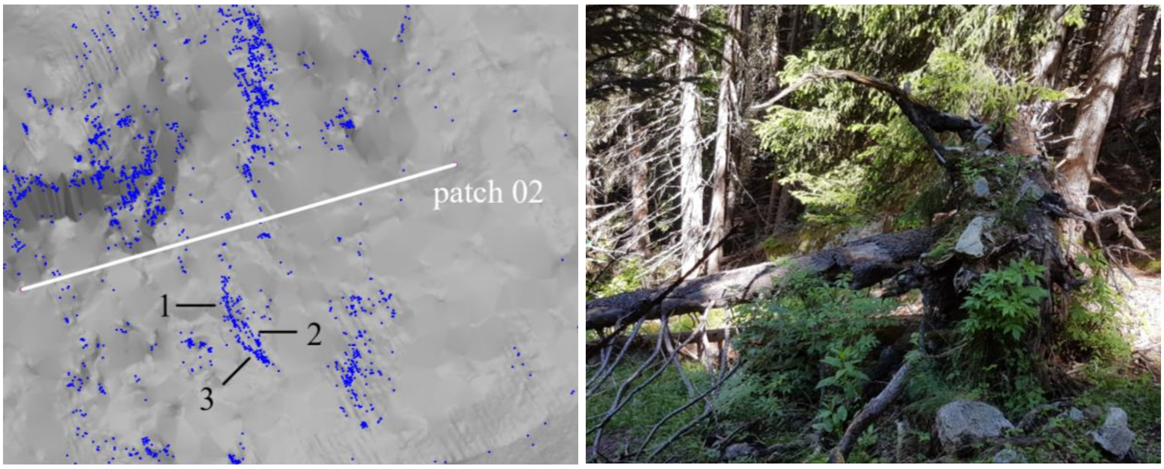
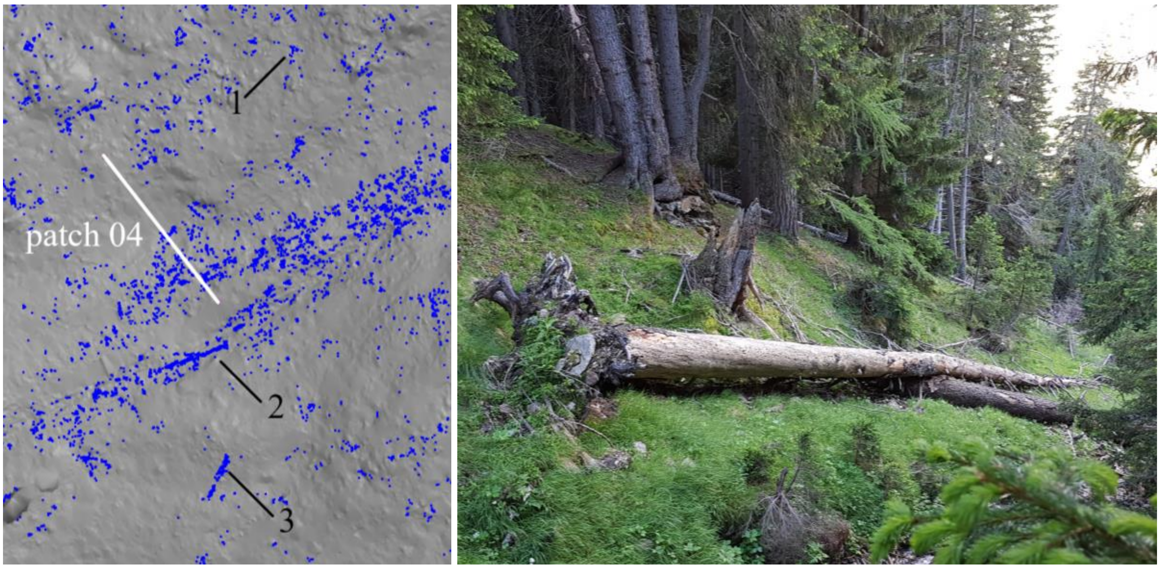


Figure 8: Point cloud comparison of different plots. Green circles mark noise, black lines show deadwood and the white lines indicate the position of the plot.

Next, point cloud samples next to pictures of deadwood are given to show in the field verified pieces. The white lines mark the field survey transects and the black lines/numbers point to lying deadwood. In figure 9a, an accumulation of uprooted trees lying on top of each other is visible. The picture is of object 1. Objects 2 and 3 cannot be seen in the picture but were also verified during the field survey. Furthermore, there is noise visible on the edge of the cliff as well as in the upper middle part of the point cloud. Figure 9b shows the point cloud of patch 04 and the picture of object 2. Despite the point cloud showing a lot of noise, the stem is well visible due to the higher point density highlighting its shape. Object 1 was confirmed to be an uprooted tree in the field, however here much more points were removed even though the same filters were used. In the last point cloud only one stem was found but the aforementioned effect of tree crown edges producing noise and the crown interior producing data holes is visible.



9a)



9b)

9c)

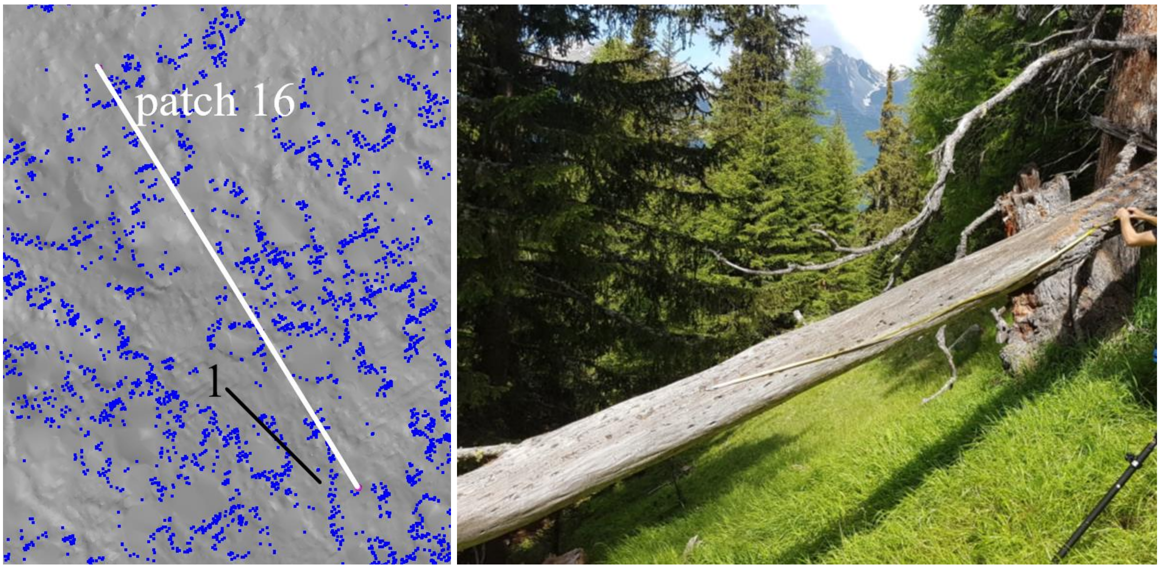


Figure 9: Point clouds of patches with photo verification of deadwood.
9a: Patch 02, picture of object 1.
9b: Patch 04, picture of object 2.
9c: Patch 16, picture of object 1.

The comparison of orthophotos and the LiDAR images delivered ambiguous results. On most patches deadwood was not visible in the orthophotos as the canopy was too dense or the trees cast their shadows in a way that limited the visibility beneath. In very open forests however, the comparison was well possible as can be seen in the next figure. In this example there were 3 lying trunks that matched on the orthophoto and the LiDAR image. There were also pieces that could be seen in the orthophoto but not in the LiDAR data, labelled with a question mark.

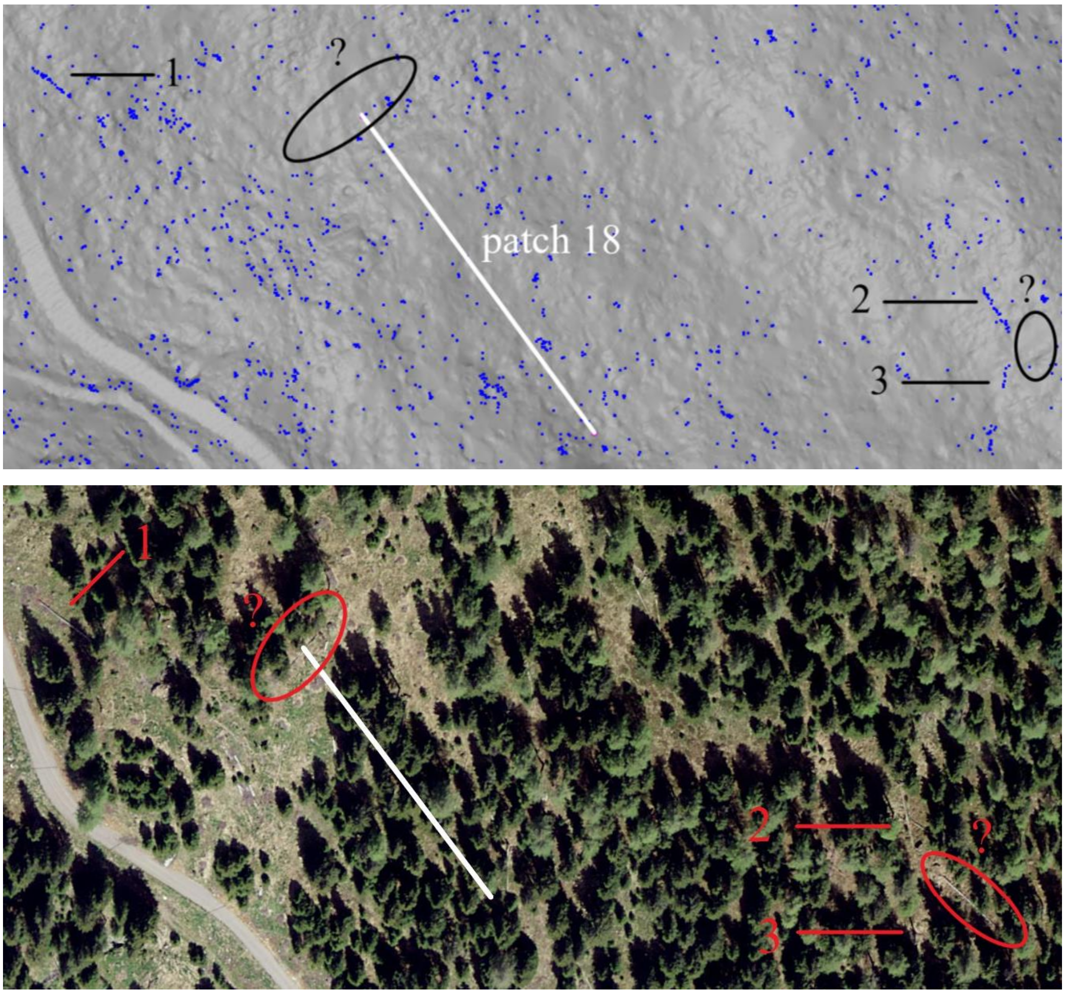


Figure 10: Comparison of a processed LiDAR image and an orthophoto. The black and red lines represent lying deadwood, the white lines are drawn where the transect was inventoried.

The automated processing of the point clouds with R-Studio through rasterization and vectorization delivered rather poor results and the accuracy was lower compared to the direct manual processing of the point clouds with CloudCompare. Even though the output products contained lines that represented deadwood pieces, there were simply too many lines to reliably tell whether a line represented deadwood or noise. In the next figure, the fine white lines were produced by the R-Code from the point clouds. Again, the example is from patch 18 and can thus be compared to the previous figure.

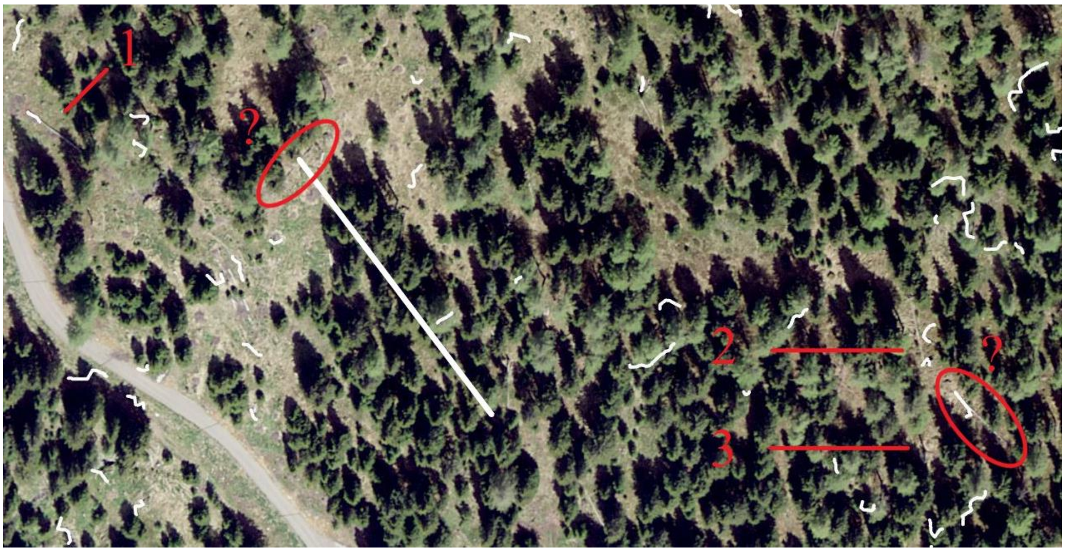


Figure 11: The fine white lines represent the R-Studio product which was derived through vectorization.

4 Discussion

4.1 Deadwood Assessment

The estimated deadwood volume of 99 m^3/ha in the study area is rather high compared to the mean deadwood volume in the alps which is 30 m^3/ha [17]. This indicates a higher terrain roughness and richness in saproxylic species than in other Swiss alpine forests [2], [18]. However, there might be a bias through the selection of the patches along elevation levels and valley sides. According to Marshall et al. (2003) [19] the extension of the transect length to find a minimum number of pieces can lead to biased volume estimates as well. Moreover, the method of line transect sampling can distort results through the edge-effect bias as for example reported by Stevens (2014) [20]. These edge-effects were also observed during the field work because the deadwood tended to aggregate in piles or in small areas. Considering the biases, the result is still thought to give an approximate order of magnitude for the volume estimation per hectare due to the fact that deadwood is important for the protection function [18] and is therefore often left behind in protection forests which cover most of the Dischma's forested area [11].

The correlation between deadwood occurrence and the levels of elevation, exposure, inclination, stand density and forestry interventions turned out to be weak which can partly be attributed to the small sample size of 243 surveyed pieces on 18 transects. Apart from the statistical methods, there was also a deviation in the surveyed data from the LeiNa database. Whether there were interventions or not as deducted from the LeiNa was not always the same as was found in the field survey. There were inventory plots with clearly visible cut stems which were not marked as intervention areas in the LeiNa. Whereas in this study no significant trend between deadwood amount and forest management was found, other studies like *Effects of forest management on the amount of deadwood in Mediterranean oak ecosystems* by Paletto et al. (2014) [21] have found significantly higher amounts in extensively managed forest or multifunctional forests than in intensively managed forests. Nevertheless, it is important to mention that their study covers a different region, therefore different management strategies and types of forests which impedes a comparison.

An interesting finding of this study was, that the northeast exposed valley side with lower timber stocks showed higher amounts of deadwood than the southeast exposed side which has higher timber stocks. This correlation is supported by the observation that open forests had the highest mean deadwood amount in the study area. However, this might partly be an autocorrelation because open forests were more often found on the northeast exposed side and dense forests on the southeast exposed side. Furthermore, there is less forest management on the northeast exposed side and therefore fewer dead trees are removed.

4.2 Protection Function

The predictions of the protective height and the plate area seem to be rather robust but should be interpreted with care at DBH values below 20 cm and above 60 cm as there were only few observed uprooted trees outside this range. According to the paper *Entscheidungshilfe bei Sturmschäden im Wald. Vollzugshilfe für die Wahl der Schadensbehandlung im Einzelbestand.* [18] the predicted protective height of 1.00 m to 1.70 m in small to medium timber stands (DBH = 24 cm – 52 cm) would prevent the formation of avalanches at snow heights of 1.50 m up to 2.20 m. This statement is only fully applicable at slope inclinations lower than 45° and in windthrow areas where there are lying trunks supporting and connecting the root plates. Only the plates themselves would probably not reach a sufficient density after a windthrow and not every fallen tree ends up with a root plate.

4.3 Remote Sensing Analysis

In the remote sensing analysis it was found that the identification of lying deadwood in subalpine, coniferous forests with LiDAR point clouds and orthophotos is possible but that there is still room for improvement in noise removal. LiDAR can detect lying trees even under closed canopy and this detection works better for trees with larger DBH. However, there is the drawback of identifying non-deadwood structures as deadwood from the point clouds in automated classification in general and in manual classification with no previous visit of the analysed area. The dependence on the DBH and the wrong interpretation of structures was encountered by Nyström et al. (2014) [22] as well. They suggest the usage of an automatic interpreter which “creates training data for the classification of falsely detected trees” to address this problem. In the study *Detection of lying tree stems from airborne laser scanning data using a line template matching algorithm*, Lindberg et al. (2013) [23] too tried to create lines representing deadwood through vectorization and figured that there were many lines actually not representing deadwood. They traced this error back to the classification of roads and ditches as lying stems and tried to minimize the error by removing overly long lines.

Parts of the errors in this study were probably caused by the initial creation of the DSM in which some lying trees were classified as ground points and were therefore removed before the actual selection of the structures representing deadwood. This strong dependence on the DSM quality was also reported by Mücke et al. (2013) [24]. In dense forest stands there was sometimes no data available from beneath the canopy and therefore no deadwood was detected. This most likely results from the laser not being able to puncture the foliage all the way through. Vice versa, in open forests there was increased noise on the crown edges with no available data directly beneath the middle of the crowns, resulting in ring-shaped structures in the filtered point clouds. This effect may come from increased scattering and reflection of the laser on foliage which reaches almost down to the ground. Therefore, not only the stand density itself is important for the quality of the LiDAR analysis but also the homogeneity of the canopy as well as the size and density of single trees.

For increasing the distinguishability of structures within the point clouds the echo-width was considered important which is supported by the findings of Sumnall et al. (2016) [25]. They achieved more precise deadwood volume estimation models when using full waveform LiDAR than when using discrete return LiDAR. Full waveform data represents a return as a continuous wave, called echo-width, in contrast to discrete return data which only records a peak per return. Additionally, they considered height and light-intensity important inputs for their models too.

Lastly, the data itself must be considered as well. The LiDAR dataset is from 2015, whereas the field survey was conducted in 2020 which likely results in deviations already only because of the time frame. The average point density of 15 points per m^2 is in the mid-range compared to other studies analysed in the review of Marchi et al. (2018) [4]. However, none of the studies made a comparison of datasets with different point densities. It is possible that a higher point density leads to an increased detectability of deadwood as even smaller objects can be detected. Nonetheless, there might be more noise with a higher resolution too. An increased point density is probably more beneficial for deadwood assessment in deciduous forests under leaf-off condition than in coniferous forests, as in this case other factors such as the DSM quality are more limiting.

5 Conclusion

Through field work and remote sensing analysis this study was able to analyse data on the amount and distribution of deadwood in the researched area. The comparatively high amount of deadwood of 99 m^3/ha in the Dischma's forests suggests a higher terrain roughness and a higher richness in saproxylic species compared to average Swiss forests. There is only a weak correlation between this amount and different elevation, exposure, stand density and slope inclination levels. Forestry interventions do not impact the distribution in the study area, there is however evidence that the deadwood amount positively correlates with less interventions in other regions. Future field surveys in the area should put more emphasis on the randomness in the patch selection as well as include bigger sample sizes to minimize sample size induced biases.

In the analysis of the root plates, the diameter at breast height of uprooted trees proved to be a good predictor for the size of the respective protective height and area of a plate. This significant, positive correlation holds potential for further studies. An interesting question is whether the diameter at breast height could also be used for the direct prediction of terrain roughness and in what way it could therefore be used in avalanche and rockfall prediction models.

Furthermore, this study investigated possibilities, difficulties and limits in the application of LiDAR and orthophotos for the mapping of lying deadwood in subalpine coniferous forests. Generally, lying deadwood can be identified from both LiDAR and orthophotos in open forests. In denser forests with closed canopy however, orthophotos cannot be used to detect deadwood. LiDAR on the other hand is to a certain extent able to puncture through the canopy and provide ground information. It would be interesting to investigate whether datasets with higher point densities deliver more ground information in dense forests than datasets with lower resolution. Moreover, the creation of the object height model is considered a crucial step. A similar study could therefore explore whether different creation methods and algorithms work better under certain conditions. There is also room for improvement in noise removal and object identification which is why this study suggests that future studies focus on these aspects as well but consider that there are limitations of LiDAR applicability in coniferous forests.

6 Acknowledgement

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Annex

A. Declaration of Originality

ETH

Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Declaration of originality

The signed declaration of originality is a component of every semester paper, Bachelor's thesis, Master's thesis and any other degree paper undertaken during the course of studies, including the respective electronic versions.

Lecturers may also require a declaration of originality for other written papers compiled for their courses.

I hereby confirm that I am the sole author of the written work here enclosed and that I have compiled it in my own words. Parts excepted are corrections of form and content by the supervisor.

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Deadwood Mapping in Davos:
Assessment and Analysis of Deadwood through Field Work
and Remote Sensing Techniques

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Name(s):	**First name(s):**
Zehnder	Luca

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Zürich, 13.08.2020	L. Zehnder

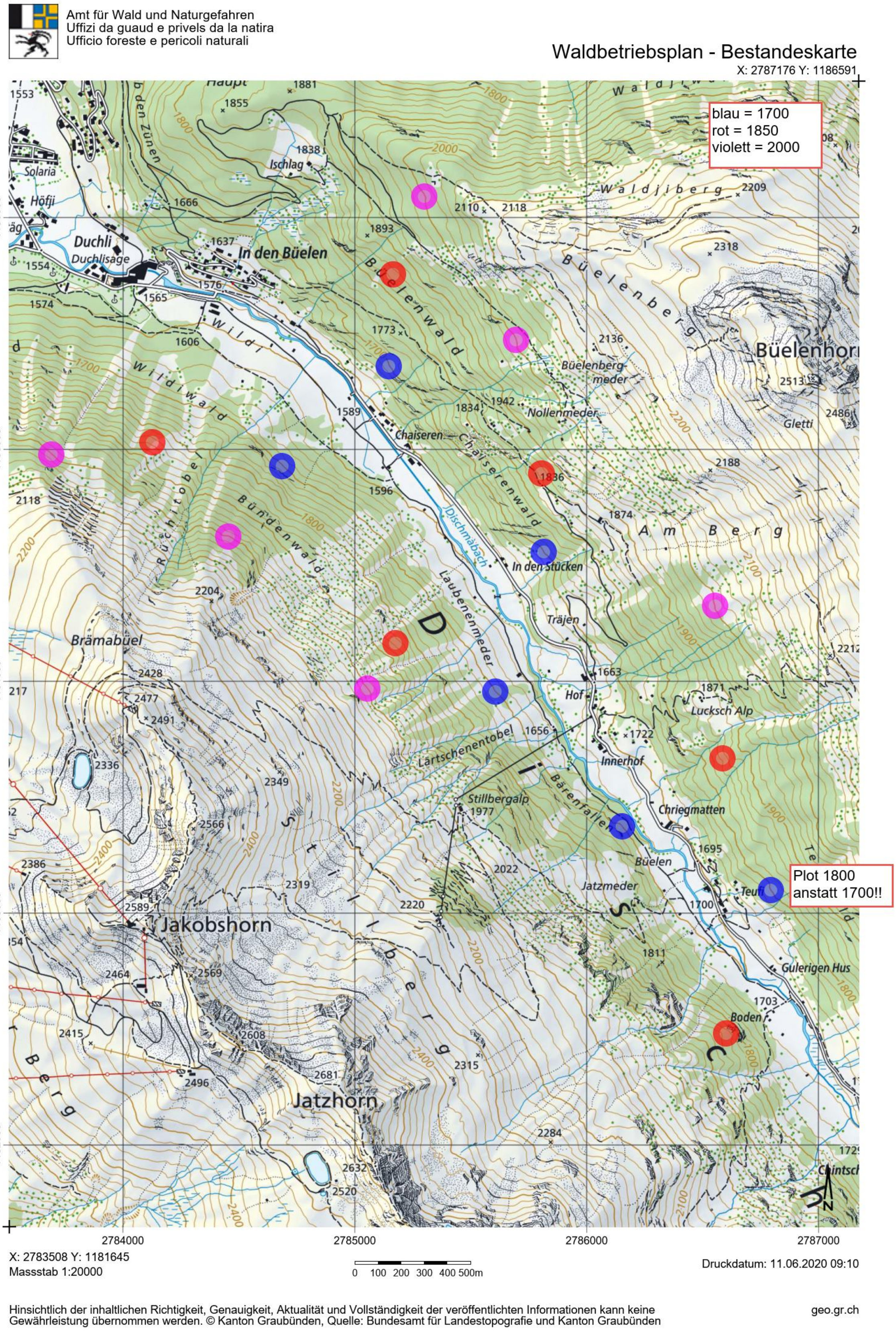
For papers written by groups the names of all authors are required. Their signatures collectively guarantee the entire content of the written paper.

B. Figures

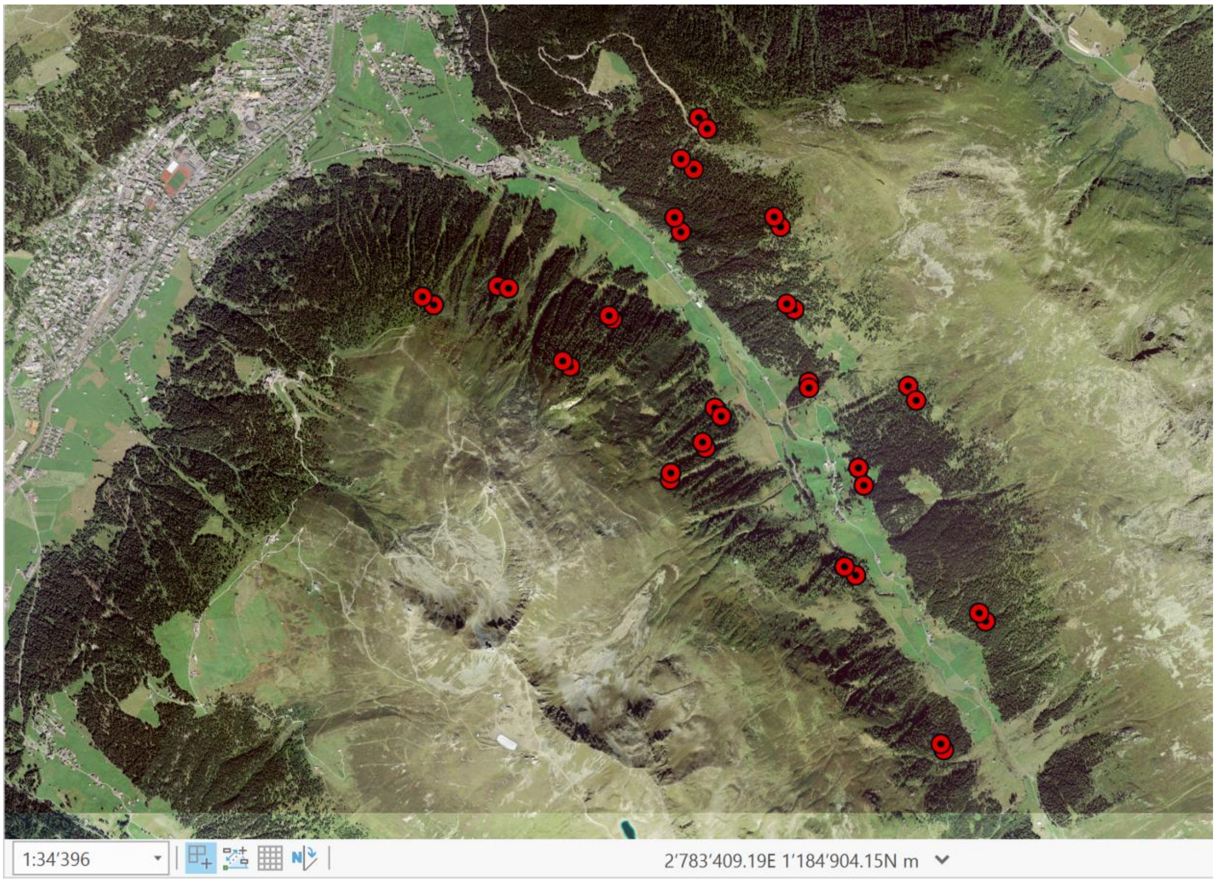
C. Tables

D. Study Area

Planned plots:



GPS measured plots:



E. Measurement Sheet

Patch Number:

					Plate only	Diameter [m]						
ID (min. 10)	Tree species	Degree of Decay (1-5)	Root plate, lying, standing, stump, snag?	Length or height? [m]	Protective height? [m]	DBH	Thin end	Thick end	$D_{horizontal}$	ST_{up}	Number of seedlings per piece (5-150cm)	Notes

Diameter: lying: thin and thick end | standing: DBH |Stump: ST_{up} (topmost stump diameter, note whether cut or broken) | snag: DBH | Plate: DBH, $D_{horizontal}$ (maximal horizontal diameter) Rounding: heights and lengths to 5 cm, diameter to 1 cm