

Sensitivity assessment on continuous landscape variables to classify a discrete forest area

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Abstract

Forest mapping at the landscape scale for resource planning and monitoring usually applies a discrete forest definition based on the primary forest use. Forest uses, however, can change in space and time. Therefore, the dependent forest definition may no longer be appropriate. We analysed how the Swiss National Forest Inventory partitions the continuous landscape resources into discrete forest/non-forest classes of the Swiss Jura mountain range and how such a binary classification affects the representation of forest resources in space. Additionally, we performed a sensitivity analysis to assess the effect of different forest classification thresholds representing different forest definitions on the spatial estimates of the dependent forest area.

Relevant landscape variables for forest area estimations were sampled from coloured aerial imagery in the Swiss Jura mountain range on a rectangular 500 m × 500 m spaced grid. Each sample plot of 50 m × 50 m dimension containing all measured landscape variables was then classified as forest or non-forest based on the Swiss National Forest Inventory definition, as well as other selected thresholds along the landscape variables' range.

The resulting forest area as defined by the Swiss National Forest Inventory covered 45.2% of the Jura mountain range containing 86.7% of the overall tree vegetation. In agreement with the original forest use, tree vegetation on forest sample plots was taller, denser and stands were larger than on non-forest plots. However, we identified considerable amounts of tree vegetation located outside of the forest dispersed all over the landscape. 73.3% of all the sample plots contained some fractions of tree vegetation, while only 18.0% were fully covered by trees. Among the different continuous landscape variables tree canopy cover had a large effect on forest area estimates, while the effects of tree canopy height and stand width were found to be moderate.

This study confirmed that the applied forest definition of the Swiss National Forest Inventory extracted the spatial domain of forests appropriately if the original forest use is of interest. However, our results also indicate that a change in forest use and hence forest definition result in considerably different spatial pattern and forest area estimation. In the presented approach forest becomes a dependent variable, whereas the independent raw data is represented by continuous landscape variables. As a consequence, different forest definitions for different forest uses can be applied in a subsequent analysis step. By this, forest area estimates can be adapted easily and consistently to a range of new forest uses as applied in the third Swiss National Forest Inventory.

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1. Introduction

Forest is usually mapped as a discrete landscape class in many forest or landscape monitoring systems. Mapping forested areas, including single or multiple forest classes, requires the application of a specific forest definition set by the monitoring or mapping system. Each landscape partition is

therefore referred to as either a *forest* or some other *non-forest* land cover type. Such discrete raster or polygon-based forest data sets exist on global (e.g. DeFries et al., 1998; Belward et al., 1999; Hansen et al., 2000), continental (e.g. EEA Task Force, 1992; European Space Agency, 1992; European Space Agency, 1993; Mùcher et al., 2000; Päävinen et al., 2001), and national levels (e.g. Köhl and Päävinen, 1996; European Commission, 1997; Schuck et al., 2002).

The definition of *forest* is usually based on the main goal of the monitoring system, and therefore depends on the particular perception of or goal for the forested land. This perception in

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turn is influenced by the experienced and expected structure, spatial distribution and species composition of the tree vegetation, and ultimately by the main forest use. The prevailing forest use thus primarily affects the definition of *forest*. Currently applied forest definitions, e.g. as used in the datasets listed above, depend on a range of continuous landscape variables, where tree cover, height and stand width are among the most frequently used ones (Köhl and Päivinen, 1996). This definition then refers to a discrete partition of the landscape.

However, forest uses and therefore also forest definitions are not constant in space. Depending on the biophysical or socio-economical domain in each geographic area, region or country, decision-makers tend to establish their own forest definitions (McConnell and Moran, 2000). Current forest definitions address forest uses ranging from timber, fibre, food, protection against natural hazards, carbon sequestration and biodiversity to socio-economical values (FAO, 2001). As these different definitions refer to separate structural classes of the landscape, a comparison between the geographic regions may become unfeasible. Such inconsistency also inhibits the comparison of monitoring results and hampers the implementation of large-scale forest planning strategies such as, for example, biodiversity assessment (Puumalainen et al., 2003), conservation planning (Parviainen and Frank, 2003), or estimation of carbon sequestration (Löwe et al., 2000). As a result, there exist numerous efforts to first standardise the forest classification scheme (EEA Task Force, 1992; Di Gregorio and Jansen, 2000; Davies and Moss, 2002) or applying post-processing techniques afterwards (Päivinen et al., 2001). However, they generally only standardise the data within the area of focus, but differences with respect to other geographic areas will remain. At best, such standardisation procedures may resolve the problem of varying uses and definitions in space, but almost never in time.

However, forest use may also change over time. While in many areas timber production was one of the main use of the forested land during the last century, forest uses have diversified increasingly towards the turn of the 21st century, including e.g., biodiversity conservation, protection, recreation, or carbon sequestration (Farrell et al., 2000). As uses have changed in number and priority over time, the traditional forest definition may no longer fit the new use. But in a forest monitoring system, where discrete forest classes are assessed, past definitions cannot be changed and any adaptation of the objective remains impossible. Discrete definitions, optimised solely with regards to the original use or purpose, may eventually become useless. Unlike in the spatial context, operational harmonisation of forest definitions over time is far from being trivial.

In Switzerland, the National Forest Inventory (NFI hereafter) is monitoring the state and dynamics of forests since 1982. The NFI-specific forest definition is applied to aerial imagery in a defined regular grid, which determines the geographic sampling extent of the subsequent field survey—the NFI is thus a double sampling inventory. The original goals of the first inventory (1982–1986), which consequently governed

the relevant forest definition, were timber volume and forest area estimation (Mahrer, 1980). Already in the second inventory (1993–1995) additional variables had to be included, representing also landscape elements outside of the forested area. Estimations for areas of *other wooded land* in the second NFI (containing tree vegetation that does not fall within the definition of the NFI) resulted in $19.7\% \pm 0.3$ of the whole territory of Switzerland (Strobel et al., 1999). However, the categories *forest*, *other wooded land* and *non-forest* were still defined in the form of discrete classes, and therefore suffer from the drawbacks of any discrete classification. For the current third inventory, measured variables of the forest monitoring system have been extended again in number and targeted resources, and now range from the original timber volume, towards biodiversity, protection and recreation. This trend of increasing diversification was observed in many European forest inventories (Puumalainen et al., 2003). The larger number of forest uses and associated definitions consequently referred to a greater diversity of forest types and therefore amplified the spatio-temporal discrepancies between different discrete forest definitions. While such adjustments offer new possibilities for state assessment, we expect it to seriously limit the potential to detect and quantify changes between states. Consequently, a new approach is needed to monitor forests consistently in a spatially and temporally varying landscape attributed with a wide range of uses (Andersson et al., 2000; FAO, 2001).

We have extended the NFI methodology and now sampled the continuous forest determining variables from aerial imagery for the entire landscape. Discrete forest area estimations were then derived in a second, independent analysis step. The aim of our study was to (1) present a novel remote sensing based approach of measuring forestry relevant variables at the landscape scale, and (2) evaluate the sensitivity of the dependent forest classifications on the state of the independent landscape variables in a multiple forest use environment. We therefore quantified the distribution of selected continuous landscape variables relevant to current forest definitions in the entire landscape. And we determined the effect of partitioning these continuous landscape variables into discrete *forest* and *non-forest* classes based on the NFI and other selected forest definitions. In turn, we evaluated the sensitive ranges of the continuous landscape variables for forest area estimations. Thus we present a method to integrate the forest ecosystem in a landscape context.

2. Materials and methods

2.1. Study area

The Jura mountain range (Gonseth et al., 2001; selected core area see Fig. 1) contains high spatial and structural tree diversity and was therefore selected to analyse forest oriented landscape discretisation. The study area approximates 4200 km^2 , i.e. ca. 10% of the area of Switzerland, ranging from 270 to 1680 m elevation above sea level with trees occurring along the full elevational gradient. The Jura mountain

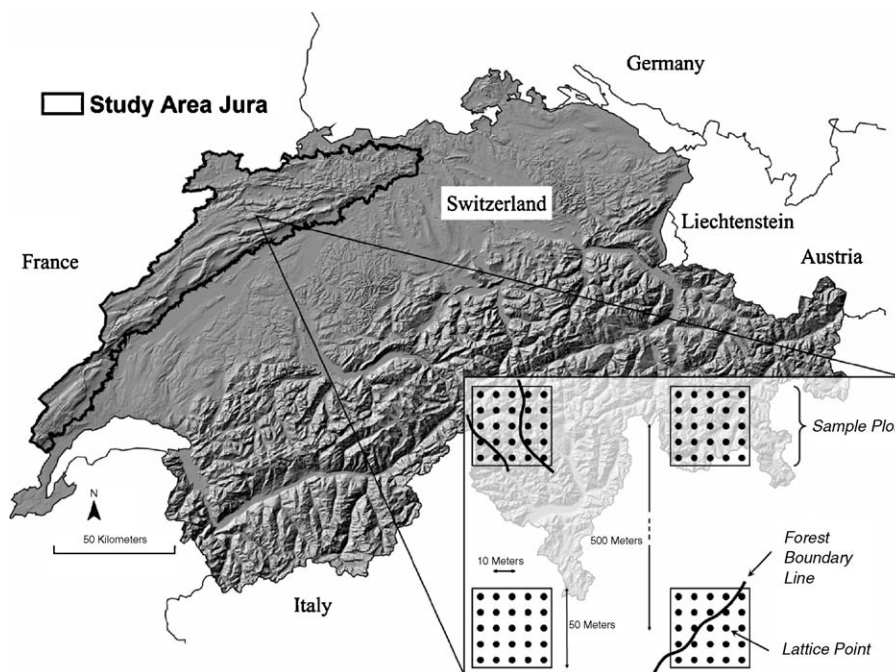


Fig. 1. The study area (black polygon) included the Jura mountain range, which represents the north-western 10% of Switzerland. Continuous variables were assessed at each sample plot spaced in a regular 500 m grid, consisting of 25 lattice points each where height and surface cover information – and where necessary – a forest boundary line was measured (DHM25 © 2006 Swisstopo DV 002232, Biogeographic Region © 2006 GEOSTAT, BFS).

range is characterised by calcareous rolling hills mostly covered by forests, pastures and meadows. Dominant tree species include *Picea abies*, *Abies alba* and *Fagus sylvatica*, and to a lesser extent *Acer pseudoplatanus*, *Fraxinus excelsior*, and *Pinus silvestris*.

2.2. Sampling design

The study is based on the first remote sensing step of the NFI double-sampling inventory, which determines the relevant sampling extent for the subsequent field survey. Continuous landscape variables were assessed on digital aerial stereo-photography using a sampling design with plots arranged in a 500 m grid (Fig. 1). Each sample plot covered a rectangular area of 50 m × 50 m on the ground, representing the basic sampling unit. Within each sample plot selected continuous variables were measured photogrammetrically using aerial imagery on 25 equally spaced (10 m) lattice points arranged in a 5 × 5 point design (Fig. 1). The analogue true colour photos were flown in 1998 at a scale of 1:30,000 and scanned at a resolution of 14 μm. The digitised photos had an average ground resolution of 0.42 m and a RMS error after aerial triangulation of <1 m. A photo interpreter assigned each lattice point to one thematic surface cover class (Table 1) using a 3D stereo softcopy station (Socet Set 5.0, BAE Systems). Since in the third NFI forest is embedded in a general landscape framework, the surface cover was assessed for a range of cover classes additional to pure tree vegetation.

In addition to surface cover, each lattice point was attributed the canopy height information calculated from the difference between the photogrammetrically measured surface elevation

by the interpreter and the bilinearly interpolated (Socet Set 5.0, BAE Systems) terrain elevation from an existing 25 m spaced terrain model from the Swiss Federal Office of Topography. Finally, in predefined forest border cases a forest boundary line was digitised on screen in addition to the lattice points to calculate stand width.

The continuous landscape variables for forest area estimation relevant to the NFI (Keller, 2001), as well as to forest inventories in general (Köhl and Päivinen, 1996), were then derived for each sample plot based on the tree lattice points. A tree lattice point in the NFI is attributed to *tree vegetation* and has a minimum height >3 m. Due to the fixed distribution of the lattice points, height measurements do not necessarily correspond to single tree heights, but rather to tree canopy heights at the lattice points. Therefore, we use the terms *tree canopy cover* and *tree canopy height*, instead of *tree cover* and *tree height*.

Table 1

One surface cover class was assigned to each lattice point

| Surface cover | Description |
|---------------------------|---|
| Tree vegetation | Woody vegetation >3 m (exception: Chapter 3.3 “tree height analysis”) |
| Shrub and herb vegetation | Herbaceous and woody vegetation <3 m |
| Soil, sand, gravel | Non-vegetated natural surface |
| Rock | Continuous rock |
| Impervious surface | Non-natural sealed surface or constructed objects |
| Open water | Standing or flowing water |

As a sample plot consists of 25 lattice points, several surface cover classes can be present on a plot.

Tree canopy cover of a sample plot was calculated as the fraction of tree lattice points relative to all 25 lattice points within a sample plot. *Tree canopy height* was derived from the height of each tree lattice point, which was measured as a continuous variable with values >3 m. *Stand width* was derived as the smallest distance between two forest boundary lines or a boundary line and the frame of the analysis window through the centre of the sample plot.

Land cover as the surface cover fraction per sample plot was not only derived for trees (i.e. tree canopy cover), but also for the other surface cover classes as the fraction of lattice points attributed with the respective surface cover relative to the total number of 25 lattice points. Consequently, on a sample plot all surface cover fractions summed up 100%. Surface cover fractions within the study area were estimated based on the cluster sampling scheme described in Cochran (1977). For general surface cover fraction the estimation and standard error were based on all 25 lattice points. For surface cover fractions strictly within NFI-forest, the estimation and standard error were only based on the lattice points within the forest boundary line.

2.3. Discrete forest classification

Each sample plot was then classified as *forest* or *non-forest* based on the continuous landscape variables described above and following the existing NFI-forest definition. According to this definition, the requirements to assign *forest* to a sample plot are: a tree canopy height of >3 m (except: burned, cut, damaged areas, afforestations, regenerations or shrub forests), a minimum tree canopy cover of 20% within the forest boundary line and a minimum stand width of 25 m. Furthermore, the definition relates stand width and tree canopy cover. At the minimum width of 25 m canopy cover within the forest boundary line needs to be 100% with decreasing minimum canopy cover required at increasing stand widths (see Keller, 2001, p. 51 ff. for a mathematical description of this definition).

The calculation of the forest proportion for the whole study area therefore depended on two discrete classes, *forest* and *non-forest sample plots*. As such a binary behaviour is best described by a binomial distribution; we followed Cochran (1977) to estimate forest proportion and associated standard errors.

Hereafter, we refer to this NFI-forest/non-forest classification, when using the terms *forest* and *non-forest*, if not indicated otherwise.

2.4. Sensitivity analyses of forest area estimation

The mapping procedure described above corresponds to an extended approach of the existing NFI method, because time series of forest estimations had to be continued from NFI1 (1982–1986) and NFI2 (1993–1995). However, in the extended approach of NFI3 general surface cover classes other than the original tree based classes were added and are now all available with height information for each lattice point at every sample plot. Thus, the main difference to earlier forest inventories is that now the continuous information and not only the classified

result is archived for further analyses and processing. Continuous raw data is therefore based on the same method and lattice point sampling density in- and outside the forest. As a result, different variable thresholds representing different forest definitions can now be applied. Sensitivity of the discrete forest area estimations to the underlying variables was therefore assessed by applying a range of selected thresholds for minimum tree canopy cover (0–100% with increments of 4%), minimum tree canopy height (3–10 m with increments of 1 m) and minimum stand width (0–45 m with increments of 5 m) when classifying tree occurrences into *forest*. Even though stand width is a continuous variable, drawing a forest boundary line includes discretisation aspects. We therefore assessed the sensitivity of fully continuous tree canopy cover and tree canopy height based on all 25 lattice points, and not just within the forest boundary line as in the Swiss NFI definition. Respective forest area and standard error were estimated after Cochran (1977). All statistical analyses were performed in the statistical environment R version 2.1.0 (R Development Core Team, 2005).

3. Results

3.1. Partitioning the continuous landscape

The Jura mountain range contained 16,797 sample plots, of which 31 were not interpretable due to shades and clouds on the aerial photographs. These 31 sample plots did not appear to follow a distinctive spatial pattern or bias and were therefore omitted from further analyses. Final results are therefore based on 16,766 sample plots, which correspond to 419,150 single lattice points.

Discrete sampling of the Swiss Jura mountain range, i.e. classifying the sample plots into *forest/non-forest* based on the NFI definition, resulted in a total forest cover of $45.2\% \pm 0.4$. These forest sample plots occurred along the full elevational gradient. Therefore, $54.8\% \pm 0.4$ of the study area was estimated to be non-forest. However, the forest partition represents only a limited range of the continuous variable space relevant to forest attributes. We first present a quantification of the general *surface cover fractions* of the study area and focus in the subsequent sections on the forest criteria *tree canopy cover*, *tree canopy height*, and *forest stand width*.

Spatially and thematically continuous sampling of tree vegetation variables (here: woody vegetation >3 m in- and outside forests) resulted in a total (continuously measured) tree cover of $45.4\% \pm 0.3$ for the entire study area, i.e. slightly more than the total (classified) forest cover of $45.2\% \pm 0.4$ (Table 2). Thus, within the entire study area, tree vegetation was the second most dominant surface cover after herbaceous and shrub vegetation ($49.3\% \pm 0.3$). Together, they covered $94.7\% \pm 0.1$ of the study area. Only impervious surfaces reached another relevant $4.4\% \pm 0.1$. After all, $73.3\% \pm 0.3$ of the sample plots had at least one lattice point attributed to tree vegetation. $18.0\% \pm 0.3$ of the sample plots had full tree canopy cover and $19.2\% \pm 0.3$ only shrub and herbaceous vegetation cover. All other surface cover classes were represented only as fractions of

Table 2

Continuous surface cover fractions per discrete geographic partition; i.e. the whole study area, and the forest and non-forest class defined by the Swiss National Forest Inventory

| Landscape type | Tree vegetation | Shrub and herb vegetation | Soil, sand, gravel | Rock | Impervious surface | Open water | Total (%) |
|----------------|-----------------|---------------------------|--------------------|--------------|--------------------|--------------|-----------|
| Study area | 45.4% ± 0.3 | 49.3% ± 0.3 | 0.4% ± 0.03 | ^a | 4.4% ± 0.1 | 0.5% ± 0.05 | 100 |
| Forest | 87.1% ± 0.2 | 11.8% ± 0.2 | 0.3% ± 0.02 | 0.1% ± 0.02 | 0.7% ± 0.03 | ^a | 100 |
| Non-forest | 11.0% ± 0.2 | 80.1% ± 0.3 | 0.5% ± 0.05 | ^a | 7.4% ± 0.2 | 0.8% ± 0.09 | 100 |

^a 0% < surface cover < 0.1%.

the sample plots. Hence, almost two third of the sample plots did not consist of pure sample plots, but of a heterogeneous surface with more than one cover class.

Among the sample plots assigned to the *forest* class, trees made up 87.1% ± 0.2 of the total surface cover (Table 2). Furthermore, 98.9% ± 0.04 of the *forest* was attributed to one of the vegetation classes, i.e. either tree, shrub or herbaceous vegetation. If the forest sample plots were reduced to the area within the NFI-specific forest boundary lines (see Fig. 1), tree canopy cover was estimated at 90.0% ± 0.2, whereas herbaceous and shrub cover reached 9.2% ± 0.2.

Within the *non-forest* class, tree canopies covered 11.0% ± 0.2 of the total surface (Table 2). The remaining surface cover was dominated by herbaceous and shrub vegetation (80.1% ± 0.3), and to a lesser extent by impervious areas (7.4% ± 0.2).

As a result, surface cover fractions were not evenly distributed throughout the landscape (Table 3). We found 86.7% of the overall tree canopy cover within the forest, while 13.3% was found within the non-forest (Table 3). Herbaceous and shrub vegetation, in contrast, showed a reverse distribution, 89.1% being outside and 10.9% inside the forest class.

3.2. Tree canopy cover

In the Jura mountain range all possible tree canopy fractions were represented at the plot level. However, the fractions varied between the *forest* and *non-forest* class (Fig. 2). The frequency distribution of all tree canopy cover fractions showed two maxima at the upper (32.9% ± 0.4 with more than 80% tree canopy cover) and lower end (17.5% ± 0.3 with some, but not more than 20% tree canopy cover). Together, the three intermediate tree cover classes in Fig. 2 represented 22.9% ± 0.3 of the total area.

Table 3

Partitioning of the continuous surface cover fractions among the two discrete landscape classes, i.e. *forest* and *non-forest*

| Land cover fraction | Forest (45.2%) (%) | Non-forest (54.8%) (%) | Total (%) |
|---------------------------|--------------------|------------------------|-----------|
| Tree vegetation | 86.7 | 13.3 | 100.0 |
| Shrub and herb vegetation | 10.9 | 89.1 | 100.0 |
| Soil, sand, gravel | 29.7 | 70.3 | 100.0 |
| Rock | 73.8 | 26.2 | 100.0 |
| Impervious surface | 6.9 | 93.1 | 100.0 |
| Open water | 2.3 | 97.7 | 100.0 |

The total of 100% per landscape fraction represents the respective partition in a general landscape as indicated by Table 2, row *study area*.

The two extremes of the continuous variable range were mostly represented by the respective landscape class (Fig. 2). 39.7% ± 0.6 of the forest samples had a tree cover of 100%, and 72.7% ± 0.5 had more than 80% tree cover. On the other hand, 20.0% ± 0.4 of the non-forest areas had still more than 20% tree canopy cover. Intermediate tree cover fractions, however, were almost evenly split into the *forest* and *non-forest* class.

Therefore, discrete forest/non-forest classifications do not necessarily correspond to actual tree canopy cover, as Fig. 2 indicates. However, Fig. 3 shows that tree canopy cover had a

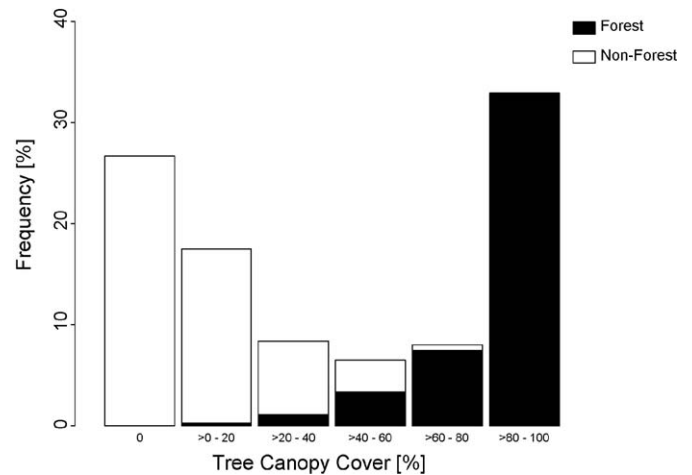


Fig. 2. Distribution of tree canopy cover classes on forest and non-forest sample plots. The forest/non-forest classification follows the Swiss NFI definition as explained in the methods section.

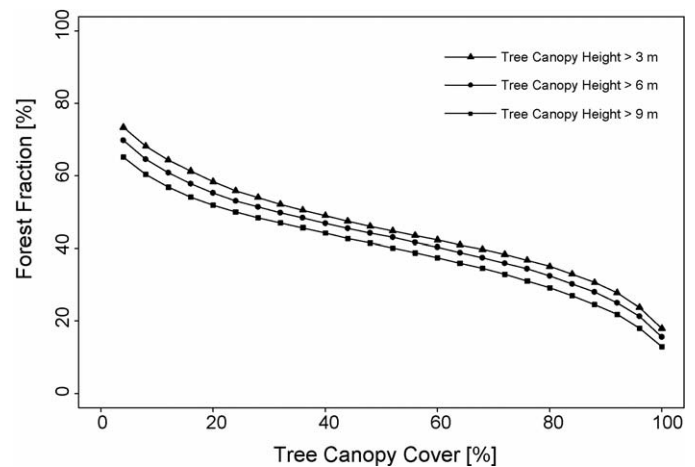


Fig. 3. The estimated forest fraction depends on the minimum tree canopy cover threshold. Each data series represents a different minimum threshold for tree canopy height.

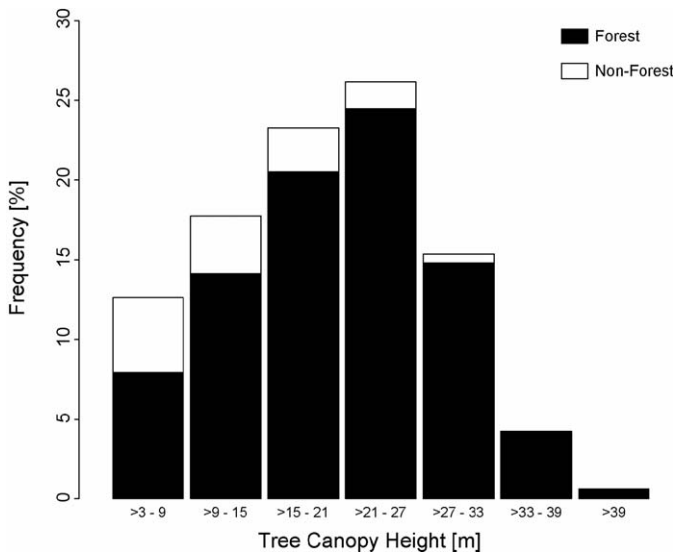


Fig. 4. Distribution of tree canopy height classes on forest and non-forest sample plots. The forest/non-forest classification follows the Swiss NFI definition as explained in the methods section.

substantial influence on the forest area estimation. Minimum tree canopy cover thresholds for the definition of forest below 20% and above 80% were especially sensitive. But also at intermediate thresholds of tree canopy cover, the influence was substantial. If the minimum tree canopy cover required was shifted from 60 to 40% while keeping the minimum tree height constant at 3 m, the dependent forest estimation increased from $42.3\% \pm 0.4$ to $49.0\% \pm 0.4$. The standard errors for the estimations were all below 1% and therefore not included in the figures due to the relative small symbol size.

3.3. Tree canopy height

In the Jura mountain range the largest fraction of tree canopy heights belonged to medium classes ranging from 21 to 27 m (Fig. 4). Frequencies of taller tree canopy height classes decreased more rapidly than did the smaller tree canopy height classes, which resulted in an asymmetric distribution. In accordance with the general perception of forests, the taller tree canopy height classes are better represented by forest than non-forest samples. The frequency of *non-forest* plots declined almost linearly with increasing tree canopy height.

At a minimum tree canopy cover fraction of 60%, a shift in minimum tree canopy height threshold from 3 to 9 m resulted in a decrease in total forest estimate from $42.3\% \pm 0.4$ to $37.4\% \pm 0.4$ (Figs. 5 and 6).

3.4. Stand width

Samples with the plot centre in the forest and containing a forest boundary line within the $50\text{ m} \times 50\text{ m}$ analysis window represented $14.1\% \pm 0.3$ of the total area, 79.8% were attributed to *forest*, and 20.2% with *non-forest*.

From the samples without a forest boundary line within the analysis window ($85.9\% \pm 0.3$), 39.5% were *forest*

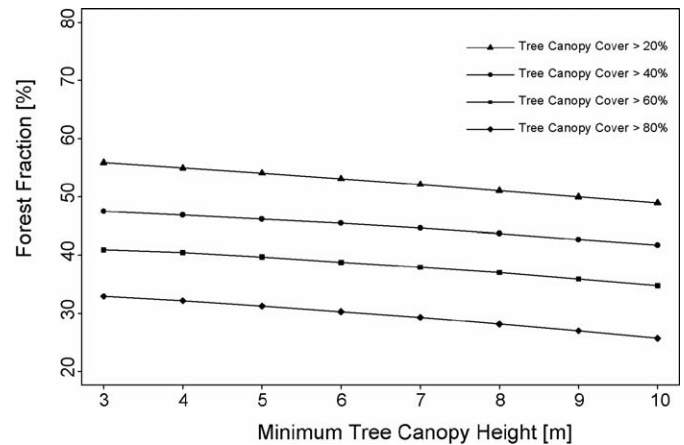


Fig. 5. Estimated forest fraction depends on the minimum tree canopy height threshold. Each data series represents a different minimum threshold for tree canopy cover.

samples, having a rather continuous tree cover, and 60.5% were *non-forest* samples, having none or only comparably few trees.

The influence of stand width on the forest area estimates was calculated for all samples with at least 20% tree canopy cover (minimum of tree canopy cover required in the NFI) within the forest boundary line ranging from >0 to 50 m ($n = 626$, 3.7% of total sample size). At a minimum tree canopy cover of 20% a shift of stand width threshold from 20 to 40 m equals a decrease in estimated forest cover from $20.5\% \pm 0.3$ to $18.6\% \pm 0.3$ relative to the entire study area (Fig. 7). The forest cover represents the sum of the threshold-dependent samples (different minimum stand width) and the threshold-independent samples, where all lattice points were attributed to tree vegetation $>3\text{ m}$ and therefore not depending on a stand width criterion.

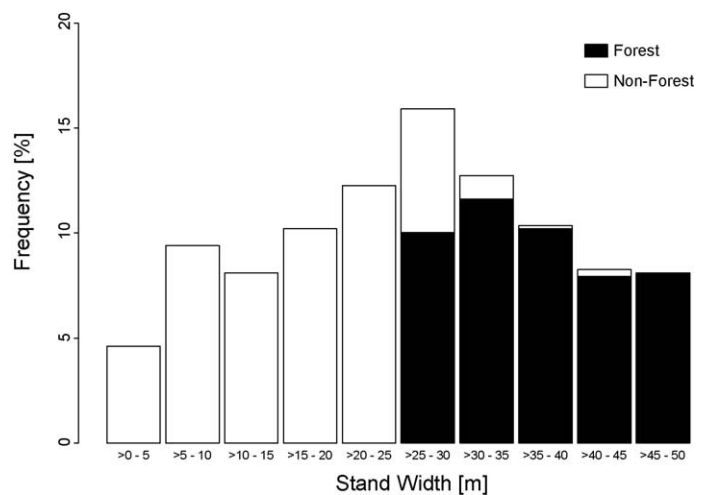


Fig. 6. Distribution of stand width classes on forest and non-forest sub-sample plots with a forest boundary line. Stands had at least 20% tree canopy cover within the forest boundary line. The forest/non-forest classification follows the Swiss NFI definition as explained in Methods section.

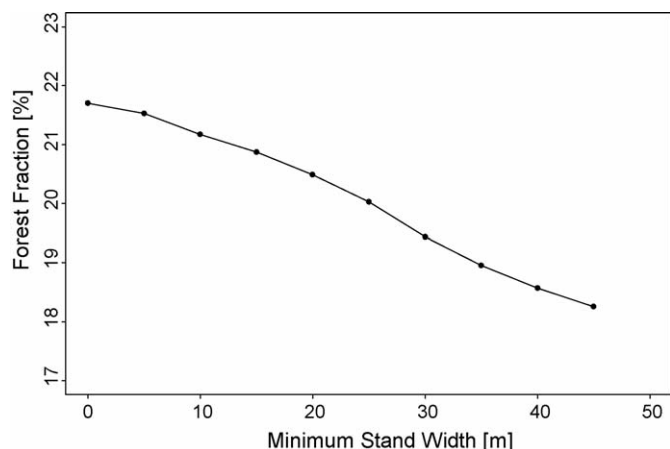


Fig. 7. Estimated forest fraction depends on the minimum stand width threshold. The threshold for tree canopy height was set at 3 m and for tree canopy cover at 20% within the forest boundary line. The plotted forest fraction represents the sum of the threshold-dependent samples (varying minimum stand width) and the threshold-independent samples, where all 25 lattice points were attributed to tree vegetation >3 m.

4. Discussion and conclusions

The discrete classification of the landscape in the Jura mountain range based on the NFI forest definition partitioned the surface into two classes; i.e. 45.2% forest, and 54.8% non-forest. In this study we investigated how this classification based on a discrete definition reflected the continuous variables relevant to forest classification at the landscape scale. And in turn, we evaluated how the independent landscape variables influence the dependent discrete forest/non-forest classification.

4.1. Continuous surface cover fractions—a matter of scale

One third of the sample plots in the Jura mountain range had all 25 lattice points attributed with the same surface cover class. Classifying this proportion of the landscape with such an aggregated distribution of surface cover for forest area estimation is generally not problematic. However, the Jura mountain range also contained a substantial amount of highly heterogeneous sample plots. The main goal of a forest classification scheme is therefore to reduce this heterogeneity for effective parameter estimation (Köhl and Päivinen, 1996). As each separate forest use refers to different aspects of the landscape, e.g. sample plots with dense, rich structured or scattered tree vegetation, the mapping and recording of the full landscape heterogeneity is crucial for a sustainable forest resource analysis as explained in the introduction.

Heterogeneity, however, is scale dependent and therefore influenced by the extent and grain of the analysis (Turner et al., 1989; Wiens, 1989; Levin, 1992). This study focused on forests, and therefore addressed the landscape scale. As a consequence, the extent of the analysis window was selected to reflect the size of an average forest stand in Switzerland (Mahrer, 1980). The grain of the raw data, however, had to be selected to minimise heterogeneity. Otherwise the resulting variance within the

analysis pixel (mixed-pixel problem) may lead to data inconsistency (Marceau et al., 1994; Treitz and Howarth, 2000). Therefore, the grain of this study represented by the lattice points was set at a local scale, where the landscape elements were homogeneously represented on the remote sensing data sources, i.e. aerial imageries. The subsequent analysis and classification, however, was then performed at the plot level, which corresponds to the stand scale, with stands being elements of the landscape.

4.2. Continuous tree vegetation in a discrete forest/non-forest landscape

Heterogeneity of landscape variables does not only exist with respect to surface cover classes, but also tree canopy cover, tree canopy height and stand width. Applying a discrete forest definition to these continuous variables reduced the full information range to two discrete landscape classes, i.e. *forest* or *non-forest*. The resulting pattern of the classified tree vegetation variables from this study reflected the original forest use and therefore goal of the NFI, i.e. growing stock and timber volume estimation (Mahrer, 1980). Tree vegetation on forest sample plots was denser, taller and stands were wider than on non-forest plots. Also, the high and low end of the distribution of these variables matched relatively well with the corresponding forest/non-forest cover classification. However, patterns varied considerably at the intermediate levels of the variables. The application of the national forest definition classified these intermediate and heterogeneous parts of the tree vegetation, often referred to as ecotones (Holland et al., 1991), into fixed and discrete classes. The more detailed information on the forest ecotones – representing richly structured areas with a special microclimatic situation (Young and Mitchell, 1994; Gehlhausen et al., 2000; Oosterhoorn and Kappelle, 2000) – is then lost for further assessment and analysis. However, resources are distinctively different in forest ecotones compared to the forest interior or open areas (Bedford and Usher, 1994; Murcia, 1995; Fry and Sarlöv-Herlin, 1997; Wolf and Batzli, 2004), and consequently addressed by a distinctive set of forest uses; i.e. biodiversity, habitat, or aesthetics. Therefore, state and dynamics of forest ecosystems cannot be analysed adequately when ignoring the interacting forest ecotone. As a consequence, the forest border or ecotone is often sampled additionally to the forest area, partly with own methods and characteristics. However, such analyses still neglect the different gradients and full variability within ecotones (Murcia, 1995; Gehlhausen et al., 2000). Results from this study confirmed that the different variables, i.e. tree canopy cover, tree canopy height and stand width, vary considerably in gradient pattern and value range and therefore represent different ecotone types.

We conclude that the presented approach of sampling each variable separately allows for individual analyses of each gradient parameter, and represents a much more flexible approach to a long term monitoring of forest resources. In doing so, also subtle changes are detected before reaching a discrete threshold value. Thus, rare events (e.g. scattered tree vegetation

or single tall trees) remain in the raw data instead of being pooled into a limited number of discrete landscape types. This is a prerequisite for a sustainable habitat management. Also, shifts in the general goal of the monitoring system may cause much fewer problems since often required classifications based on the continuous variables can be adjusted retrospectively. The major difference suggested here is to use the continuous representation as the target monitoring object, and not the classified object derived thereof.

4.3. Relationships between tree vegetation variables and forest classification

Based on the continuous range of the individual tree canopy and surface cover related variables a range of forest definitions may be applied. In this study sample plots were classified according to the NFI forest definition. This definition was optimised for timber volume estimation and therefore represented the respective part of the overall tree vegetation well. However, for other forest uses (Andersson et al., 2000), where all tree vegetation is relevant (e.g. carbon sequestration, recreation or biodiversity), a considerable fraction of the tree vegetation would be omitted from further analyses and monitoring activities. This is a problem still faced in many forest inventory systems (FAO, 2001).

Forest-ecotones refer to additional forest uses and require yet other forest definitions and variable thresholds. At the Jura mountain range varying variable thresholds resulted in considerably different forest cover estimates. However, the influence on the dependent forest estimates varied between variables. Changes in tree height within the range currently relevant to forest estimations had the smallest influence, because the analysed height range represents only a limited time span of a tree's life. Usually, trees are either smaller, i.e. as seedlings, or grown to a taller stage. The influence of stand width on forest estimation was moderate as this variable is strongly related to the landscape configuration. Forest estimates, however, were sensitive to changes in the tree canopy cover threshold, probably the most important variable in present forest classifications (Köhl and Päivinen, 1996).

In conclusion, this study shows that a specific forest definition – here from the Swiss National Forest Inventory – may extract the appropriate variable space of the tree vegetation for the respective forest use the classification was made for. However, it also indicates that for other forest uses the respective forest estimations may differ substantially. Varying forest uses in space and time require an adaptive management and consequently also an adapted and flexible sampling and monitoring system. The described spatially and thematically continuous sampling approach allows classifying the landscape adaptively to different forest uses and management schemes posterior to the sampling. The landscape can now be queried for the various aspects of sustainable forest management or for other emerging uses.

The spatially and thematically continuous sampling using aerial image analysis, however, represents only the first part of a double sampling inventory. The second stage is the terrestrial

field survey, which records many of the tree and stand variables. Currently, the samples visited by the field survey follow only one or few strata based on the discrete NFI definition applied to the aerial imagery. This study, however, suggests that the different variables relate to different landscape classes and would therefore require another sample size and design. Further research is therefore needed to integrate the remote sensing and field survey into an adapted double-sampling scheme.

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