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## Abstract

A trend of forest area expansion after decades of decline is taking place in many countries around the globe. In Switzerland, forest cover has been expanding since at least the mid-19$^{th}$ century. However, little is known about the patterns of forest area dynamics on a long-term, national scale, nor regarding the precise time of forest transition (FT). In the present study, we reconstruct the trajectories of forest cover over the past 150 years based on historical maps and contemporary national forest inventory (NFI) data for the purpose of analyzing forest area dynamics at multi-spatial scales. At the national scale, total forest area increased continuously from around 20% in 1850 to 30% in 2000, while ancient forest area, decreased from 20% in 1850 down to 11% in 2000. FT events occurred at the regional scale in the Eastern, Southern and Western Alps around 1880. Since then, forest area has almost doubled In the Southern Alps. In contrast, the Central Plateau is the biogeographical region with the most stable forest cover. The results from the analysis at the local scale confirm the high dynamics in forest cover throughout the study period, causing a steady decline in ancient forest area. These variations in forest cover dynamics confirm the crucial importance of the choice of spatial scale. Historical maps were essential for this long-term study.

Keywords: Forest Transition Theory, multi-scale approach, historical maps, forest area change, Switzerland

## Introduction

In the course of the $20^{th}$ century, in various regions around the world, deforestation has given way to reforestation (Mather and Fairbairn 2000). This change from shrinking to expanding forest area as well as its underlying processes and key mechanisms were first described in the Forest Transition Theory by Mather (1992), who analyzed long-term patterns in land-use change in several countries (Mather et al. 1998, Mather et al. 1999, Mather 2004). The point at which forest decline halts and forest area begins to expand again, is called forest transition (FT). FT Theory offers a conceptual framework to explain long-term trends in forest area. Originally, FT was considered as a one-phase process with a U-shaped forest cover curve (Mather 1992). However, Grainger (1995) suggested that this forest cover curve is actually a two-phase process, separating deforestation from reforestation. He argued that the decline in forest area is related to the national land-use change process, whereas reforestation occurs separately in response to increasing demand for wood and other environmental services supplied by forests. More recently, Kauppi et al. (2006) developed FT Theory further into the forest identity concept which relates the carbon that is sequestered in forests to changes in forest area, growing stock and biomass.

Other scientists have followed Mather and documented FT on regional scale in Europe (Foster et al. 1998; Krausmann 2006; Kozak 2003; Marey-Perez and Rodriguez-Vicente 2009), Central and Latin America (Farley et al. 2007; Izquierdo et al. 2008; Perz and Skole 2003) and Asia (Bae et al. 2012; Meyfroidt and Lambin 2008). Few studies have been carried out at continental (Mather 2001) or global scales (Rudel et al. 2005; Palo and Vanhanen 2000; Pagnutti et al. 2013).

FT Theory has been well received and used by various scholars around the world, but it has also faced criticism. One point mentioned is that the documentation of FT is often restricted to the national scale (Perz 2007). At such highly aggregated scales, decline occurring in one location might be offset by forest recovery in another location (Redo et al. 2009; Yeo and Huang 2013a). Local and regional studies can therefore reveal significant forest dynamics which would otherwise go unnoticed. In addition to the spatial scale, the choice of temporal scale is decisive in order to be able to detect FT events and forest area dynamics. If the study period is too long, back and forth changes between forest and non-forest go by unnoticed, while overly short periods might be redundant (Fuchs et al. 2015a).

A further point of criticism is the lacking distinction between primary and secondary forests (Perz 2007). Secondary forests usually occur in fragmented landscape mosaics which vary in terms of human disturbance and ecological value (Yeo and Huang 2013b). As FT Theory only considers net change, a loss in primary forest area with ecologically valuable primary forest species might be offset by an increase in secondary forest area. The term “primary” forest implies that it has never been cleared. In studies based on historical maps this status cannot be proved. Alternatively, terms such as “ancient” vs. “recent” forest may be used (Hermy and Verheyen 2007). Ancient forest area refers to that which has existed continuously since at least a specified threshold date (e.g., the oldest maps available), while recent forest area refers to secondary forest regrowth after that specified date.

In Switzerland, the concept of FT was applied by Mather and Fairbairn (2000), who analyzed the forest area changes at national scale based on secondary literature and statistical data. These early forest statistics (date back to 1843) lack consistency due to dissimilar categories as well as limited information regarding the applied survey methods (Brändli 2000; Decoppet 1912).

To date, it has not been possible to determine the point in time of FT in Switzerland. This paper presents a multi-scale approach (Supplementary material, Fig. A) based on spatial-explicit forest area data in order to reveal the patterns of FT and forest area dynamics in Switzerland between 1850 and 2000. The following questions are decisive for this study:

- Did a FT event occur at the national or regional scale after 1850 in Switzerland? Does changing the spatial scale influence the observed FT and forest area dynamics?
- Did the dynamics in forest area vary over space and time?
  - How did the proportion of ancient and recent forest area change? Did the decline in ancient forest area continue after the FT event?
  - To what extent are forest area dynamics underestimated by accounting only for net forest area changes in comparison to gross changes?

- Are there significant clusters of forest area change that are independent of political or biogeographical borders at the local scale?

## Data and methods

An alternative approach to searching for a FT event and forest area dynamics based on forest statistics is the reconstruction of forest area trajectories based on historical maps. Their main advantage is the spatially explicit representation of forests allowing for a stratified and scaled approach. Therefore, the data sources for this empirical study are two historical map series (1850-1940), a contemporary topographic map (2000), as well as spatial forest information from the National Forest Inventory (NFI) (1980-2000). The comparison of these sources enables the study of the spatio-temporal dynamics of Swiss forest coverage in considerable detail at various scales for a period of 150 years (1850 - 2000). At the national and regional scale, the gain and loss of ancient and recent forest area was calculated for five periods between 1850 and 2000. In this study forest area is considered to be ancient if it has been forested at least since 1850, independently of the type of forest management. Forest area which developed after 1850 is defined as recent forest area. A difference in forest area between any two years indicates a change in net forest area. To avoid the underestimation of forest area dynamics, the gross change in forest area was calculated as well.

### Study area

The unit of analysis is the entire country of Switzerland covering an area of 41,285 km². Switzerland is characterized by a high variability in environmental and cultural conditions, ranging from densely populated lowlands to remote areas in the high mountains. Due to its topography, there is also high variation in climate (Rutherford et al. 2008). Based on the spatial distribution of flora and fauna, Switzerland can be divided into the following six biogeographical sub regions (Fig. 1): Jura Mountains, Central Plateau, Northern Alps, Eastern Alps, Southern Alps and Western Alps (Gonseth et al. 2001).

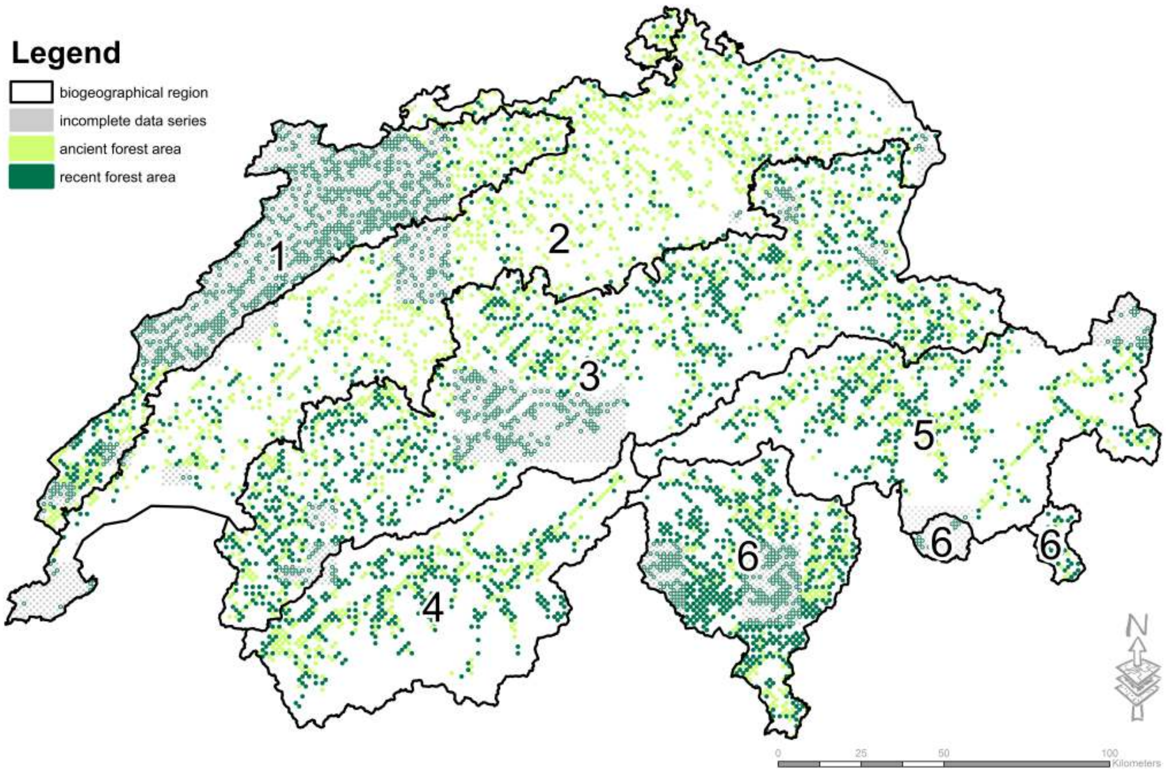


**Fig. 1: Distribution of ancient (light green, plots forested since at least 1850) and recent (dark green, plots forested after 1850) forest areas within the six biogeographical regions of Switzerland (1 = Jura Mountains, 2 = Central Plateau, 3 = Northern Alps, 4 = Western Alps, 5 = Eastern Alps, 6 = Southern Alps). The grey parts indicate the areas with data gaps for one of the periods in the time series.**

## Data

In order to quantify forest area dynamics in Switzerland, forest trajectories were reconstructed for the past 150 years based on historical (1850-1940) and contemporary (1980-2000) forest data (Supplementary material, Fig. B). The required maps and forest inventory data are available at the Swiss Federal Institute for Forest, Snow and Landscape Research (WSL). In addition, most of the map series can be viewed online (Swisstopo 2015a).

### Historical forest data

For the time prior to the advent of aerial photography, historical topographic maps are known to be one of the most reliable representations of past landscapes (Leyk 2005). For Switzerland, the only sources that represent forest cover at the national scale in the 19$^{th}$

century are the Dufour Original Survey Maps and the Siegfried Maps. Both map series were drawn at the same scale (1:25,000 in the Jura Mountains and Central Plateau, 1:50,000 in the regions of the Alps) and in repeated mapping campaigns. Due to the duration of these mapping campaigns, maps covering all of Switzerland, are based on map sheets drawn in the course of several years.

*Dufour Original Survey Map*

The sheets of the Dufour Original Survey Map were drawn between 1834 and 1863 (Supplementary material, Fig. B). These sheets are the original drawings of the Dufour Map, published later (between 1845 and 1865) at a scale of 1:100,000 (Swisstopo 2015b). Guillaume-Henri Dufour worked together with scientists, topographers and copperplate engravers to create a topographic map of Switzerland. Field measurements were based on the traditional technique of graphical triangulation on ordinance survey maps (Imhof 1927). For the estimation of forest area around 1850, the Dufour Original Survey Map series was chosen because forest area is shown in green, in contrast to the black and white coloring of the Dufour Map.

*Siegfried Map ("Siegfried-Atlas")*

Hermann Siegfried proposed 1867/68 to publish the Dufour Original Survey Maps in their original scale (1:25,000 and 1:50,000). At that point in time, part of the map series was several decades old and therefore, the maps required an update. Only a few maps in the Central Plateau could be published after minor changes, while most of the map sheets required major revisions (Grosjean 1996). The Siegfried Map series, published between 1870 and 1949 (Supplementary material, Fig. B), comprises 462 map sheets at a 1:25,000 scale for the Jura Mountains and Central Plateau and 142 map sheets at a 1:50,000 scale for the Swiss Alps (Swisstopo 2015c).

*Map accuracy*

Historical maps provide a unique data source for studies on historical forest cover change. While such maps provide spatially explicit forest area representations, they have specific weaknesses as well. One weakness is that map inaccuracies can arise from the production, transformation and/or application process (Leyk 2005). Production-orientated uncertainty has its origin in data collection and map production (Goodchild 1991). Transformation-orientated uncertainty is caused by data processing, such as digitalization and geo-referencing (Goodchild 1991). The amount of application-orientated uncertainty depends on the intended application (Beard 1989), for instance, the comparison of historical with current data sources.

In the Dufour Map production guidelines, no quantification of accuracy exists, other than that the landscape must be measured as accurately as possible. To quantify the distortion of the Dufour Map, Rickenbacher (2009) analyzed a part of the map based on more than 2,500 control points and revealed a mean deviation of 153 m in natura (1.5 mm on the map). In contrast to the Dufour Map, the guidelines regarding the accuracy of the Siegfried Map are more precise. In the mapping instructions, it is specified that the mean deviation must not exceed 35 m in natura (0.7mm on the map) for the 1:50,000 scale and 12.5 m (0.5 mm) for the 1:25,000 scale (Swisstopo 2015c).

Leyk & Zimmermann (2004) assessed the map accuracy of the first edition of the Siegfried Map in a case study for the municipality of Pontresina (Canton Grisons) located in the eastern Swiss Alps. As a reference, they utilized maps belonging to a map series that preceded the official cadastral maps. This series was produced at a scale of 1:5,000 or 1:10,000 based on detailed mapping instructions (including forest). The results show that accuracy decreases with increasing slope or elevation. The root mean square error (RMSE) resulting from geo-referencing varied between 8.0 and 15.6 m (depending on the region – lowlands or mountains). The quantitative pixel-based comparison of the Siegfried Map and reference maps resulted in global accuracy measures which confirmed the relationship between topography and accuracy. Both the percent correctly classified (PCC) and Cohen's Kappa decrease with increasing slope (Leyk et al. 2005).

Contemporary forest data

The data provided by the Swiss National Forest Inventory (NFI) was assessed to detect more recent changes in forest area. The NFI collects data about trees, stands and sample plots to record the state as well as changes in forest area based on field surveys and aerial photo interpretation (Supplementary material, Fig. B) on a regular grid of 1.4 x 1.4 km. So far, three surveys were conducted at an interval of approximately 10 years, 1983-1985 (NFI 1), 1993-1995 (NFI 2) and 2004-2006 (NFI 3). For this study, the data from the NFI 1 and NFI 3 were analyzed. To evaluate the agreement between terrestrial NFI data and forest information from maps, NFI 2 and NFI 3 data were compared to the digital topographic map from the Federal Office of Topography from 2000 (Tab. 1)

**Spatially explicit reconstruction of forest area in Switzerland**

The calculation of forest area was made for six points in time. Due to the fact that the maps and NFI data were drawn or collected over a span of several years (Supplementary material, Fig. C), the respective points in time 1850, 1880, 1910, 1940, 1980, 2000 are based on certain mapping campaigns defined in Tab.1. For comparison, the forest area from the contemporary topographic map was available.

Both historical map series are, unfortunately, partly incomplete as shown in Fig. 1. The Dufour Original Survey Map covers e.g. only 40% of the biogeographical region Jura Mountains around 1850. Out of the missing 60%, 23% were covered with forest in the following mapping campaign of the Siegfried Map. The missing forest area on further data gaps (Siegfried Map) is less than 4%.

**Tab. 1: Overview of available data for the estimation of long-term changes in forest area.**

| Spatial Scale | Temporal Scale | | Source | Forest Information |
|---|---|---|---|---|
| | Year | Mapping Campaign | | |
| Switzerland | 1850 | 1834-1863 | Dufour Original Survey Map | forest/non-forest, forest edge, copse |
| | 1880 | 1870-1895 | Siegfried Map | |
| | 1910 | 1904-1925 | Siegfried Map | |
| | 1940 | 1930-1949 | Siegfried Map | |
| | 1980 | 1983-1985 | National Forest Inventory 1 | |
| | 1990 | 1993-1996 | National Forest Inventory 2 | |
| | 2000 | 2004-2006 | National Forest Inventory 3 | |

| | | |
|---|---|---|
| 2000 | 1994-2000 | Topographic Map |

Forest/non-forest decisions on the 1880, 1910, 1940 and 2000 map series were made using the NFI forest definition on the NFI sampling grid (Ginzler et al. 2011). Sample raster sizes are 1.4 x 1.4 km, resulting in forest/non-forest decisions for the 20,618 sampling plots (Supplementary material, Fig. D). In this study, the same procedure was followed to obtain forest/non-forest decisions for the 1850 map series. Changes or persistence in forest cover were determined by comparing each sample point over time.

On the basis of this lattice grid, the total forest area, variance and standard error were calculated according to the NFI approach (Brassel and Lischke 2001). In a first step, the forest area proportion ($p$) was estimated using:

$$p = \frac{n_w}{n} \tag{1}$$

where $n_w$ is the number of forest plots on the lattice grid and $n$ is the number of all plots on the grid. The variance of the forest area proportion ($v(p)$):

$$v(p) = s_p^2 \approx \frac{pq}{n} \tag{2}$$

is the square of the standard error ($s_p$) of $p$, which is equal to $p$ multiplied by the proportion of non-forest area ($q$) divided by the number of all plots ($n$). The standard error ($s_p$) was calculated as follow:

$$s_p = \sqrt{v(p)} \tag{3}$$

Finally, the total forest area ($\hat{A}_w$)) was calculated by multiplying the total area ($A$) of Switzerland by the forest area proportion ($p$):

$$\hat{A}_w = \frac{n_w}{n} A = pA \tag{4}$$

together with variance ($v(\hat{A}_w)$) and standard error ($s(\hat{A}_w)$) of the total forest area:

$$v(\hat{A}_w) = A^2 s_p^2 \tag{5}$$

$$s(\hat{A}_w) = \sqrt{v(\hat{A}_w)} \quad (6)$$

For national and regional scales, the amount of total, ancient and recent forest area were calculated. In addition, national-scale net and gross changes were calculated. Net change refers to area gain minus area loss, and gross change refers to the total of all area gains and losses. The gross/net ratio is calculated to determine the underestimation of spatial changes when calculating net changes. The ratio is expressed as a percentage and is calculated by dividing gross change by net change and multiplying by 100 (Fuchs et al. 2015a). This ratio is especially important when the number of gross changes is high but net change is near zero.

At the local scale, statistically significant spatial clusters of de- and reforestation in Switzerland were identified independently of political or geographical borders. This analysis was carried out in ArcGIS 10.2 using the hot spot analysis tool. Each of the 20,618 sample points was analyzed within the context of neighboring sample points for each period. The specified threshold for the Euclidian distance was set to 2000 m. This enables the inclusion of all eight direct neighbors of each sample point. This hot spot tool returns a z-score and p-value for each plot measuring the statistical significance.

## Results – Swiss forest area dynamics over the past 150 years

### National scale

In Switzerland, forest area increased continuously from 20% in 1850 to 30% in 2000 (Fig. 2).

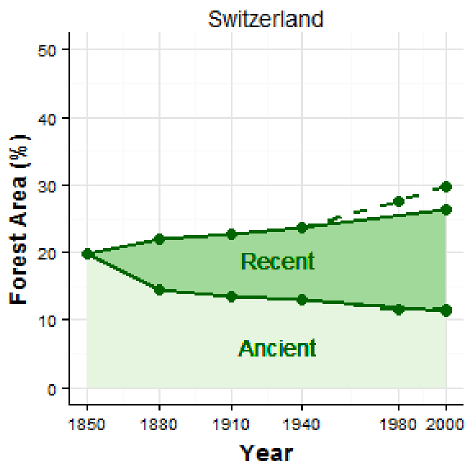


**Fig. 2: Swiss forest area dynamics at the national scale. Ancient forest area (light green) decreased while recent forest area (dark green) and total forest area increased. These consecutive estimates of forest area are based on maps (continuous lines) and NFI data (dotted lines).**

The most rapid reforestation took place in the decades after 1940. Simultaneous to an increase in recent forest area, ancient forest area (plots forested since at least 1850) decreased continuously from 20% in 1850 down to 11% of total surface in 2000, when only 43% of total forest area was of ancient origin. This percentage drops further to 39% in NFI data (Fig. 2).

The gross/net ratio result for the 150-year period shows that gross changes in forest area exceeded net changes by 282%. The highest gross changes occurred from 1850 to 1880 followed by the period 1940 to 1980 (Fig. 3). The highest net changes took place in the period 1980-2000 followed by the period 1940-1980.

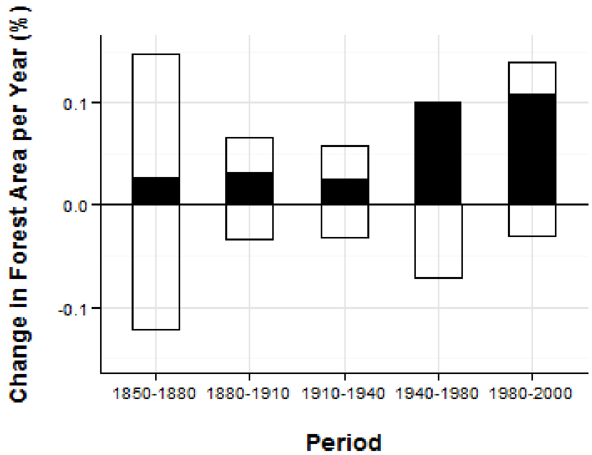


**Fig. 3: Net and gross changes in Swiss forest area for five periods from 1850 to 2000. Bars illustrate the gross change in forest area per period. The filled part of the bars represents the net changes in forest area.**

## Regional scale

In contrast to the national trend of increased forest area in Switzerland since 1850, strong variation in the intensity of forest area dynamics was observed over time and space in the six biogeographic regions (Fig. 4). In the Eastern, Southern and Western Alps, FT events occurred around 1880.

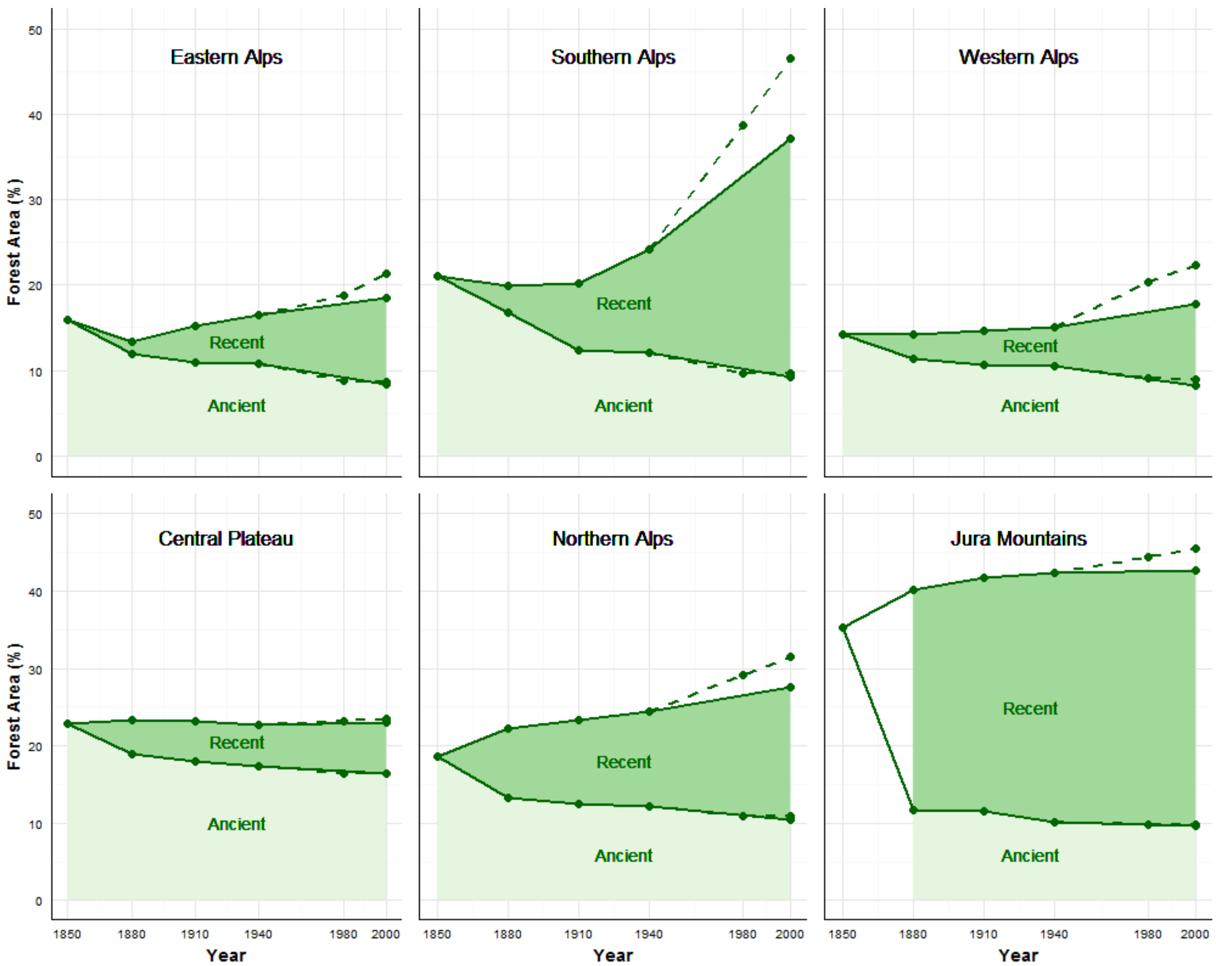


**Fig. 4: Swiss forest area dynamics at the regional scale. Ancient forest area (light green) decreased while recent forest area (dark green) and total forest area increased. These consecutive estimates of forest area are based on maps (continuous lines) and NFI data (dotted lines). For the Jura Mountains no change is presented for the first period due to a considerable data gap for the year 1850 (details given in section 2.3).**

Forest area dynamics in the Northern Alps and Jura Mountains were very similar to those at the national scale as both areas show a steady increase in forest area over the entire study period. However, the percentage of land covered by forest is much higher in the Jura Mountains compared to the Northern Alps. In contrast, forest area in the Eastern Alps decreased by 2.6% from 1850 to 1880, after which forest cover increased continuously. A similar dynamic was observed in the Southern Alps, where forest area decreased slightly from 1850 to 1880 and increased afterwards. Out of all the biogeographic regions in Switzerland, the Southern Alps had the highest gain in forest area, from a low of about 20%

forest cover in 1880 up to 37% in 2000. In contrast to the high dynamics in the Southern Alps, forest area in the Western Alps changed little (decrease/increase) from 1850 to 1940 and increased afterwards. Over the whole study period, forest area in the Central Plateau remained the most constant.

Not surprisingly, all regions show a steady decrease in ancient forest area over the whole study period of 150 years. In 2000, the highest amount of ancient forest area was found in the Central Plateau, where almost 70% of the total forest area had existed since at least 1850. Ancient forest was found to cover the Western Alps (40%) and Eastern Alps (41%) in similar proportions to that of the entire country (39%). The lowest level of ancient forest area in 2000 was found in the Southern Alps (21%).

### Local scale

During the 150-year study period, significant clusters of deforestation were found in all biogeographic regions. The number of clusters with forest area loss, however, was highest from 1850 to 1880. Over the following decades, the number declined continuously (Fig. 5).

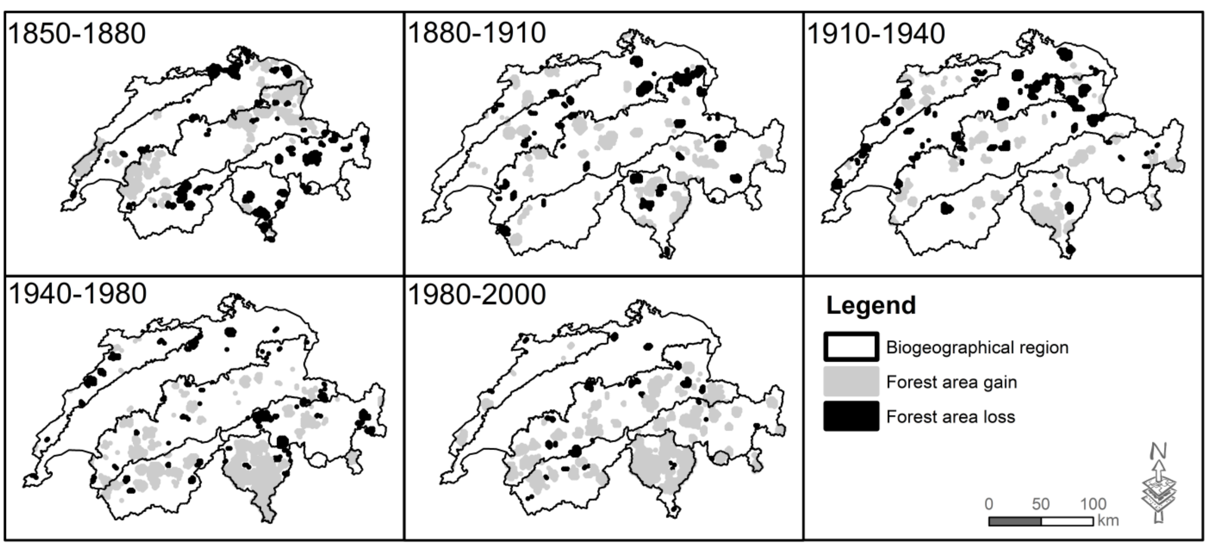


**Fig. 5: Spatial distribution of plots with significant forest area loss and gain at local scale in Switzerland between 1850 and 2000.**

Between 1850 and 1880, the two major clusters of significant gains in forest area were identified in the eastern and western part of the Northern Alps bordering the Central Plateau. In the following decades, significant clusters of forest area increase appear to be scattered randomly across the country. In the Central Plateau, the number of reforestation clusters decreased continuously over time to the point that no cluster of reforestation was found between 1980 and 2000. In contrast, especially in the Southern Alps, clusters of reforestation increased over time, peaking between 1940 and 2000.

## Reliability of changes over time

The number of changes for each sample point from 1850 to 2000 was used as an indicator of the reliability of the results. Theoretically, sample points could change their status five times over the six points in time. From an economic and ecological point of view, frequent changes from forest to non-forest or vice versa are rather unlikely. Therefore, we consider up to two changes over the whole period of 150 years as quite possible, three changes as still possible but less likely, and four changes as artifacts caused by, for example, mapping errors (details given in section 4.2.). Our analysis revealed that about 80,6% of the 20,618 sample points did not change at all (Tab. 2). About 18.4% changed once or twice, and 1% of the points changed three to four times.

**Tab. 2: Number of changes per sample point (1850-2000).**

| Possible number of changes | 0 | 1 | 2 | 3 | 4 |
|---|---|---|---|---|---|
| Identified number of changes (%) | 80.6 | 14 | 4.4 | 0.9 | 0.1 |

## Comparability of forest area estimation derived from different data sources

As already explained in section 2.3, forest area estimations are based on maps for the years 1850 to 1940. This time frame was extended with data from NFI for the years 1980 and 2000. The forest area estimates from these two data sources, i.e. NFI and map, were compared for the same point in time. This comparison revealed that the estimates based on the topographic map result in a lower forest area than when based on NFI data (Tab. 3). Given that the topographic map sheets were published from 1994 to 2000 (section 2.3, Supplementary material, Fig. C), total forest area should range between NFI 2 (1993-1996) and NFI 3 (2004-2006) values. The difference between map and NFI estimation was found to be highest for the Northern Alps.

**Tab. 3: Estimation of forest area (1000 ha) and standard error ($s_p$) for the six biogeographical regions and in total for Switzerland based on different data sources.**

| Biogeographical region | Topographic map (1994-2000) | | NFI 2 (1993-1996) | | NFI 3 (2004-2006) | |
|---|---|---|---|---|---|---|
| | Area | $s_p$ | Area | $s_p$ | Area | $s_p$ |
| Central Plateau | 259 | 6 | 261 | 6 | 262 | 6 |
| Eastern Alps | 109 | 4 | 117 | 4 | 125 | 4 |
| Jura Mountains | 186 | 5 | 195 | 5 | 196 | 5 |
| Northern Alps | 319 | 7 | 349 | 7 | 363 | 7 |
| Southern Alps | 138 | 4 | 151 | 4 | 171 | 4 |
| Western Alps | 87 | 4 | 100 | 4 | 108 | 4 |
| Switzerland | 1097 | 13 | 1173 | 13 | 1225 | 13 |

## Discussion

### Forest area dynamics and driving forces

National scale

At the national scale, no FT event was detected, i.e. no point of inflection in forest area occurred during the 150-year period under analysis. This finding is in line with the study of Mather and Fairbairn (2000) who estimated the forest cover in Switzerland based on statistical surveys. They proposed that the FT event occurred in the first half of the 19$^{th}$ century. We agree to that statement: FT events occurred around 1880 in parts of Switzerland on regional level, i.e. on national level it probably occurred few decades before. Regarding the amount of forest cover in 1850, the studies differ slightly due to different data sources. While Mather and Fairbairn (2000) estimated a forest cover of around 15%, the present study, based on spatial forest data, revealed 5% more forest coverage in 1850 (20%). Both studies, however, confirm a continuous increase in forest cover at national scale since at least 1850.

Prior to this gain, the loss in forest cover continued over centuries due to a growing demand for wood as well as the demand for agricultural land (Schuler 1988, Stuber & Bürgi 2001). In the 19th century, deforestation had reached far up the alpine region (Richard 1999). Several heavy floods and landslides in the 19th century caused harm to people and damaged infrastructure. Despite extreme weather events were decisive for these events, they still contributed to a growing environmental awareness (Stöckli 2002), and as a consequence, the Forest Police Law, came into effect in 1876. Initially, these federal regulations only referred to the “high mountains”, but were later expanded to the whole country (Bertogliati 2014).

Regional and local scale

At the regional scale, FT events were detected for the Eastern, Western and Southern Alps. The change from decreasing to increasing forest area occurred during the mapping campaign of the Siegfried 1880 map. The highest gain in forest area overall occurred in the Southern Alps, were it has more than doubled according to our results. This is in line with Pezzatti et al. (2013) findings that forest area in the Canton of Ticino, which encompasses the lager part of the Southern Alps region, more than doubled from 1900 to 2000. What might have caused this pronounced development? In the 19th century, Ticino was a poor canton where people earned their money through traditional agricultural activities and wood exportation. The golden era of wood export was from 1830 to 1860 (Ceschi 2003), which is in line with the decrease in forest area which we found for the Southern Alps from 1850 to 1880. After 1880, the time of the FT event, the prices for wood decreased drastically and sales stagnated, as the new railway imported wood more cheaply (Ceschi 2003). Many young people were constrained to emigrate from Ticino also because agriculture did not supply staples for the whole population (Cheda 1993). As a result, the reduction of labor caused farm abandonment and forest re-growth began. During the last post-war period, the Canton of Ticino experienced a drastic socio-economic change towards a more service-orientated economy. While this ensured prosperity and stimulated a strong increase in the population, at the same time it caused the almost total abandonment of agriculture and a corresponding increase of natural re-forestation (Conedera 2009), which is in line with the strong increase in forest area found in our results after 1940 (Fig. 4).

Parallel to natural regrowth on former alpine pastures due to agricultural abandonment (Gellrich et al. 2007), many afforestation projects began between 1880 and 1920 mainly in Jura Mountains and Northern Alps (Brändli 2010, Schuler 1988). Considering the possible time lag from reforestation to the creation of a new Siegfried map series, these afforestation projects could be an explanation for the visible higher reforestation rate after 1940, especially in the Northern Alps. Empirical evidence for the long-term trend of increasing forest area in the Northern Alps was documented by Hahn (2011) for the case study region Entlebuch. A further case study in the Northern Alps, conducted by Gerber (1989) for the catchment area of the river Emme, presents the forest area increase between 1860 and 1980. In contrast, forest area in the Central Plateau is the most stable in comparison to the other five biogeographical regions. The results from Hersperger and Bürgi (2007) who studied changes in the Limmat Valley between 1930 to 2000, confirm the trend of stable forest area.

Ancient forest area

In addition to the overall trend of forest area expansion at the national scale, a decrease in ecologically valuable ancient forest area occurred during all periods. Undoubtedly, not all Swiss ancient forest areas, which have been continuously forested since at least 1850, are necessarily covered with ecologically valuable forests due to intensive forest management, especially in the Swiss lowlands (Bürgi 1999). While the purpose of the present study was not to identify ancient forests, the spatially explicit map which identifies continuously forested areas since at least 1850 (section 2.1, Fig. 1) can serve as the basis for the identification of ancient forests with high conservation value (Bütler et al. 2015). Continuity is a determining factor impacting, especially for ancient forest species with a low colonization capacity which limits their distribution and abundance (Hermy and Verheyen 2007; Norden et al. 2014), their adaptability to global changes (von Oheimb et al. 2014) as well as the storage of C and nutrient in soils (Leuschner et al. 2014).

Net vs. gross changes

Further indicators of forest area dynamics, in addition to developments in ancient forest area, are the net and gross changes. To avoid an underestimation of land-cover dynamics which may occur when considering only net changes (Wilkenskjeld et al. 2014), gross changes in forest area were also evaluated. On average, the gross change in forest area for the 150-year period under analysis is about 282% higher than the net change. These fluctuations in forest cover affect, for example, timber growth as well as net carbon flux and storage (Vilén et al. 2012).

We found that gross changes between 1850 and 1880 and from 1940 to 1980 are much higher than during the other periods (section 3.1). However, this higher gross change might be due to the different data sources used. Forest cover around 1850 was sampled from the Dufour Original Survey Map while the Siegfried Map was the source for forest cover estimations from 1880 to 1940. For 1980 and 2000, forest information was derived from terrestrial survey and aerial images within NFI surveys. An evaluation of the quality and accuracy of the data is crucial for reliable gross change analysis (Fuchs et al. 2015a).

**Data quality**

Over the years, measurement methods have become more accurate. A comparison with independent estimates of Swiss forest area from various sources (Fig. 6) revealed that the amount of forest area from the Dufour Original Survey Map slightly exceeds the estimation from the historical statistics. The forest area estimation based on the first edition of the Siegfried Map exceeds other independent estimations as well. Around 1920, however, the forest area equals other sources and in the last Siegfried Edition the estimation is slightly lower. Nevertheless, the general trend of increasing forest area since at least 1840 is represented in all sources.

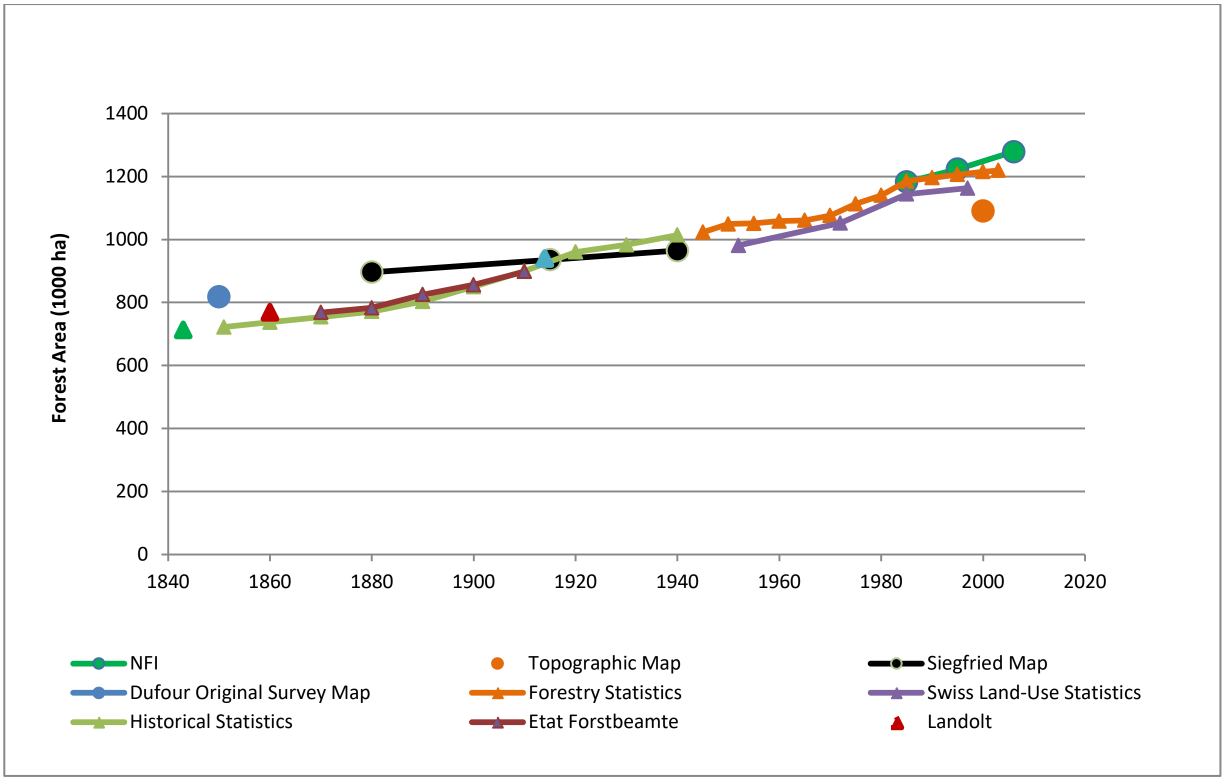


**Fig. 6: A comparison of changes in Swiss forest area since 1840 based on different data sources, e.g. statistics, maps and National Forest Inventory (NFI). Source: Based on Ginzler et al. 2011 and Brändli 2000**

A comparison of NFI data with the topographic map shows that current maps show less forest cover (Tab. 3), especially in mountainous regions with open forests, where the definition of forest is of crucial importance (Ginzler et al. 2011). One reason for this difference in forest area might be that the definition of forest is precise for the NFI terrestrial field survey but vague for the map production. Many areas which are mapped in the Topographic Map as rock or scree actually fulfill the terrestrial NFI-forest definition.

The reliability of the results of forest area loss and gain was assessed using the number of changes per plot (section 3.4). Only 1% of the sample plots have a rather unlikely number of changes (three to four times) from forest to non-forest area or vice versa. This confirms the high quality of the data base.

Even though historical maps showed some inaccuracy, they are the most reliable sources representing past landscapes in a spatially explicit way for the time prior to aerial photography (Leyk 2005). Moreover, the Dufour Original Survey Map and Siegfried Map are suitable for comparison as they were drawn at the same scale and based on the same technique of graphical triangulation. Fuchs et al. (2015b) showed that the accuracy of land allocation in historical reconstructions can be improved significantly by using historical maps.

## Conclusion

Historical maps together with contemporary spatial forest information from National Forest Inventory (NFI) are particularly useful for the long-term analysis of forest area dynamics and Forest Transition (FT). The choice of spatial scale was found to be of crucial importance in such analysis. While at the national scale, forest area in Switzerland appeared to increase continuously, at the regional scale a decrease in forest area and subsequent FT events were found in several biogeographical regions for the earliest period under study. At the local scale, significant patches of decrease and increase in forest area draw a very dynamic picture of forest area changes in Switzerland. The overall constant loss of ancient forest area in Switzerland is in line with the findings of Fuchs et al. (2015a) who pointed out that despite a net trend of increasing forest area, the loss of (ancient) forest area is still a significant process in Europe. The spatially explicit results of this study can serve as the basis for further analysis regarding the underlying processes driving these changes in forest area, which could be cultural, economic, political, technological or natural in origin.

## Acknowledgements

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## References

Bae JS, Joo RW, Kim YS (2012) Forest transition in South Korea: Reality, path and drivers. Land Use Policy 29:198-207. doi:10.1016/j.landusepol.2011.06.007

Beard MK (1989) Use error: The neglected error component. In: Proceedings of the Ninth International Symposium on Computer-Assisted Cartography (Auto-Carto 9). Baltimore, pp 808-817

Bertogliati M (2014) Dai boschi protetti alle foreste di protezione: comunità locali e risorse forestali nella Svizzera italiana (1700-1950). Casagrande, Bellinzona

Brändli U-B (2000) Waldzunahme in der Schweiz - gestern und morgen. Inf.bl. Forsch.bereich Landsch. 45:1-6

Brändli U-B (2010) Schweizerisches Landesforstinventar. Ergebnisse der dritten Erhebung 2004-2006. Birmensdorf, Eidgenössische Forschungsanstalt für Wald, Schnee und Landschaft WSL. Bundesamt für Umwelt (BAFU), Bern

Brassel P, Lischke H (2001) Swiss National Forest Inventory: Methods and Models of the Second Assessment. Swiss Federal Research Institute WSL, Birmensdorf

Bürgi M (1999) A case study of forest change in the Swiss lowlands. Landsc Ecol 14:567-575. doi:10.1023/a:1008168209725

Bütler R, Bolliger M, Commarmot B (2015) Die Suche nach altem Wald in der Schweiz. Schweiz. Z. Forstwes. 166:67-74. doi:10.3188/szf.2015.0067

Ceschi R (2003) Geschichte des Kantons Tessin. Huber, Frauenfeld

Cheda G (1993) Dal medèe al dery. Contadine ed emigranti per conoscere la storia del mondo alpino. Armando Dadò Editore, Locarno

Conedera M (2009) Implementing fire history and fire ecology in fire risk assessment: the study case of Canton Ticino (southern Switzerland). Dissertation, University of Karlsruhe

Decoppet M (1912) Produktion und Verbrauch von Nutzholz. Einige statistische Angaben über die forstlichen Verhältnisse der Schweiz. Orell Füssli, Zürich

Farley KA (2007) Grasslands to tree plantations: Forest transition in the Andes of Ecuador. Ann. Assoc. Am. Geogr. 97:755-771. doi:10.1111/j.1467-8306.2007.00581.x

Foster DR, Motzkin G & Slater B (1998) Land-use history as long-term broad-scale disturbance: regional forest dynamics in central New England. Ecosystems 1:76-95. doi:10.1007/s100219900008

Fuchs R, Herold M, Verburg PH, Clevers JGPW & Eberle J (2015a) Gross changes in reconstructions of historic land cover/use for Europe between 1900 and 2010. Glob. Chang. Biol. 21:299-313. doi:10.1111/gcb.12714

Fuchs R, Verburg PH, Clevers JGPW & Herold M (2015b) The potential of old maps and encyclopaedias for reconstructing historic European land cover / use change. Appl. Geogr. 59:43-55. doi:10.1016/j.apgeog.2015.02.013, 2015

Gellrich M, Baur P, Zimmermann NE (2007) Natural forest regrowth as a proxy variable for agricultural land abandonment in the Swiss mountains: a spatial statistical model based on geophysical and socio-economic variables. Environ. Model. Assess. 12:269-278. doi:10.1007/s10666-006-9062-6

Gerber, B (1989) Waldflächenveränderungen und Hochwasserbedrohung im Einzugsgebiet der Emme. Dissertation, University of Bern

Ginzler C, Brändli U-B, Hägeli M (2011) Waldflächenentwicklung der letzten 120 Jahre in der Schweiz Schweiz. Z. Forstwes. 162:337-343. doi:10.3188/szf.2011.0337

Gonseth Y, Wohlgemuth T, Sansonnens B, Buttler A (2001) Die biogeographischen Regionen der Schweiz. Erläuterungen und Einteilungsstandard. Umwelt Materialien Nr. 137 Bundesamt für Umwelt, Wald und Landschaft, Bern, 48p.

Goodchild M F (1991) Issues of quality and uncertainty. In: Muller JC (ed) Advances in Cartography. Elsevier, London, pp 113-139

Grainger A (1995) The forest transition: an alternative approach. Area 27:242-251, available online: http://www.jstor.org/stable/20003580?seq=1#page_scan_tab_contents. Accessed 15 May 2015

Grosjean G (1996) Geschichte der Kartographie. Geographisches Institut der Universität Bern. doi: 10.4480/GB2013.U8

Hahn, P (2011) Zeitspuren im Entlebuch. Waldentwicklung und Landschaftswandel im 20. Jahrhundert. Haupt, Bern

Hermy M, Verheyen K (2007) Legacies of the past in the present-day forest biodiversity: a review of past land-use effects on forest plant species composition and diversity. Ecol. Res. 22:361-371. doi:10.1007/s11284-007-0354-3

Hersperger AM, Bürgi M (2007) Driving Forces of Landscape Change in The Urbanizing Limmat Valley, Switzerland. In: Koomen E, Stillwell J, Bakema A, Scholten H (eds) Modelling Land-Use Change, vol 90. The GeoJournal Library. Springer Netherlands, pp 45-60. doi:10.1007/978-1-4020-5648-2_3

Imhof E (1927) Unsere Landkarten und ihre weitere Entwicklung. Zeitschrift für Vermessungswesen und Kulturtechnik. Buchdruckerei Winterthur

Izquierdo AE, De Angelo CD & Aide TM (2008) Thirty Years of Human Demography and Land-Use Change in the Atlantic Forest of Misiones, Argentina: an Evaluation of the Forest Transition Model. Ecology and Society 13(2):3, available online: http://www.ecologyandsociety.org/vol13/iss2/art3/. Accessed 15 May 2015

Kauppi PE, Ausubel JH, Fang J, Mather AS, Sedjo RA, Waggoner PE (2006) Returning forests analyzed with the forest identity. Proc. Natl. Acad. Sci. U.S.A. 103:17574-17579. doi:10.1073/pnas.0608343103

Kozak J (2003) Forest cover change in the Western Carpathians in the past 180 Years. Mt. Res. Dev. 23:369-375. doi:10.1659/0276-4741(2003)023[0369:FCCITW]2.0.CO;2

Krausmann F (2006) Forest transition in Austria: a socio-ecological approach. Mitt. Österr. Geogr. Ges. 148:75-91

Leuschner C, Wulf M, Bäuchler P, Hertel D (2014) Forest Continuity as a Key Determinant of Soil Carbon and Nutrient Storage in Beech Forests on Sandy Soils in Northern Germany. Ecosystems 17:497-511. doi:10.1007/s10021-013-9738-0

Leyk S (2005) Computing the Past - Utilizing Historical Data Sources for Map-Based Retrospective Landscape Research. Dissertation, University of Zürich

Leyk S, Boesch R, Weibel R (2005) A Conceptual Framework for Uncertainty Investigation in Map-based Land Cover Change Modelling. Trans. GIS 9(3):291-322. doiI:10.1111/j.1467-9671.2005.00220.x

Leyk S, Zimmermann NE (2004) A Predictive Model for Filed-Based Survey Maps Using Generalized Linear Models. GIScience 191-205. doi:10.1007/978-3-540-30231-5_13

Marey-Perez MF & Rodriguez-Vicente V (2009) Forest transition in Northern Spain: Local responses on large-scale programmes of field-afforestation. Land Use Policy 26:139-156. doi:10.1016/j.landusepol.2008.02.004

Mather AS (1992) The forest transition. Area 24:367-379, available online: http://www.jstor.org/stable/20003181?seq=1#page_scan_tab_contents. Accessed 15 May 2015

Mather AS (2001) The transition from deforestation to reforestation in Europe. In: Angelsen A, Kaimowitz D (ed) Agricultural Technologies and Tropical Deforestation, CABI, Wallingford, pp 35-52. doi:10.1079/9780851994512.0035

Mather AS (2004) Forest transition theory and the reforesting of Scotland. Scot. Geog. J. 120:83-98. doi:10.1080/00369220418737194

Mather AS, Fairbairn J (2000) From Floods to Reforestation: The Forest Transition in Switzerland. Environ. Hist. 6(4):399-421. doi:10.3197/096734000129342352

Mather AS, Fairbairn J & Needle CL (1999) The course and drivers of the forest transition: the case of France. J. Rural Stud. 15:65-90. doi:10.1016/S0743-0167(98)00023-0

Mather AS, Needle CL & Coull JR (1998) From resource crisis to sustainability: the forest transition in Denmark. Int. J. Sust. Dev. World 5(3):182-193. doi:10.1080/13504509809469982

Meyfroidt P & Lambin EF (2008) Forest transition in Vietnam and its environmental impacts. Glob. Chang. Biol. 14:1319-1336. doi:10.1111/j.1365-2486.2008.01575.x

Norden B, Dahlberg A, Brandrud TE, Fritz O, Ejrnaes R, Ovaskainen O (2014) Effects of ecological continuity on species richness and composition in forests and woodlands: A review. Ecoscience 21:34-45. doi:10.2980/21-1-3667

Pagnutti C, Bauch CT, Anand M (2013) Outlook on a Worldwide Forest Transition PLoS ONE 8. doi:10.1371/journal.pone.0075890.g001

Palo M & Vanhanen H (ed) (2000) World Forests from Deforestation to Transition? Kluwer, Dordrecht

Perz SG (2007) Grand theory and context-specificity in the study of forest dynamics: Forest transition theory and other directions. Prof Geogr 59:105-114. doi:10.1111/j.1467-9272.2007.00594.x

Perz SG & Skole DL (2003) Secondary forest expansion in the Brazilian Amazon and the refinement of forest transition theory. Soc. Nat. Resour. 16:277-294. doi:10.1080/08941920390178856

Pezzatti GB, Zumbrunnen T, Bürgi M, Ambrosetti P, Conedera M (2013) Fire regime shifts as a consequence of fire policy and socio-economic development: An analysis based on the change point approach. For. Policy Econ. 29:7-18. doi:http://dx.doi.org/10.1016/j.forpol.2011.07.002
Redo D, Bass JOJ & Millington AC (2009) Forest dynamics and the importance of place in western Honduras. Appl. Geogr. 29(1):91-110. doi:10.1016/j.apgeog.2008.07.007
Richard T (1999) Eisenbahn und Wald. SBB CFF FFS Forstdienst. Luzern
Rickenbacher M (2009) Napoleons Karten der Schweiz. Landvermessung als Machtfaktor 1798-1815. Dissertation, University of Basel
Rudel TK, Coomes OT, Moran E, Achard F, Angelsen A, Xu J, Lambin E (2005) Forest transition: towards a global understanding of land use change. Glob. Environ. Chang. 15(1):23-31. doi:10.1016/j.gloenvcha.2004.11.001
Rutherford GN, Bebi P, Edwards PJ, Zimmermann NE (2008) Assessing land-use statistics to model land cover change in a mountainous landscape in the European Alps. Ecol. Model. 212:460-471. doi:10.1016/j.ecolmodel.2007.10.050
Schuler A (1988) Forest area and forest utilization in the Swiss pre-alpine region. In: Salbitano F (ed) Human influence on forest ecosystems development in Europe. Bologna, pp 121-127
Stöckli V (2002) Der Bannwald. Lebensgrundlage und Kultobjekt. In: Pfister C (ed) Am Tag danach – Zur Bewältigung von Naturkatastrophen in der Schweiz 1500-2000. Haupt, Bern, pp 101-112
Stuber M, Bürgi M (2001) Agrarische Waldnutzungen in der Schweiz 1800-1950. Waldweide, Waldheu, Nadel- und Laubfutter. Schweiz. Z. Forstwes. 152(12):490-508. doi: http://dx.doi.org/10.3188/szf.2003.0360
Swisstopo (2015a) Journey through time – Maps. Federal Office of Topography, available online: https://map.geo.admin.ch/?X=190000.00&Y=660000.00&zoom=1&lang=en&topic=swisstopo&bgLayer=voidLayer&catalogNodes=1392,1482&layers_timestamp=18641231&time=1864&layers=ch.swisstopo.zeitreihen. Accessed 17 August 2015
Swisstopo (2015b) Background information on the Dufour Map. Federal Office of Topography, available online: http://www.swisstopo.admin.ch/internet/swisstopo/en/home/topics/geodata/historic_geodata/ma_col/duf_map.html. Accessed 17 August 2015
Swisstopo (2015c) Background information on the Siegfried Map. Federal Office of Topography, available online: http://www.swisstopo.admin.ch/internet/swisstopo/en/home/topics/geodata/historic_geodata/ma_col/sig_map.html. Accessed 17 August 2015
Vilén T, Gunia K, Verkerk PJ, Seidl R, Schelhaas MJ, Lindner M, Bellassen V (2012) Reconstructed forest age structure in Europe 1950–2010. For. Ecol. Manage. 286:203-218. doi:10.1016/j.foreco.2012.08.048
von Oheimb G, Hardtle W, Eckstein D, Engelke HH, Hehnke T, Wagner B, Fichtner A (2014) Does Forest Continuity Enhance the Resilience of Trees to Environmental Change? Plos One 9. doi:10.1371/journal.pone.0113507

Wilkenskjeld S, Kloster S, Pongratz J, Raddatz T, Reick CH (2014) Comparing the influence of net and gross anthropogenic land-use and land-cover changes on the carbon cycle in the MPI-ESM. Biogeosciences 11:4817-4828. doi:10.5194/bg-11-4817-2014

Yeo IY & Huang C (2013a) Forest Dynamics in Mississippi, USA: A Hybrid Statistical and Geospatial Analysis. Reg. Environ. Change 13(3):583-599. doi:10.1007/s10113-012-0340-3

Yeo IY & Huang C (2013b) Revisiting the Forest Transition Theory with Historical Records and Geospatial Data: A Case Study from Mississippi (USA). Land Use Policy 32:1-13. doi:10.1016/j.landusepol.2012.09.017

## Supplementary material


**Fig. A: The three spatial scales (national, regional, local) for the analysis of forest transition (FT) and forest area dynamics in Switzerland.**

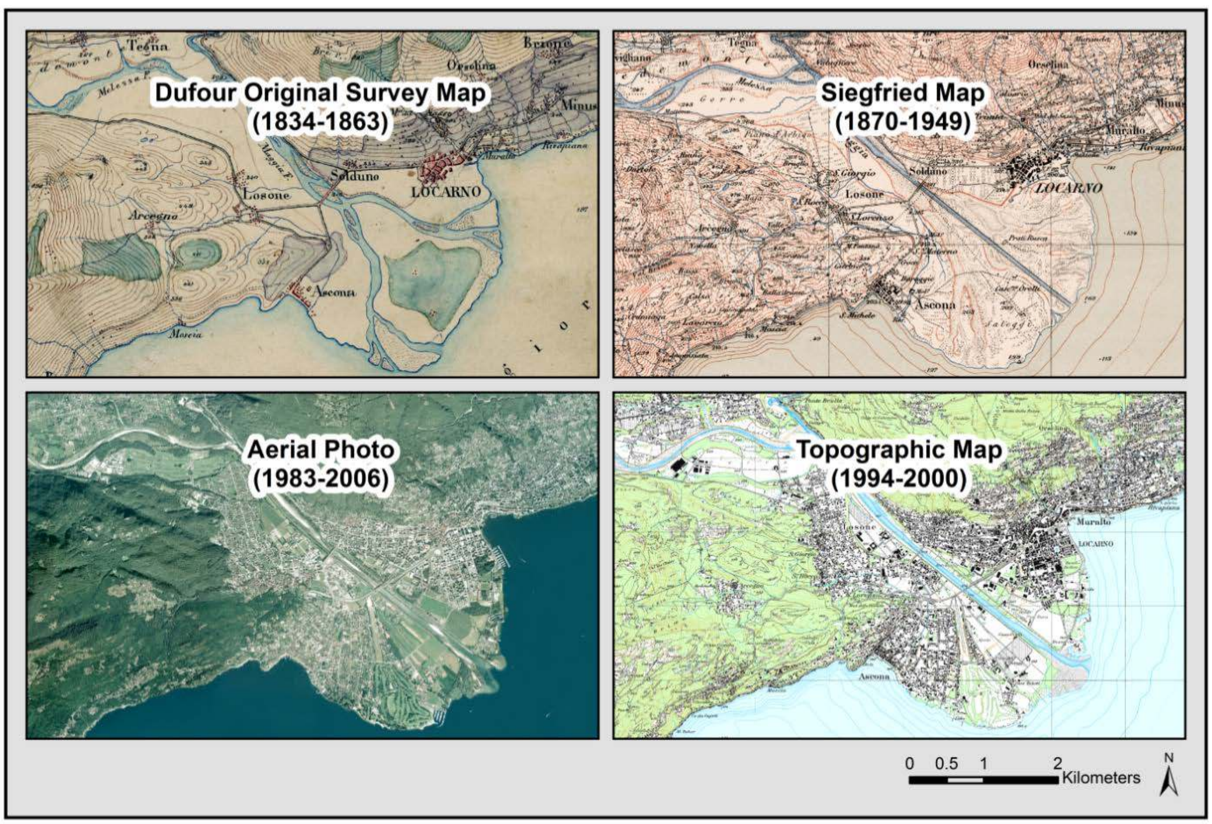


**Fig. B: Samples of historical and contemporary maps as well as one aerial photo on which the analysis of forest area dynamics is based. The forest area is represented in green color in the Dufour Original Survey Map, Aerial Photo and Topographic Map. In the Siegfried Map it is represented with small black circle-like symbols and thin black lines indicate forest boundaries.**

**Source: Swiss Federal Institute for Forest, Snow and Landscape Research (WSL), swisstopo (C) 2015 (5704000000)**

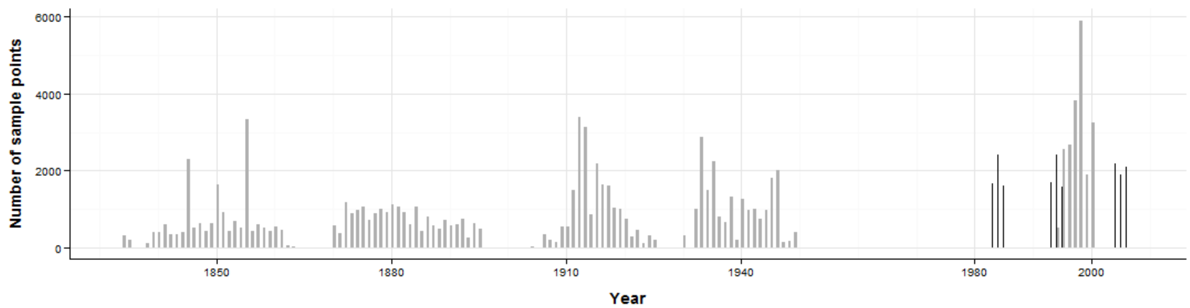


**Fig. C: Number of sample points per mapping campaign for map series (grey) and National Forest Inventory (NFI) (black). Map series sample points include forest and non-forest points while NFI survey sample points contain only forest points (about 1/3 of the total points).**

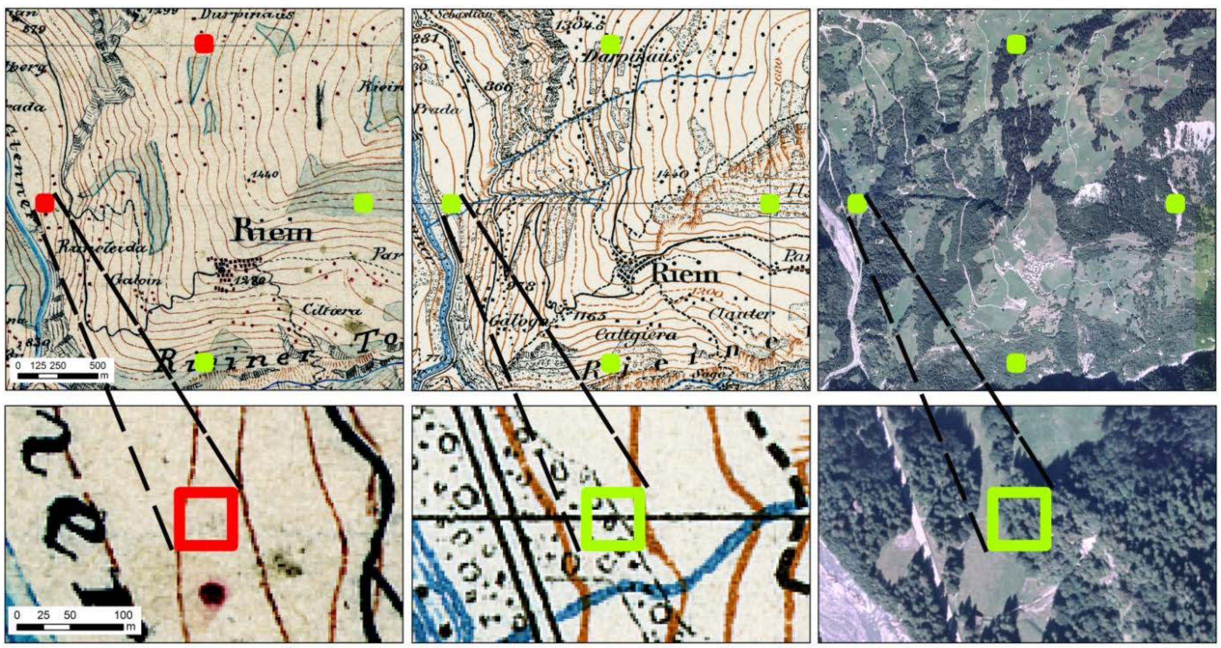


**Fig. D: Examples from the Dufour Original Survey Map (1845), Siegfried Map (1884) and Aerial Photo used for NFI (2002) (left to right) to compare the change in forest area over time. The squares in green (forest) and red (non-forest) are part of the sample raster (1.4 x 1.4 km) with a total of 20,618 plots across Switzerland.**