

Quantifying disturbance effects on vegetation carbon pools in mountain forests based on historical data

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Abstract Although the terrestrial carbon budget is of key importance for atmospheric CO₂ concentrations, little is known on the effects of management and natural disturbances on historical carbon stocks at the regional scale. We reconstruct the dynamics of vegetation carbon stocks and flows in forests across the past 100 years for a valley in the eastern Swiss Prealps using quantitative and qualitative information from forest management plans. The excellent quality of the historical information makes it possible to link dynamics in growing stocks with high-resolution time series for natural and anthropogenic disturbances. The results of the historical reconstruction are compared with modelled potential natural vegetation. Forest carbon stock at the beginning of the twentieth century was substantially reduced compared to natural conditions as a result of large scale clearcutting lasting until the late nineteenth century. Recovery of the forests from this unsustainable exploitation and systematic forest management were the main drivers of a strong carbon accumulation during almost the

entire twentieth century. In the 1990s two major storm events and subsequent bark beetle infestations significantly reduced stocks back to the levels of the mid-twentieth century. The future potential for further carbon accumulation was found to be strongly limited, as the potential for further forest expansion in this valley is low and forest properties seem to approach equilibrium with the natural disturbance regime. We conclude that consistent long-term observations of carbon stocks and their changes provide rich information on the historical range of variability of forest ecosystems. Such historical information improves our ability to assess future changes in carbon stocks. Further, the information is vital for better parameterization and initialization of dynamic regional scale vegetation models and it provides important background for appropriate management decisions.

Keywords Forest carbon stock · Terrestrial carbon sinks · Windthrow · Bark beetle · Forest management · Historical ecology

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Introduction

Forests store 10–20 times more carbon in their vegetation per unit area than all other land cover types (Olson et al. 1983), and 60–80% of the global terrestrial carbon is stored by forest plants and soils (Waring and Schlesinger 1985; Perruchoud and Fischlin 1995). Consequently, forests play a major role in the exchange of CO₂ between the atmosphere and biosphere (Apps and Price 1996). Forests of the northern hemisphere are known to currently absorb considerable amounts of atmospheric carbon each year, thus acting as carbon sinks (Goodale et al. 2002). The main contributors to this effect are changes in the age structure

of forests, expansion of forest area following agricultural abandonment, and enhanced tree growth under enhanced N deposition, warmer climatic conditions as well as CO₂ fertilization (Caspersen et al. 2000).

Natural disturbances and forest management strongly affect the size of carbon pools and alter biogeochemical cycles in forested landscapes (Houghton et al. 2000; Houghton and Hackler 2000). However, it is difficult to disentangle the different impacts and interrelations between all these factors (Magniani et al. 2007). Repeated statistical sources such as national forest inventories and census data (Houghton et al. 1999; Houghton and Hackler 2003; Naabuurs et al. 2003; Fang et al. 2005; Woodbury et al. 2006) or series of remote imagery (Asner et al. 2003) are useful to quantify large scale effects of land use changes such as forest clearing or re-growth after agricultural abandonment on forest carbon pools. In contrast, regional case studies based on detailed historical evidence are suitable for an in-depth analysis of the impact of anthropogenic and natural disturbances. Such approaches are particularly important to gain a better understanding of the current state of forest ecosystems and help to anticipate the range of future dynamics. In addition, a wide range of modelling studies have been conducted in the past years to elucidate the role of the terrestrial biosphere in the global carbon cycle (e.g., Cramer et al. 1999) and with respect to biospheric feedback effects to the climate (e.g., Friedlingstein et al. 2006). It remains largely unknown, however, how well these models are able to match historical patterns of biospheric carbon pools, and what the exact initial conditions for scenario calculations into the future should be. From this point of view, it is surprising that only a few attempts have been made to date to reconstruct regional long-term dynamics of terrestrial carbon stocks based on historical data (e.g., Gingrich et al. 2007).

The Alptal, a 47 km² valley in the eastern Swiss Prealps is predominately forested with spruce (*Picea abies*) and fir (*Abies alba*) at higher altitudes and beech (*Fagus sylvatica*) in the lower parts. The valley is a region for which a broad range of historical material exists that allows us to link the dynamics of vegetation carbon stocks with anthropogenic and natural disturbance history over the past 100 years. Therefore, the aims of our study are (1) to reconstruct centennial time series for standing volume, growth increment, and highly resolved series for anthropogenic and natural disturbances to detect changes in vegetation carbon pools over the past 100 years for this valley, (2) to quantify the relative contribution of management, natural disturbances and their interactions to historical changes in carbon pool sizes, and (3) to assess to what degree the carbon storage capacity of this landscape has been reached during the twentieth century and thus to quantify the future potential for further carbon accumulation.

Data and methods

Study region

The Alptal region is located in the eastern Prealps of Switzerland (Fig. 1). It contains the catchment area of the Alp river with a total area of 47.1 km². Elevation ranges between 1,899 m above sea level at the highest point at the southern end of the valley and 840 m above sea level at the valley bottom. Current land cover data indicate that more than 52% of the area is covered by forests (BFS 2001). Grasslands in the flat parts of the valley bottom and alpine pastures at higher altitudes cover an additional 41%. The remaining area is covered by urban land cover types (5%) and rock (2%). The city of Einsiedeln and the village of

Fig. 1 Location of the study area in the eastern Prealps of Switzerland

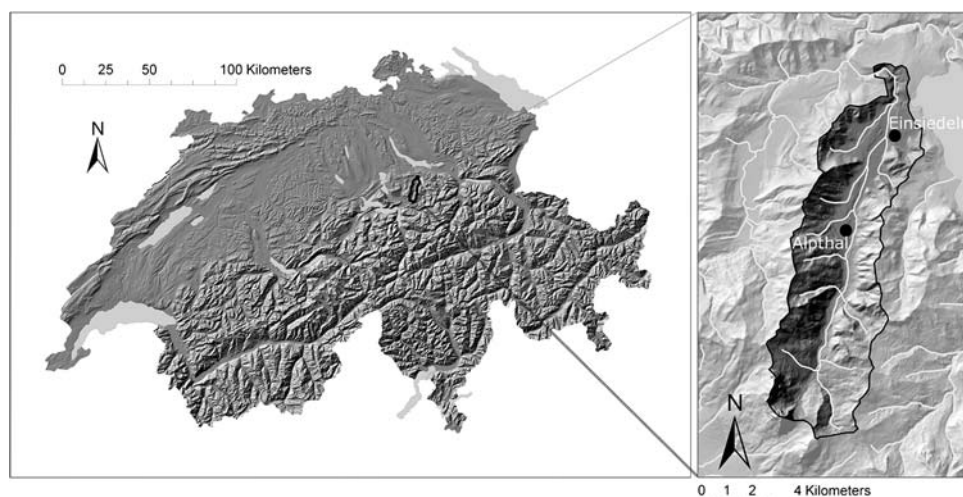


Table 1 Available forest management plans (MPs) for the Alptal

Owner	Area covered (ha)	1st MP	2nd MP	3rd MP	Digital stand map
Oberallmeindkorporation Schwyz (OAK)	1,206	1926	1952	1981	1999
Stiftthaleri Kloster Einsiedeln	251	1929	1951	1972	1999
Genossame Trachelau	217	1927	1952	1972	1999
Genossame Dorf-Binzen	182	1924	1949	1972	1999
Genossame Schwyz	130	NA	1957	1987	1999
Genossame Alpthal	126	NA	1956	1983	1999
Kirche Alpthal	91	1937	1962	1983	1999
Frauenkloster Allerheiligen in der Au	61	1926	1947	1972	1999
Genossame Bennau	27	1935	1957	1972	1999

Alpthal are the two largest settlements in the study area. With an average annual precipitation in Einsiedeln of 1,753 mm (data from MeteoSwiss), the valley is among the wettest regions of Switzerland.

Historical reconstruction

The reconstruction of twentieth century carbon budget of the Alptal is based on information from forest management plans (MPs). The MPs cover almost 70% of the total forested area of the Alptal in 1999 and 35% of the total area of the valley. Our reconstruction is restricted to this part of the valley. MPs have been and continue to be the main planning tool in Swiss forestry. Therefore, they are a valuable source for reconstructing forest changes in Switzerland (Bürgi 1999; Gimmi and Bürgi 2007; Gimmi et al. 2008). For the study area, we analyzed 25 MPs from the archive of the forest district that were written between 1924 and 1987 (Table 1). Each plan refers to the forests of one owner. In the Alptal these are either monasteries or agricultural cooperatives. As the plans are irregularly distributed over time, they were grouped into three different time steps: 1925 (MPs from 1924 to 1937); 1950 (MPs 1947–1962); and 1975 (MPs 1972–1987). In addition, for a fourth and last time step we used a digital stand map based on aerial photographs from 1999 (Bestandeskarte Kanton Schwyz). The MPs contain standing timber inventories by full caliper [100% cruise with a lower limit of diameter at breast height (DBH) = 16 cm] for the first two time steps and by systematic sampling for the third time step. The inventories provide precise information on growing stock, stem numbers, tree species composition, and percentage of forest cover for every management unit. The stand map of 1999 provides the same stand classification as used for the sampling at time step 1975. The data for standing timber volume were calculated for DBH \geq 16 cm throughout all time steps. Based on data from 1999 we calculated the current state for 2006 including timber harvest and natural disturbance records from 2000 to 2006 (see below), and

Table 2 Procedure for converting growing stock into aboveground carbon stock, following IPCC standard methodology (Penman et al. 2003) applying species and region specific values for Switzerland (Thüring and Schmid 2008)

	Conversion factor (ρ) dry biomass from stemvolume (t m^{-3})	Expansion factor (e) from stem biomass to total biomass (g g^{-1})	C content (g C g^{-1} biomass)
Spruce	0.40	1.48	0.5
Fir	0.40	1.48	0.5
Beech	0.55	1.49	0.5

from the full data set we estimated tree growth and forest expansion (annual mean values of the period 1925 to 1999).

We used the IPCC standard methodology to convert growing stock into total vegetation carbon stock (Penman et al. 2003). The procedure includes a wood density conversion factor (ρ) for calculating dry biomass from stem volume, and a biomass expansion factor (e) in order to consider total vegetation biomass including compartments such as branches, twigs, leaves, understorey, roots, and fine roots (Table 2). We applied species- and region-specific values for biomass expansion factors and wood densities used for carbon budgets in Swiss forests (Thüring and Schmid 2008). Finally, we calculated carbon content from total biomass, whereby we assumed a carbon content of 50%.

The MPs also contain annual time series for timber harvesting and unplanned fellings caused by natural disturbances for each stand from 1906 to 2006. For the first half of the twentieth century, most MPs give only the total amount of wood removal, because the distinction between regular timber harvesting and unplanned felling was introduced only in the 1950s. Conversion from volumes to carbon units is not possible for the timber harvesting data as information on tree species is lacking in most cases. Additionally, qualitative information about natural disturbances is available from the annual reports of the forest

administration. From 1906 to 2006, the MPs contain complete annual time series for afforestation; this information is given by the number of planted trees by species for each stand in most cases along with information on the planted area.

Besides quantitative information, MPs also include qualitative information about previous forest uses, the current state of the forests and guidelines for future practice. These data were used as background information for the interpretation of the quantitative time series.

Estimating regional carbon storage capacity

We used simulated potential natural vegetation as a benchmark for natural conditions and as a plausibility test of the historical reconstruction. Comparison of reconstructed historical carbon pools for the Alptal with simulated local potential carbon storage capacity allows us to quantify to what extent carbon storage capacity has been reached historically and to assess the future potential for further carbon accumulation.

Potential natural vegetation for the Alptal was simulated using the Terrestrial Ecosystem Model LPJ-GUESS (Sitch et al. 2003; Smith et al. 2001), but using tree-specific parameters based on Morales et al. (2005, 2007) and Koca et al. (2006). As climatic drivers, we used the daily data of the meteorological stations in Einsiedeln (910 m) and Pilatus (2,106 m), from 1931 to 2005, and interpolated the elevation gradient for temperature and precipitation for each 100 m change in elevation using linear regression for each month separately. To provide a benchmark for the reconstructed carbon data, we ran a model “spin-up” (1,000 years), using the 1901–1931 CRU climate data repeatedly in random order of years (Mitchell et al. 2004, http://ipcc-ddc.cru.uea.ac.uk/obs/cru_climatologies.html, 0.5° resolution, monthly resolution) to determine potential natural vegetation for every 100 m elevational band. To estimate the temperature and precipitation for 1901–1931, we used the monthly trends as observed from the CRU data to calculate the anomalies compared to the period 1931–1960, where both data sets overlap. To maintain the interannual variation in daily temperature and precipitation we added these anomalies to a randomized sample of the observed years (1931–1960, from the two stations Pilatus and Einsiedeln). Disturbances were modelled as random events, with an expected return interval of 100 years which had produced good results in earlier studies for plant functional types composition for temperate and boreal forests in Europe (Badeck et al. 2001; Smith et al. 2001) and North America (Hickler et al. 2004). Patches were treated as being independent. The model was run for each 100 m elevation with a replicate of 100 patches, using the following plant functional types: evergreen needle-leaved

shade-tolerant trees (represented by fir; *Abies alba*, and spruce; *Picea abies*), evergreen needle-leaved shade-intolerant trees (represented by pines; *Pinus* sp.), deciduous broadleaved shade-tolerant trees (represented by beech; *Fagus sylvatica*), deciduous broadleaved shade-intolerant trees (represented by birches; *Betula* sp.) and grasses. For the comparison with observations, the average carbon mass for total vegetation from the simulation of the period 1981–2000 was summarized into two classes: coniferous and deciduous trees.

Results

Forest change and carbon balance

Over the first 50 years of the study period (1925–1975), growing stock increased monotonically with rates of about 10% per decade from 359,000 m³ in 1925 up to 462,000 m³ in 1950 and 531,000 m³ in 1975, before dropping back to 492,000 m³ in 1999 (Fig. 2). Likewise but at lower rates, stem numbers increased from about 510,000 to almost 630,000 between 1925 and 1975. In the last 25 years, stem numbers declined, similarly to the growing stock, to numbers slightly above the levels of 1950. The average volume per tree increased gradually from 0.7 m³ in 1925 to 0.9 m³ in 1999.

Forest area remained constant at about 1,500 ha in the first period (1925–1950) and increased at a rate of 2% (or 30 ha) per decade to 1,660 ha in 1999 (Fig. 2). Stock density increased from 238 m³ ha⁻¹ in 1925 to almost 335 m³ ha⁻¹ in 1975 and was then reduced to 296 m³ ha⁻¹ in 1999.

Tree species composition remained largely unchanged during the entire study period (Table 3). Spruce was clearly

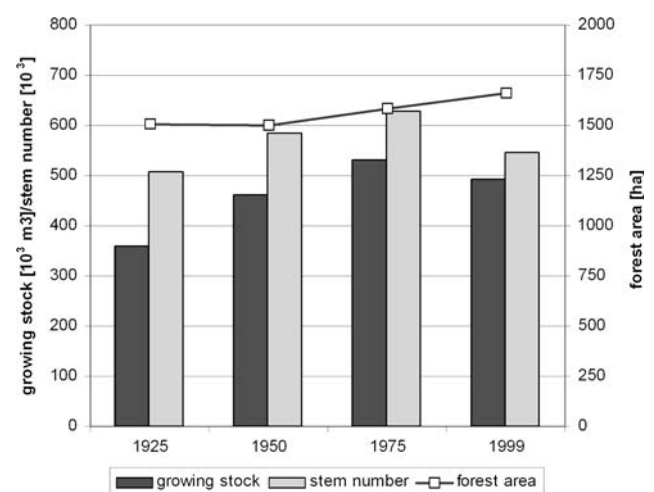
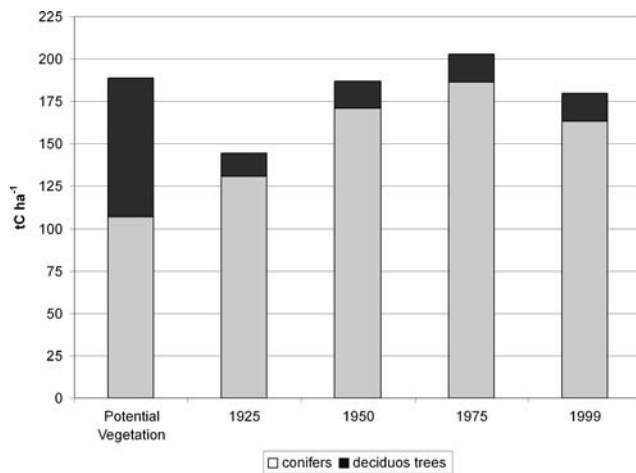


Fig. 2 Changes in growing stock and forest area from 1925 to 1999

Table 3 Changes in tree species composition as a percentage of total growing stock between 1925 and 1999

	1925	1950	1975	1999
Spruce (%)	76.3	79.5	77.9	75.3
Fir (%)	16.7	14.3	15.9	17.8
Other conifers (%)	0.0	0.0	0.2	0.2
Beech and other deciduous trees (%)	6.9	6.2	6.0	6.7

**Fig. 3** Comparison between carbon density of modeled potential natural vegetation and reconstructed historical vegetation

the dominant species at all time steps with a slight trend towards a dominance reduction in the last period.

Carbon density for the modelled potential natural vegetation was calculated to amount to almost 190 tC ha^{-1} (Fig. 3). This value can be interpreted as the maximum density that would be reached under natural conditions, i.e. it provides an upper bound for regional scale carbon stocks in natural vegetation under the current climate. By comparison, reconstructed historical carbon density increased from 144 tC ha^{-1} in 1925 (77% of long-term average potential natural vegetation) to 187 tC ha^{-1} in 1950 and, at a lower rate, to 202 tC ha^{-1} (108%) in 1975. However, by 1999 carbon density had declined again to 180 tC ha^{-1} (95%). The proportion of deciduous trees is substantially higher in the potential vegetation than in all time steps of the historical data, reflecting the strong human impacts on vegetation composition e.g., via the conifer-oriented planting regime (see below). Especially at lower altitudes in the Alptal, a much higher amount of beech would be expected under natural conditions (Frehner et al. 2005).

Overall, the studied forests of the Alptal, representing 70% of total forest area, acted as a net carbon sink by accumulating $0.66 \text{ tC ha}^{-1} \text{ year}^{-1}$ or more than 80,000 tC totally over the entire period. From 1925 to 1975, carbon accumulation amounted to $1.24 \text{ tC ha}^{-1} \text{ year}^{-1}$

(103,300 tC in total), whereas in the last period (1975–1999) forests turned into a carbon source as they lost almost 22,700 tC, or $0.57 \text{ tC ha}^{-1} \text{ year}^{-1}$.

Anthropogenic influences and natural disturbances

The main natural disturbances in the Alptal over the past 100 years were windthrow and bark beetle attacks, while other natural disturbances played only a minor role, with the exception of some notable damage caused by snow pressure. Until 1955, we only have quantitative information about total wood removals (Fig. 4a), which remained fairly constant with an average removal of about $5,000 \text{ m}^3 \text{ year}^{-1}$. Two storm events were reported for the years 1919 and 1925, whereby the qualitative descriptions and some rough quantitative estimation of these events given in the annual reports of the forest administration indicate low to medium damages compared to the storm events in the late twentieth century. Subsequent bark beetle infestations after the 1919 and 1925 storm events are not reported at all. This clearly indicates that for the period 1925–1950 natural disturbances were of minor importance compared to timber harvesting. In the period 1950–1975, annual wood removals were still relatively constant with an average of $7,000 \text{ m}^3 \text{ year}^{-1}$ (Fig. 4a). The largest part (85%) was removed by timber harvesting activities, whereas natural disturbances continued to be of relatively low importance (Fig. 4b–d). After 1975, the disturbance pattern changed strongly. The two peaks in total wood removal in the early 1990s and 2000s occurred as a consequence of large unplanned fellings due to two severe windthrow events (storms ‘Vivian’ in February 1990 and ‘Lothar’ in December 1999, Fig. 4c) and subsequent bark beetle damage (Fig. 4d). The winter storm ‘Vivian’ caused unplanned fellings of approximately $47,000 \text{ m}^3$ and the additional removal of almost $13,000 \text{ m}^3$ of wood damaged by bark beetle attacks in the following 5 years. Almost a decade later, storm ‘Lothar’ caused damages of almost $100,000 \text{ m}^3$ in the study area ($62,000 \text{ m}^3$ direct losses by storm and $33,000 \text{ m}^3$ subsequent insect damages). The annual amount of timber harvesting in the period 1975–1999 ranged between $5,000$ and $10,000 \text{ m}^3 \text{ year}^{-1}$ (Fig. 4b), except for years with large unplanned fellings when regular timber harvesting was reduced or even completely suspended.

Figure 5 shows the changes in growing stock between 1925 and 1999 according to stands with different levels of storm and insect damage caused by the Vivian event in 1990. The increment and the mean growing stock in heavily disturbed stands were enhanced in the period before the Vivian event (until time step 1975). In contrast, relatively undisturbed stands show low, but constant accumulation rates over the entire period (1925–1999).

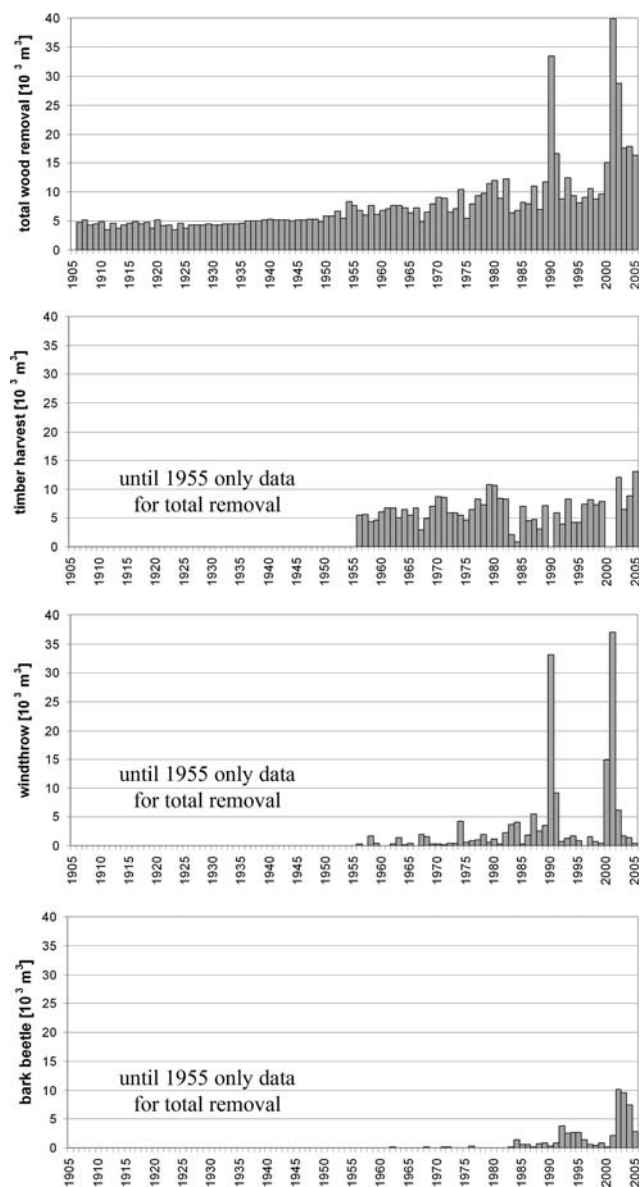


Fig. 4 Time series for **a** total wood removal (1906–2005), **b** timber harvest (1956–2005), and unregulated felling due to **c** windthrow and **d** bark beetle damages (1956–2005)

During the twentieth century, there were two main periods that featured large afforestations (Fig. 6). In the first decades of the twentieth century, large clearcut areas from the nineteenth century were afforested with spruce, fir and beech. Afforestation from the 1960s to the 1980s was executed as a compensation for clearcutting activities outside the valley, such as highway construction at the Swiss Plateau. For that purpose preferably small patches of wet meadows within the existing forest area were drained and planted predominately with spruce and several deciduous species.

Figure 7 synthesizes all time series by showing the anthropogenic and natural disturbances as well as changes

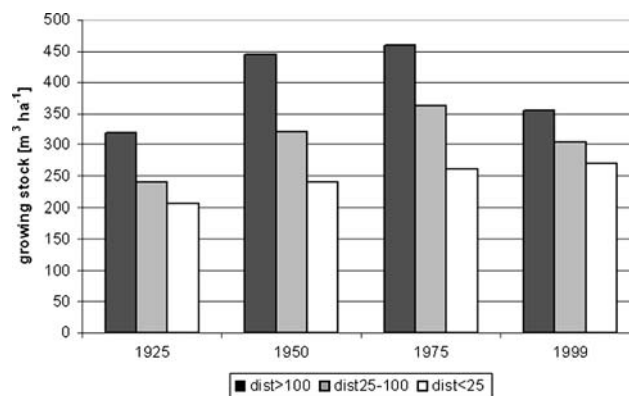


Fig. 5 Comparison of development in growing stocks between stands with high ($\text{dist} > 100 \text{ m}^3 \text{ ha}^{-1}$), intermediate ($25\text{--}100 \text{ m}^3 \text{ ha}^{-1}$) and low ($< 25 \text{ m}^3 \text{ ha}^{-1}$) wind and insect damage in conjunction with storm Vivian (cumulative damage storm and bark beetle)

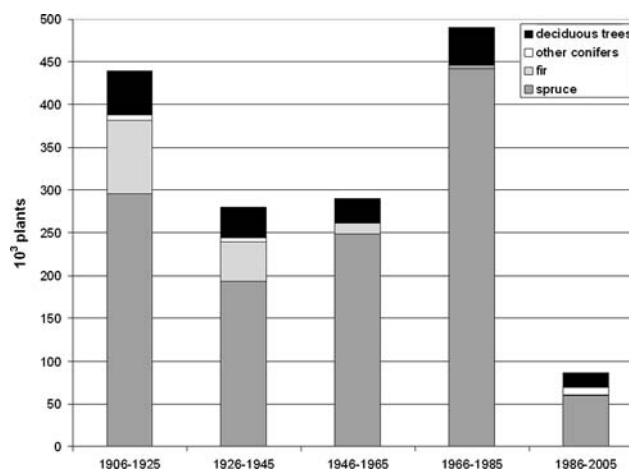


Fig. 6 Afforestations from 1906–2005

in forest area and tree growth as fluxes. For the first half of the twentieth century, tree growth was larger than tree removals, and as a consequence the growing stock increased. The subsequent large storm events and bark beetle attacks resulted in a decrease of the growing stock, as tree growth could not compensate for the amount of wood removed.

The typical trajectory of forest change in the Alptal can be visualized nicely by a series of photographs of the “Klosterwald” near Einsiedeln. The picture of 1893 (Fig. 8a) shows the forest after a large clearcut executed a decade earlier. At the beginning of the twentieth century, the area was reforested predominately with spruce. In 1977 (Fig. 8b), the Klosterwald appears as a dense spruce high forest. The recent photograph (Fig. 8c) documents the still visible traces of the Vivian and Lothar events and the considerably larger fraction of deciduous trees as compared to 1977.

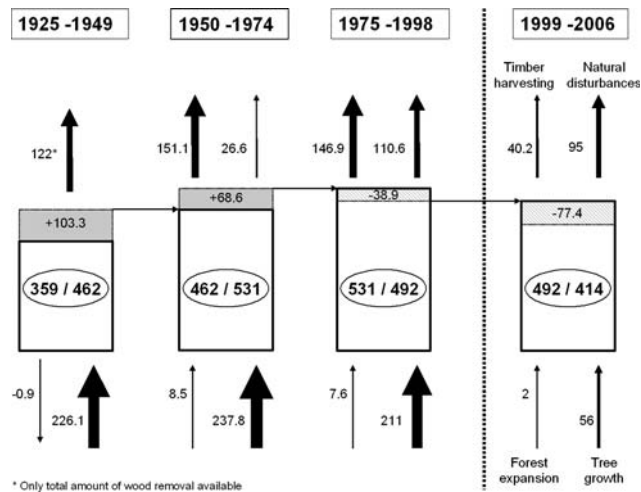


Fig. 7 Summary of historical changes in forest biomass and fluxes. The **bold line box** represents the standing volume at the start of the respective period. **Solid grey areas** indicate the net increase and **shaded grey areas** indicate the net decrease in standing volume for the respective time period. The absolute values for growing stock at the beginning and end of the respective period are given by the numbers in the ovals. Net change in standing volume is the result of tree growth (*right arrows and values below the boxes*), change in forest areas (*left arrows and values*); timber harvest and natural disturbances (*arrows and volumes above the boxes*). All values are given in 1,000 m³ biomass. Sizes of *boxes* and *arrows* are proportional to their values

Discussion

The substantial change in the growing stock and carbon accumulation from 1925 to 1975 was mainly a result of forest recovery from past human disturbances, and was driven largely by systematic forest management. The Alptal was an important wood reservoir for the city of Zurich starting as early as the sixteenth century (Bitterli 2004). Clearcutting was practiced until the late nineteenth century and the wood was floated on the Alp and Sihl rivers to the urban centers. Thus, the initial growing stock in 1925 was comparatively low as a consequence of these activities. The trees that were planted at the beginning of the twentieth century on clearcut areas gradually reached the calliper limit of 16 cm DBH around the middle of the twentieth century and thus began to appear in the statistics. The consistency of the forest management schemes is evident e.g., from the monotonous increase of the mean volume per tree. For economic reasons, forest managers used selective thinning methods with the aim of promoting trees with large diameters. In this period, there was a constant, but low anthropogenic disturbance due to the removal of wood, whereas the forest carbon budget was largely unaffected by natural disturbances (annual unplanned fellings between 1956 and 1975 amounted to less than 0.3% of the total growing stock), probably

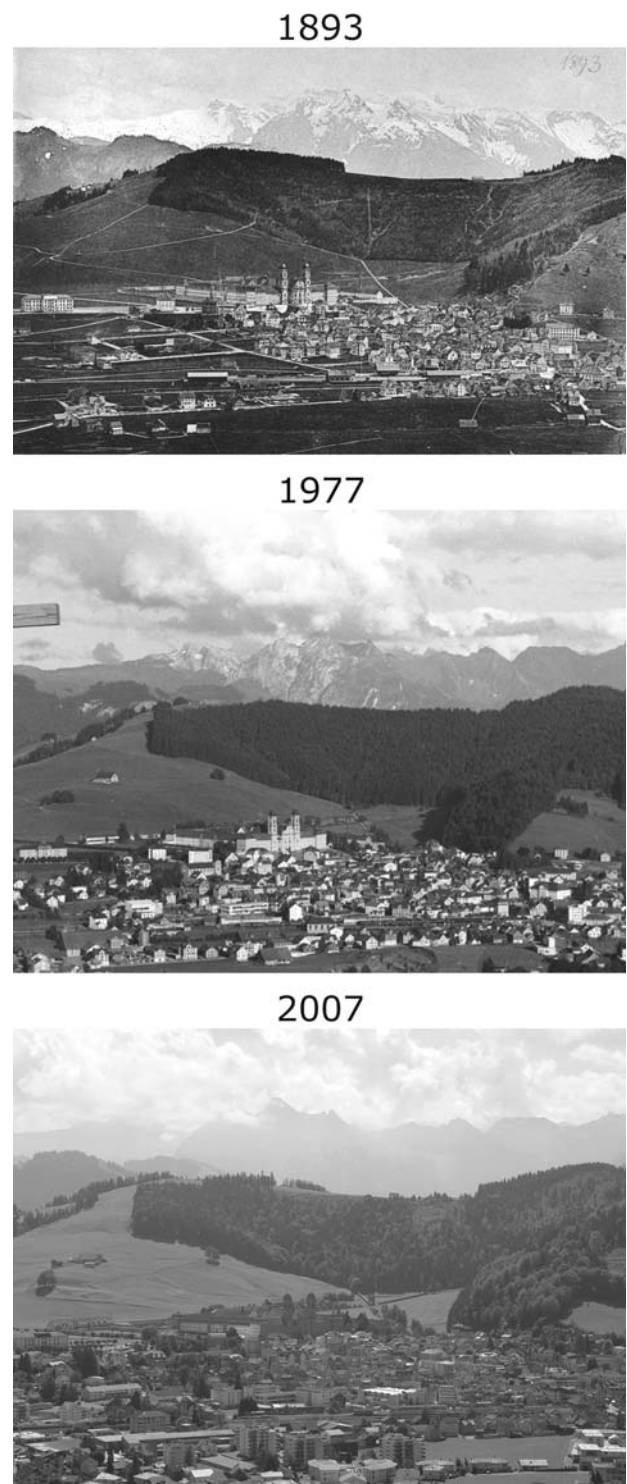


Fig. 8 Series of terrestrial photographs of the “Klosterwald” near Einsiedeln. **a** 1893: forest after clear cutting, **b** 1977: forest 50–70 years after reforestation and **c** 2007: current state with still visible traces of Vivian and Lothar

because highly susceptible stands were largely absent. Altogether these factors led to remarkably high accumulation rates of the growing stock and thus to a relatively

large carbon accumulation by forest vegetation in the first 50 years of the investigated period. The accumulation rates observed in the Alptal are two to three times higher than large scale inventory-based estimates for Eurasian temperate forests (Myneni et al. 2001) and European forests (Kauppi et al. 1992; Nabuurs et al. 2003). By 1975, reconstructed carbon densities in the forests of the Alptal reached values slightly above the model-based estimates for potential natural vegetation. These values are relatively high in comparison to studies at larger scales (Olson et al. 1983; Houghton et al. 2000; Luyssaert et al. 2007) but also at regional scale (Erb 2004; Gingrich et al. 2007). Our results show that local values for carbon accumulation and carbon densities can differ considerably from average values over larger areas as a consequence of local land-use history. In the case of the Alptal intensive forest uses in the nineteenth century led to a high proportion of young stands with a high potential of carbon accumulation in the beginning of the twentieth century.

In contrast to the first 50 years of the study period, large natural disturbances dominated the period from 1975 to 2006, i.e. windthrow and subsequent bark beetle damages. Damages caused by Vivian represented more than 11% of the total growing stock of 1975, but total growing stock was reduced only moderately from 1975 to 1999, as the losses from natural disturbances were largely compensated by high rates of tree growth in less affected stands, and by forest expansion. In December 1999, the study region was hit by a second heavy winter storm ('Lothar'), causing unplanned felling of almost 62,000 m³ and another 33,000 m³ from subsequent bark beetle infestations. We estimate the remaining growing stock to amount to about 414,000 m³, which is still 115% of the historical growing stock calculated for 1925 (Fig. 7). These natural disturbances differ in their character greatly from the lower, but constant wood removals due to forest management.

Areas with a high average growing stock and a high increment were particularly strongly affected by the Vivian event (Fig. 5). The large number of thick spruces (diameter ≥ 40 cm), which had been favored by forest management, probably made these areas more vulnerable to wind and insect disturbances (Schütz et al. 2006). This conforms with recent findings that, as a consequence of climate change, the frequency of storms and related insect outbreaks is likely to increase in the future (e.g., Fuhrer et al. 2006). However, forest susceptibility to wind storm damage is not only a result of high standing volume and fast increment but also a consequence of the interactions between several factors such as slope, aspect, soil properties, tree species composition, and forest management in the affected stands (Nilsson et al. 2004).

The substantial increase in growing stock in the first half of the twentieth century showed that forest management

can foster a fast increase of carbon stocks. Stands with low amounts of timber harvesting were found to have much lower rates of increment in growing stock than stands with medium amounts of timber harvesting where selective cutting aimed at the promotion of large diameter trees was practiced. Simultaneously, these practices apparently increased the vulnerability of forest stands to disturbances. Still, we suggest that although severe disturbance events have considerable short to medium-term effects on the local forest carbon budget, management is able to compensate for such losses within a relatively short time, i.e. a few decades at most. Therefore, forest managers need to adapt their management strategies in order to take into account the interactions between management effects and natural disturbances, particularly if the latter are to become more frequent.

Finally, the question remains to what extent historical carbon pools reflect potential carbon storage capacity and how big the future potential for additional carbon storage is in this region. The ecosystem model LPJ-GUESS estimated the carbon budget for potential natural vegetation, which means that it did not include any management and assumed a moderate disturbance of 1% year⁻¹. Particularly the effects of large clearcuttings from the nineteenth century were not taken into account by the ecosystem model. Thus, the historical carbon stock in 1925 was considerably below the values for the potential vegetation, indicating a large sink capacity as biomass was low due to past management. Within the first 50 years of the study period historical carbon stocks exceeded the modelled carbon storage capacity. The surpassing beyond the modelled storage capacity could be due to the tendency of models to generalize and consequently models are often not able to grasp peak values, such encountered in the Alptal in the 1975 data. Despite carbon losses due to large storm events future potential for further carbon accumulation seems to be strongly limited in the Alptal, at least under current climatic conditions. The results highlight the importance of taking past disturbance and management regimes into account when we use models to estimate the change in carbon storage across the twentieth century. Lastly, if storm frequency or management will change in the future, the model would have to take these drivers into account in the form of scenarios to provide an accurate depiction of future trajectories of carbon storage in the Alptal.

Conclusions

Our study shows that historical sources provide rich material for quantifying the forest carbon budget and assessing the historical range of variability of forest

ecosystems. The increase of growing stock density and, to a lesser extent, the expansion of forest area led to a significant net carbon accumulation during the last 75 years in the Alptal. Recovery from past human disturbances, systematic forest management and the absence of major natural disturbance events are identified as the main underlying processes of increasing vegetation carbon stocks until 1990. Two large storm events and subsequent bark beetle infestations in the 1990s significantly reduced current stocks again to levels comparable with the mid-twentieth century.

Our results have a number of implications in the context of assessing the future dynamics of carbon stocks at the regional scale. While it is clear that carbon accumulation can be achieved either through the extension of the forest area or through the increase of growing stock density, it is a non-trivial issue to decide how to accomplish such a goal in a given landscape. In the Alptal example, forest area is high already (almost 60% of the productive area), and thus a substantial forest expansion would be possible only by reducing either agricultural land or ecologically valuable areas such as wet meadows. Thus, any efforts in this direction would inevitably clash with the interests of farmers, local tourism, and/or environmentalists. However, enhancing the growing stock density on the existing forest area would make forests more susceptible to wind and insect disturbances, and such events are more likely to occur under future climate conditions, thus strongly increasing the risk of destroying carbon storage. Therefore, we conclude that the potential for a substantial carbon accumulation is strongly limited for regions such as the Alptal, as forest recovery after unsustainable forest uses of the nineteenth century seems to approach equilibrium with the natural disturbance regime.

Consistent long-term observation of carbon stocks and their changes are extremely rare; using such historical information can greatly assist in improving models of terrestrial biogeochemical cycles (Friedlingstein et al. 2006). The detailed data presented here allow for a refined initialization of the models, and the high-resolution information on management and disturbance regimes enable us to better validate the models, which is a prerequisite for making robust reconstructions of the past (e.g., regional scale changes in carbon fluxes) as well as for extrapolating future changes in carbon stocks.

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