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Carbon storage versus albedo change: Radiative Forcing of forest expansion in temperate mountainous regions of Switzerland

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Abstract

Forestation is seen as a possible option to counter climate change by sequestering carbon in forests and thus reducing the atmospheric concentration of carbon dioxide. However, previous studies suggest that the Radiative Forcing (RF) caused by forestation-induced albedo change in snow-rich boreal regions may offset the carbon sequestration effect. The Swiss mountains are characterized by snow-rich areas with strongly varying environmental conditions and forest expansion is currently the dominant land-use change process. Thus, quantifying both carbon sequestration and albedo change on appropriately high resolution in this region will improve our understanding of the forests potential for climate mitigation. We calculated the albedo RF based on remotely sensed datasets of albedo, global radiation and snow cover. Carbon sequestration was estimated from changes in carbon stocks based on National Inventories. Our results show that the net RF of forest expansion ranges from $-24\,\mathrm{W\,m^{-2}}$ at low elevations of the Northern Prealps to $2\,\mathrm{W\,m^{-2}}$ at high elevations of the Central Alps. The albedo RF increases with increasing altitude, which offsets the CO_2 RF at high elevations with long snow-covered periods, high global radiation and low carbon sequestration. Results indicate that the albedo RF is particularly relevant during transitions from open land to open forest and not in later stages of forest development. The albedo RF offsets the CO_2 RF by an average of 40 % between 1985 and 1997 when overall forest expansion in Switzerland was approximately 4 %. We conclude that the albedo RF should be considered at an appropriately high resolution when estimating the climatic effect of forestation in temperate mountainous regions.

1 Introduction

The United Nations Framework Convention on Climate Change (UNFCC) declared in the Kyoto Protocol (Decision 11/CP.7) that changes in the carbon stocks of ecosystems, induced by LULUCF (Land Use, Land Use Change and Forestry) activities can

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be included in the greenhouse gas emission budget of the signatory nations (UNFCC, 2001). Beside biogeochemical processes, LULUCF also influences biogeophysical processes (Betts, 2011, Bonan, 2008), but these effects are not yet considered in current climate policies.

Global climate models suggest that biogeochemical and biogeophysical effects vary greatly with latitude (Schaeffer et al., 2006; Bala et al., 2007; Bathiany et al., 2010; Davin and de Noblet-Ducoudre, 2010; Arora and Montenegro, 2011). In the tropics, biogeochemical and biogeophysical effects tend to act in the same direction, since tropical forests cool climate through both evaporative cooling and carbon sequestration (Costa and Foley, 2000; Gibbard et al., 2005). However, at middle and high latitudes, biogeophysical processes tend to counter the biogeophysical effect (Gibbard et al., 2005; Betts, 2000; Govindasamy et al., 2001), thus making the net LULUCF effect more challenging to assess. Indeed, forestation in boreal regions lowers the albedo and thus counterbalances the cooling effect of carbon storage.

Global climate models are important for understanding the climatic processes related to LULUCF and for quantifying the impacts on climate of forestation or deforestation over large areas. However, in highly heterogeneous landscapes such as mid-latitude mountain ranges, global climate models are limited by their relatively coarse resolution, and the concept of Radiative Forcing (RF) (Myhre et al., 2013) can provide a useful alternative. The RF concept has already been employed to investigate the balance between biogeophysical (mainly albedo) and biogeophysical effects following forestation or deforestation. While some studies suggest that albedo RF can completely offset CO_2 RF (Betts, 2000; Bernier et al., 2011; de Wit et al., 2013), others have found that the offset is rather small (e.g. Montenegro et al., 2009; Kirschbaum et al., 2011). The offset seems to vary widely depending on the regional characteristics of the determining variables: global radiation, snow-cover, albedo change and carbon sequestration. These factors vary greatly, but little research has focused on how each of them influences RF (Kirschbaum et al., 2011), and only few attempts have been made to quantify RF in a spatially explicit way (e.g. Betts, 2000; Montenegro et al., 2009). Betts

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(2000) estimated spatially explicit RF data on a resolution of 3.75° longitude by 2.5° latitude. Montenegro et al. (2009) performed their analysis on a resolution of 5 to 25 km. However, RF varies on much smaller scales. Moreover, decisions in regional planning are usually based on very local and regional information. Consequently, it is crucial to quantify RF at finer resolutions.

Forest cover has increased in many temperate mountainous regions (Alewell and Bebi, 2011; MacDonald et al., 2000; Ramankutty et al., 2010; Kozak, 2003; Hagedorn et al., 2014) and analysis of LULUCF change in the Alps suggest that changes in forest cover near the tree-line will further increase (Gehrig-Fasel et al., 2007). Some of the effects of this increase on various ecosystem services are already relatively well known (MacDonald et al., 2000; Laiolo et al., 2004; Bolliger et al., 2008) and have increasingly been considered in management strategies and subsidizing systems for agriculture and forestry (e.g. Gret-Regamey et al., 2013). However, few attempts to quantify RF in such regions have been made, even though snow-cover and hence albedo in temperate mountains varies greatly. To optimize the effects of future land-use decisions, further research on the climatic impacts of forests is essential and should be included in spatially explicit valuation methods (Bebi et al., 2012).

Switzerland is a particular suitable study area for researching the effects of changes in forest cover, since forest expansion is an ongoing dominant process of land-use change and many high quality datasets are available. Forest cover is expanding by 4 % per decade at the country scale and by 8 % per decade in alpine areas (NFI). The spatially explicit data series available are on land use/land cover (1 ha raster), snow cover (1 km), global radiation (2.2 km), albedo change and carbon sequestration (both explicit for biogeographical regions) for the whole area of Switzerland, to estimate (i) to which extent albedo RF offsets CO_2 RF in different parts of temperate mountainous regions, (ii) how each input parameter influences RF, and (iii) what the inclusion of albedo change implies for the greenhouse gas inventory in Switzerland.

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2 Data and methods

2.1 Study area

Switzerland covers an area of 41 284 km^2 and can be divided into five biogeographical regions (Fig. 1). Each region has biogeographical features that can be found globally at temperate latitudes:

(1) Jura, oceanic low mountain range, elevations averaging 800 m a.s.l.; (2) Plateau, oceanic lowlands, elevations averaging 550 m a.s.l.; (3) Northern Prealps, oceanic subalpine mountain range, elevations averaging 1400 m a.s.l.; (4) Central Alps, continental alpine mountain range with elevations averaging 2150 m a.s.l.; (5) Southern Prealps, mediterranean/insubric subalpine mountain range, elevations averaging 1500 m a.s.l. In each region, deciduous forests and mixed deciduous forest dominate at low elevations (mostly *Fagus sylvatica*), while coniferous forests are dominant at higher elevations (mostly *Picea abies*).

The Swiss landscape was strongly affected by several centuries of intensive human land-use (Bürgi and Schuler, 2003; Schneeberger et al., 2007; Gimmi et al., 2009) followed by the widespread abandonment of marginal agricultural land and the subsequent expansion of forest cover since the end of the 19th century (Baur, 2006). Due to unfavorable pedologic and climatic conditions and high slope angles, marginal land and forest expansion are mainly found at higher elevations (Baur, 2006). Tree line is often the result of former land use, but also depends on various climatic factors and is generally higher in the central Swiss Alps (approx. 2100–2300 m) than in the Northern and Southern Prealps (approx. 1800–2000 m) (Fig. 3f and Körner, 2012).

2.2 Land use/land cover (LULC) change

We use aerial photographs processed by Swiss Statistics at a spatial resolution of 100 m to derive changes in land use. These aerial photographs are from the Swiss Federal Office of Topography and are fully available for the two inventory periods 1979–

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1985 and 1992–1997 (Humbel et al., 2010). We reclassified the data of the different inventory periods into five aggregated classes (Rutherford et al., 2008). While 18 classes were aggregated into four classes: Closed Forest, Open Forest, Extensively and Intensively Used Open Land (Fig. 2), the remaining 56 were classified as Other, and consisted mainly of settlements, water and non-vegetated land.

To calculate RF of land use change between 1985 and 1997, we included five transitions: (1) Intensively Used Open Land → Closed Forest, (2) Extensively Used Open Land → Closed Forest, (3) Intensively Used Open Land → Open Forest, (4) Extensively Used Open Land → Open Forest and (5) Open Forest → Closed Forest. We focused on transitions where forest cover and carbon stocks increase, because these transitions highly exceeded transitions with forest decrease in Switzerland. In fact, the Swiss law strongly protects forests so that there have been only few changes from forest to agriculturally used land during the last 30 years (Bloetzer, 2004; Rutherford et al., 2008).

2.3 CO_2 RF

An increase in carbon stocks in terrestrial ecosystems is related to a sink of atmospheric CO_2, followed by a change in the earth's radiation balance. Myhre et al. (1998) developed a parameterization to derive RF, related to a change in the CO_2 concentration in the atmosphere, based on radiative transfer schemes:

$$\Delta\mathrm{RF}(t) = 5.35 \ln \frac{C(t)}{C_0}, \tag{1}$$

where ΔRF(t) is the radiative forcing, $C(t)$ is the atmospheric CO_2 concentration after perturbation and C_0 is the unperturbed atmospheric CO_2-concentration. Equation (1) can be solved if the CO_2 concentration in the atmosphere after perturbation is known.

Following Switzerland's Greenhouse Gas Inventory 1990–2010 (Heldstab et al., 2012), which is based on the Good Practice Guidance for Land Use, Land Use Change and Forestry (IPCC, 2003), we calculated the carbon stock changes resulting from land-use changes as the differences between the carbon stocks of the land-use categories before and after a transition. This takes into account changes in living plant biomass, dead wood and soil carbon stocks.

Data on carbon stocks in the living biomass and dead wood of closed forests and open forests was derived from the third National Forest Inventory (NFI) (Brändli, 2010). The data is based on 6608 field plots measured on a regular sampling 1.4 × 1.4 km grid from 2004 to 2006. Two concentric circles with 200 m^2 in size are used for trees with 12 cm ≤ diameter at breast height (DBH) < 36 cm, and 500 m^2 in size for trees with DBH ≥ 36 cm. This results in DBH measurements of approximately 11 trees per plot. On a sub-sample of approximately two trees per plot, the diameter at 7 m tree height and the tree height are measured. The biomass of all single trees is estimated according to allometric functions. The assessment of stem-wood over bark, including stock, coarse branches (≥ 7 cm) and small branches (< 7 cm) is based on Kaufmann (2001), and that of needles/leaves on (Perruchoud et al., 1999). Roots are estimated with equations from Wirth et al. (2004) for coniferous trees and Wutzler et al. (2008) for deciduous trees. Estimates for branches, foliage and roots were derived from the DBH only, while for stem-wood over bark including stock the diameter at 7 m tree height and the total tree height were also required (Kaufmann, 2001). For this study, only living trees were considered. The NFI data was stratified for each biogeographical region of Switzerland and three elevation strata (Appendix Table A2). Open Forest is represented by forest plots permanently reduced in stocking, and Closed Forest by all forest plots minus plots permanently and temporarily reduced in stocking.

The estimates of soil carbon stocks were taken from previous assessments in approximately 1000 soil profiles in forests (Hagedorn et al., 2010; Nussbaum et al., 2012) and 500 soil profiles in open land across Switzerland (Leifeld et al., 2005; Bolliger et al., 2008), where each soil profile in the forest had been sampled according to horizons analyzed for their C content using a C/N analyzer. The bulk density and volumetric stone content measured, were used to calibrate pedotransfer functions. The carbon stock changes in soils were calculated as the differences between the stocks of different

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LULC classes. Since soil carbon stocks in agriculturally used open land and forest correlate fairly well across different altitudes (Sjörgersten-Turner et al., 2011), we decided to use the difference between mean soil carbon stocks in open land and forest for the whole Switzerland.

Changes in carbon stocks in ecosystems can be related to changes in atmospheric CO_2 concentrations by including the molecular masses of carbon, dry air and the mass of the atmosphere (Schwaiger and Bird, 2010; O'Halloran et al., 2012):

$$\Delta C_\mathrm{A} = \frac{\Delta m_\mathrm{C} M_\mathrm{a}}{M_\mathrm{C} m_\mathrm{a}}, \tag{2}$$

where ΔC_A is the change in atmospheric CO_2 concentration, Δm_C the mass of carbon sequestrated in ecosystems (assuming an equilibrium before and after a change in LULC), M_C is the molecular mass of carbon, m_a is the mass of the atmosphere and M_a is the molecular mass of dry air. Before using this CO_2 value (ΔC_A) to calculate ΔRF (Eq. 1), we took into consideration the fact that each CO_2 pulse emitted to the atmosphere disappears partly in sinks of the global carbon cycle (e.g. ocean). A carbon pulse response function can be used to describe such fluxes (Forster et al., 2007):

$$\mathrm{fr}(t) = a_0 + \sum_{j=1}^{3} a_i e^{\frac{-t}{\tau_j}}, \tag{3}$$

where $\mathrm{fr}(t)$ is the fraction of a CO_2 pulse, which can still be found in the atmosphere after time t. Generally the coefficients a_0 to a_3 and τ_1 to τ_3 have no direct process-based meaning, but are fitting parameters chosen to represent a given model-based carbon-pulse response function (Joos et al., 2013). CO_2 sequestration equals negative CO_2 pulses (CO_2 removal from atmosphere). The carbon-pulse response function can be applied to negative pulses because a reduced CO_2 concentration in the atmosphere will reduce the amount of CO_2 sequestrated by the terrestrial biosphere and oceans. To estimate how much carbon dioxide from continuous CO_2 pulses after time

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t stays airborne, a widely used convolution function can be applied (Siegenthaler and Oeschger, 1978; Cherubini et al., 2011):

$$C(t) = \int_0^t g(t')y(t-t')\mathrm{d}t', \tag{4}$$

where $C(t)$ stands for the yearly change in the carbon dioxide in the atmosphere that can be exclusively related to carbon sequestration during forest expansion, $g(t')$ characterizes the carbon sequestration due to forest expansion, depending on the gradient of CO_2 uptake during succession and $y(t-t')$ accounts for the reduced uptake of carbon dioxide in the carbon cycle. We estimate the integral using a simple numerical approximation and time intervals of 1 year:

$$C_t = \sum_{i=1}^{t} g_i y_{t-i}. \tag{5}$$

We kept the background CO_2-concentration fixed to solve the radiative transfer parameterization (Eq. 1) and accordingly used parameters that describe carbon sequestration in the carbon cycle for a fixed CO_2 background concentration. The CO_2 concentration and parameters for the carbon cycle will, however, change (IPCC, 2001) and it is not clear whether it is necessary to take these changes into account. Joos et al. (2013) showed that Radiative Forcing was more or less constant when CO_2 pulses were emitted to atmospheres with different CO_2 background concentrations. They suggest that not only does the carbon uptake per unit atmospheric CO_2 decrease with a high background concentration of CO_2, but so too does the RF per unit change in atmospheric CO_2. They both decrease in such a way that RF of a CO_2-emission is almost identical at preindustrial and present day conditions. Keeping background CO_2 concentrations and carbon cycle parameters constant thus seems a reasonable approximation.

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2.4 Albedo RF

The yearly Radiative Forcing $\Delta\mathrm{RF}(t)$ of an albedo change is calculated (modified from Montenegro et al., 2009) as the seasonal average:

$$\Delta\mathrm{RF}(t) = \frac{1}{12}\sum_{t=1}^{12} I_t\,\Delta\alpha_t - 0.23\,I_t\,\Delta\alpha_t, \tag{6}$$

where I_t is the monthly global radiation, $\Delta\alpha_t$ is the albedo difference between two LULC classes depending on the monthly fraction of snow-cover and 0.23 is a factor to account for the absorption of the reflected radiation in the atmosphere. The first part of Eq. (6) describes which part of the global radiation is absorbed at the surface. The second part describes which part of the reflected shortwave radiation is absorbed in the atmosphere. The factor of 0.23 is that used by Montenegro et al. (2009) who modified the value 0.3 given by Weaver et al. (2001).

We used gridded global radiation data from MeteoSwiss (MeteoSwiss, 2012) in monthly datasets averaged over the period from 2004 to 2010 to eliminate inter-annual variability. The spatial resolution of the global radiation datasets is 2.2 km. The derivation of the global radiation data was based on the Heliosat method (Cano et al., 1986; Beyer et al., 1996; Hammer et al., 2003), applied to Meteosat SEVIRI data. It was verified using high-quality surface measurements and sensitivity runs for key input parameters (Durr et al., 2010). The albedo was estimated using the following equation (Barnes and Roy, 2010; Roesch et al., 2002):

$$\Delta\alpha(t) = f(t)\Delta\alpha_\mathrm{s} + (1 - f(t))\Delta\alpha_v, \tag{7}$$

where $\Delta\alpha(t)$ is the monthly albedo-difference between two LULC classes, $\Delta\alpha_\mathrm{s}$ the seasonally averaged albedo difference between two LULC classes when snow-covered, $\Delta\alpha_v$ the seasonally averaged albedo difference between two LULC classes when snow-free and $f(t)$ the fraction of snow-cover per month. The seasonal variation of

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the albedos of different land-use classes is very similar. Thus, seasonally averaging snow-covered and snow-free albedo differences results in a fairly good approximation.

Monthly datasets on snow-cover were provided by the Remote Sensing Research Group at the University of Bern. Raw 1 km data from AVHRR (Advanced Very High Resolution Radiometer) was processed using an algorithm to estimate the snow cover (SPARC – Seperation of Pixels using Aggregated Rating Over Canada). The algorithm was adapted to the mountainous region of the European Alps and verified (Hüsler et al., 2012). Again we calculated an average value for each month using data of the years 2002–2009 to eliminate inter-annual variability.

For assigning albedos to different LULC classes, we overlaid NASA's MODerate-resolution Imaging Spectroradiometer (MODIS) 0.5 km BRDF/Albedo Product – MCD43A and gridded 0.1 km LULC data from the Swiss Area Statistics aggregated into five categories (see Sect. 2.2). We used MODIS data between 2004 and 2009 and the Area Statistics from the third inventory period 2004–2009 to ensure a temporal overlap between the albedo and the LULC records. Since not all the LULC data for south-eastern Switzerland is available yet, we complemented the Area Statistics (2004–2009) with data from the second inventory period (1992–1997) and accepted a temporal displacement for this region.

We applied several different methods for calculating land use specific albedos. First, we retained albedo pixels of the highest quality (full BRDF inversion) for our analysis. To reduce the error caused by assigning albedo values to a mixed pixel (several 0.1 km LULC classes in one 0.5 km albedo pixel), we only assigned albedo values to a specific LULC class if at least 92 % of the albedo pixel were covered by just one LULC class (similar to Kvalevag et al., 2010). The threshold of 92 % (23 out of 25 pixels) is a trade-off between using as many albedo pixels in the study area as possible and at the same time reducing the error due to 8 % random land cover (2 out of 25 pixels). If not enough pixels covered by at least 92 % of one LULC class were available, we applied additional methods to calculate specific albedos, accepting the trade-off of using more pixels, but with less quality. For the first step, we included albedo values of

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lower quality produced with magnitude inversion (Liu et al., 2009). If still not enough pixels were available, we changed the cell size of the Area Statistics to 0.5 km (according to the most frequent LULC class within a pixel) and assigned albedo values to this new LULC dataset. To estimate Closed Forest albedos, we only used pixels of at least 92 % land cover and best quality (full BRDF inversion). Open Forest values were mainly calculated using lower quality values (magnitude inversion) and the resampled pixels (Appendix Table A1). For Extensively and Intensively Used Open Land, we used the average albedo values for the whole study area because it was not possible to derive specific values for each region (For example, Extensively Used Open Land hardly occurs below 600 m a.s.l. and Intensively Used Open Land hardly occurs above 1200 m a.s.l.). We accepted a bias of open land albedos in these regions since they were usually not important for LULC change. For instance, LULC change below 600 m involves almost exclusively Intensively Used Open Land.

The MCD43A product is online available for free. It provides atmospherically corrected gridded albedo data for a variety of spectrums. We used broadband white-sky albedo (0.3–5.0 µm). In order to distinguish between snow-covered and snow-free areas, we applied the quality flags of the MODIS product MCD43A2. The albedo product MCD43A3 has been produced applying the MODIS BRDF/Albedo algorithm (Strahler et al., 1999). This algorithm makes use of 16 days worth of multi-date data from both the Terra and Aqua platforms and a semiempirical kernel-driven bidirectional reflectance model to determine a global set of parameters describing the BRDF (Bidirectional Reflectance Distribution Function) of the land surface (Schaaf, 2010).

2.5 Temporal signature of RF

Both, albedo RF and CO_2 RF are a function of time. The annual variation of CO_2 RF depends on the carbon pulse response function and the yearly carbon sequestration in biomass and soil during succession. The annual variation of albedo RF depends on the albedo change during succession. For both, carbon sequestration and albedo change we had to rely on the static difference between land-use classes e.g. open

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land (as starting point) and closed forests (end of succession). We assumed that carbon sequestration as well as albedo change follow linear trends until they reach an approximately steady state. Since a detailed description of the temporal evolution of albedo-change and carbon sequestration is complex and varies with location, we used a simplified scheme in which we assumed that albedo change completes after 30 years, carbon sequestration in biomass after 50 years and carbon sequestration in soils after 100 years. This seems to be a reasonable approximation since albedo change is likely to end before carbon accumulation in biomass does (Kirschbaum et al., 2011; de Wit et al., 2013) and carbon sequestration in soils will most likely not end before 100 years (Poeplau et al., 2011). We assumed that albedo-change and carbon sequestration stop after a certain time. However, interactions with the global carbon cycle will still cause changes in the atmospheric CO_2-concentration. Thus, we compared the temporal mean of Radiative Forcing for two different time horizons, 100 and 1000 years. For the representation of our results, we chose the mean RF in 100 years. The temporal average of RF is not only useful when representing spatial variability, but also for a comparison with earlier studies on spatial variability of RF, which did not explicitly include temporal variation (Betts, 2000; Montenegro et al., 2009).

2.6 Spatial variability of RF and RF of Swiss forest expansion

We calculated the net RF and the offset of CO_2 RF through albedo RF ($\Delta RF_{CO_2}/\Delta RF_{albedo}$) to show the spatial variability of RF in Switzerland and to calculate RF of Swiss forest-cover expansion between 1985 and 1997. To illustrate the spatial variability of RF in Switzerland we calculated a value of RF for every location in Switzerland, excluding non-vegetated land, water, settlement and areas that lie above the tree line (Fig. 3). These are hypothetical values, because we calculated RF for the change from open land to forest for all vegetated areas, and not only for the ones where forest expansion was actually observed. At lower elevations, transitions from Intensively Used Open Land to forest are frequent, while in higher elevations transitions are almost exclusively from Extensively Used Open Land to Forest. We considered this

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by separating our estimation of the hypothetical RF in transitions from Intensively Used Open Land to forest below 1000 m and transitions from Extensively Used Open Land to Forest above 1000 m. The results of the spatial variability of RF are shown in maps of the study area (Fig. 4c and d).

To obtain results for RF of forest-cover expansion between 1985 and 1997 in Switzerland we calculated net Radiative Forcing as the sum of RF for all pixels where forests expanded. This meant including information on the type of forest expansion and on the location of forest expansion:

$$\Delta \mathrm{RF}_{\mathrm{ges}} = \frac{\sum_{x=1}^{n} \mathrm{RF}_{x,T}}{A_{\mathrm{E}}}, \quad (8)$$

where $\Delta\mathrm{RF}_{\mathrm{ges}}$ is the net Radiative Forcing (net RF), n the number of pixels where forests expanded and RF the Radiative Forcing, which depends on the location x and the type of transition T. The sum over RF is devided by the the earth's surface A_{E} to convert local RF into a global average RF.

2.7 Sensitivity analysis

In a sensitivity analysis we tested how the spatial variability and uncertainty of each input factor influence our results. We based the sensitivity analysis on FAST (Fourier amplitude sensitivity test), developed by Saltelli et al. (1999), and used an implementation (fast99) provided in the R package "sensitivity" (Pujol et al., 2014). Applying a sensitivity analysis with FAST allowed us to show how varying input factors influenced the variance of the output including first order effects and interactions for each parameter. We approximated input as either uniform or normal distributed, according to the distribution of each input factor in the study area. We assumed input factors were uncorrelated, which only holds to a certain degree since e.g. all factors either increase or decrease with elevation. We separated our sensitivity analysis into two parts. First, we applied data on spatial variability. Each of the factors, carbon sequestration,

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snow-cover, global radiation, albedo difference (snow-covered) and albedo difference (snow-free) vary spatially and temporally. We averaged every input factor temporally and applied the spatial minimum and maximum of each factor to the function fast99 (Appendix Table A3). The minimum and maximum of snow-covered albedo differences are e.g. 0.208 (Alps 600–1200) and 0.375 (Jura > 1200). This analysis showed which factor had the greatest influence on the variation in RF caused by change in forest cover at a specific location. In a second sensitivity analysis, we applied the uncertainty values of each factor (for uncertainties, see Appendix Table A3). The sensitivity analysis of uncertainties, represented by random sampling and measurement errors, indicates which parameter causes high or low uncertainty in the output.

3 Results

In the forest, average C stocks in biomass ranged from 95 to 170 t C ha^{-1} (NFI). In the soil (mineral soil 0–100 cm + organic layer) the average across Switzerland was 143 t C ha^{-1} (Nussbaum et al., 2012). In the Intensively Used Open Land, the average value for biomass was 4.34 t C ha^{-1} (Heldstab et al., 2012) and 91 t C ha^{-1} in the soils. In comparison, the C stocks of the Extensively Used Open Land amounted to 7 t C ha^{-1} in the biomass and 63 t C ha^{-1} in the soil. Minimum and maximum carbon sequestration in Switzerland of transitions from Intensively or Extensively Used Open Land to Closed Forest thus ranged from 143 to 241 t C ha^{-1} (Fig. 3e). This corresponded to a CO_2 RF of −16 to −27 W m^{-2} (Fig. 4b).

The albedos of snow-covered Closed Forest ranged from 0.168 to 0.267, while those of snow-free Closed Forests ranged from 0.101 to 0.139. Similarly, the albedos of snow-covered Open Forest ranged from 0.217 to 0.307 and those of snow-free Open Forests from 0.117 to 0.141 (Appendix Table A1). The average albedo of Intensively Used Open Land was 0.170/0.475 (snow-free/snow-covered) while that of Extensively Used Open Land was 0.154/0.549 (snow-free/snow-covered). The albedo differences between transitions from Intensively or Extensively Used Open Land to Closed Forest

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thus ranged from 0.208 to 0.375 (snow-covered) and from 0.023 to 0.066 (snow-free) (Fig. 3c and d). Albedo change in Switzerland caused albedo RF ranging from 2 to 21 $\mathrm{W\,m^{-2}}$ (Fig. 4a).

The net RF at different locations in the study area ranged from $-24\,\mathrm{W\,m^{-2}}$ to $2\,\mathrm{W\,m^{-2}}$ and the offset of CO_2 RF caused by albedo RF differed between 11 and 109 %. The differences were particularly marked on an elevational gradient and between the 5 bioregions. Below an elevation of 600 m a.s.l., the albedo RF offset CO_2 RF by 15 % on average. Between 600 and 1200 m, the offset was 22 % and above 1200 m 54 %. The highest RF was observed in high snow-rich alpine regions. In the Central Alps, 13 % of all possible LULC areas had an offset of more than 80 %. In the Southern Prealps 7 % of all possible LULC areas had an offset higher than 80 %. In the Central Alps as well as in the Southern Prealps we found areas where net RF was positive. However, these areas amounted to less than 0.2 % of both regions. We only found positive RF at elevations above 1850 m. The albedo RF was lowest in the Plateau region and at low elevations of the Jura. Albedo RF accounted, on average, for less than 14 % of the CO_2 RF in these regions. The lowest net RF (average $-20\,\mathrm{W\,m^{-2}}$) was found in the Northern Prealps below 1200 m. Above 1200 m the net RF in the Northern Prealps was lower than in Southern Prealps and Central Alps, although the snow-cover in the Northern Prealps was persistent. However, the effect of a persistent snow-cover in the Northern Prealps was outweighed by the low global radiation, the low tree line and the high carbon sequestration in this alpine region (see Fig. 3).

The net RF forcing of forests across the mountainous terrain in Switzerland strongly depended on the elevation (Fig. 5). The albedo RF increased with altitude, with several factors contributing to this increase (Fig. 3). First, global radiation increased with altitude, reaching maxima in continental parts of the Alps. Second, albedo (snow-free, snow-covered) of forests was in general lower above 1200 m a.s.l. (where coniferous species dominate). Third, both snow cover and snow cover period strongly increased with altitude. The carbon sequestration potential of forests decreased with altitude (due to unfavorable climatic conditions towards tree line).

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Radiative Forcing depended not only on location, but also on the type of LULC transition. LULC transitions from Open Land to Open Forest had a higher offset (approx. 80 %) than transitions from already established Open Forest to Closed Forest (approx. 40 %.). Transitions from Open Forest to Closed Forest were generally associated with relatively high amounts of carbon sequestration (around 70 t C ha^{-1}), and relatively small albedo change (for snow-covered albedo < 0.06 and for snow-free albedo < 0.01).

Between 1985 and 1997, all five types of LULC transitions (Fig. 2) took place on an area of 24000 ha. More than 70 % of them were situated above 1000 m. Above 1000 m, the most frequent transition was the one from Open to Closed Forest (50 %), followed by transitions from Extensively Used Open Land to Open Forest (20 %) and from Extensively Used Open Land to Closed Forest (13 %). Land use change occurred especially in high altitude regions where albedo RF strongly offsets CO_2 RF (Fig. 5). At the same time, the most frequent transition was the one from Open Forest to Closed Forest, where albedo RF had the least influence on net RF. In summary, the CO_2 RF for all land use transitions that were part of the forest expansion and succession between 1985 and 1997 in Switzerland was reduced by approximately 40 %, if the albedo RF is taken into account.

The net RF varied greatly on small spatial scales. In our study area, the parameter that had the most significant influence on the spatial variability of RF was snow-cover, followed by carbon sequestration, difference in snow-covered albedo, global radiation and difference in snow-free albedo (Fig. 6a). Thus, if the average snow-cover (in days $year^{-1}$) and carbon sequestration at a certain location were known, the net RF and the offset of CO2 RF through albedo RF could be estimated well without including all factors in an explicit calculation. We found that the offset of CO_2 RF can only be higher than 50 % if the snow-cover lasted over 120 days $year^{-1}$. An increase in snow-cover caused an exponential increase in albedo RF. Because, first, persistent snow-cover was found in regions with high global radiation and second because the

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longer snow covered the surface, the longer it would be present during the days with high global radiation in March, April and May.

The uncertainty of net Radiative Forcing was mainly attributed to uncertainties in carbon sequestration, followed by snow-covered albedo difference, global radiation and snow-free albedo-difference. The main effects of uncertainty related to each input factor were much more relevant than the contribution of interactions between all input factors (Fig. 6).

4 Discussion

Our detailed assessment of Radiative Forcing across Switzerland shows that the albedo RF increases with increasing altitude, which offsets the CO2 RF at high elevations with long snow-covered periods, high global radiation and low carbon sequestration. The altitudinal RF gradient in Switzerland is very strong in comparison to the latitudinal gradient in boreal regions (Betts, 2000; Montenegro et al., 2009). The persistence of snow-cover increases with increasing elevation and increasing latitude. However, while persistence of snow-cover and global radiation are usually positively correlated in mountainous regions, causing high RF, they are negatively correlated in boreal regions. The strong altitudinal RF gradient found in this study is likely to be even more pronounced if altitudinal changes in forest structure and its influence on albedo and carbon sequestration are included on higher resolution because forests with very low carbon stocks can also have a low albedo (de Wit et al., 2013).

However, despite the general increase of RF with elevation, each biogeographical region has its specific characteristics. While the Jura and Plateau (under 600 m a.s.l.) are characterized by albedos of 0.136/0.139 (snow-free) and 0.272/0.276 (snow-covered), the albedo in the Southern Prealps under 600 m is respectively comparably low (0.112 and 0.185). This regional difference may be related to the different forest types and soil characteristics. Whereas beech dominates in the Jura and the Plateau, many stands in the Southern Prealps are dominated by chestnut. Moreover, forest soils in the low-

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lands of the Southern Prealps contain particularly high fractions of "black" fire derived carbon (Eckmeier et al., 2010). The darker soil colour may lower the albedo in addition to differences in the canopy.

Our spatially highly resolved estimates of RF are in agreement with the results of Betts (2000) and Montenegro et al. (2009) which are based on much coarser resolutions. In Betts (2000), the two pixels encompassing Switzerland show a net carbon sequestration of 100–150 and 150–200 $\mathrm{t\,C\,ha^{-1}}$ associated with reforestation of pasture, while in Montenegro et al. (2009), the pixels indicate a drawdown ranging between 100–150 $\mathrm{t\,C\,ha^{-1}}$ (maximum scenario) and 0–20 $\mathrm{t\,C\,ha^{-1}}$ (minimum scenario). However, many pixels are missing in alpine regions. In our study, we found similar values for the drawdown with values ranging from −10 to 160 $\mathrm{t\,C\,ha^{-1}}$ (minus 10 indicates emission instead of drawdown).

Small-scale variability, especially in topographically complex areas, was not captured in these former studies. Here, we used data on global radiation and snow-cover on a resolution of 2.2 km (MeteoSwiss) and 1 km (Hüsler et al., 2012). To calculate differences in carbon sequestration and albedo, we relied on a biogeographical categorization and altitudinal stratification, which are based on major differences in vegetation and other ecological factors (Gutersohn, 1973; Wohlgemuth, 1996). Although the spatial resolution was high in our study, it should be refined further to allow for instance a comparison of RF on northern and southern slopes and a better capture of forest types and structures near the tree line.

The global sensitivity analysis with FAST showed that interactions between the input parameters were small in comparison to the main effects of each parameter. Thus, we verified the results of our global sensitivity analysis in a local analysis by estimating the partial derivates for each factor. Both analyses showed good agreement since not only the interactions, but also non-linear effects had little influences. The amount of RF at a specific location is essentially influenced by carbon sequestration and snow-cover (Fig. 6a). These two factors are good indicators for estimating the amount of RF. Global radiation and snow-covered albedo are also important, but they influence RF

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five times less than carbon sequestration and even seven times less than snow-cover. The factors with the most potential for improving our results are better estimates of carbon sequestration (Fig. 6b), followed by reducing albedo uncertainty and the global radiation. The average parameter for atmospheric absorption (0.23) could be replaced by a specific parameter for each region or the specific top of the atmosphere albedo could be used. If the specific absorption of the atmosphere is included, the effect of global radiation on RF could be more pronounced since absorption of the atmosphere is higher in regions with low global radiation and lower in regions with high global radiation. However, improving data on atmospheric absorption will have only a small influence on the results (Fig. 6b).

The sensitivity analysis with FAST is based on uncertainty estimates because exact values are not available. For example, MODIS values can be assigned to an average uncertainty of 10 % (O'Halloran et al., 2012; Strahler et al., 1999). This uncertainty is likely to be much higher in topographically complex areas than in even terrain as the algorithm used to produce albedo values only indirectly accounts for topography. Moreover, the uncertainties associated with the different input parameters do not always refer to the same statistical measures and are thus not completely consistent (references of uncertainties are listed in Appendix Table A3).

Regarding the different time horizons, RF increased by 17 % for a time horizon of 1000 years compared with a horizon of 100 years. Larger time horizons increased RF since CO_2 RF constantly decreased due to interactions of atmospheric CO_2 with the carbon cycle, while albedo RF became constant after forests reached a steady state. Since we used a time horizon of 100 years, we rather underestimated albedo RF. This apparently goes against the findings of Schaeffer et al. (2006) and Kirschbaum et al. (2011) who both argue that CO_2 RF becomes more dominant for larger time horizons. However, they consider relatively short time periods (including rotations) where carbon sequestration does not end before the forests are removed. We think it is also necessary to include large time horizons when estimating RF, but it is of course an oversimplification to assume a fixed state after transition, since forests are frequently

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disturbed (e.g. O'Halloran et al., 2012). Over longer periods snow-cover will be less persistent in the Alps, which will potentially decrease the albedo RF (de Wit et al., 2013; Pitman et al., 2011).

The maps of the possible carbon sequestration and albedo of forests in each biogeographical region (Fig. 3) reflect mainly ecosystem characteristics. However, forests in Switzerland have long been under permanent anthropogenic influence and are thus not in a naturally balanced equilibrium, i.e. at the end of succession. For example, forests at high elevations in the Jura are often used for pasturing. Hence, they are less dense and sequester less carbon than they would if left to develop as undisturbed forests. The relationship between albedo RF, CO_2 RF and net RF will thus always depend on the actual and previous forest and land management. Our analysis of transitions from Extensively Used Open Land to Closed Forest and Open Forest corroborates this conclusion. The results indicated that the climatic benefit will be smaller if forests are kept in an open structure (e.g. due to pasturing) than when the canopy closes during succession. These findings are in line with former studies that estimate the effects of succession and forest structure on RF and show that changes in carbon stocks and changes in albedo are not linearly related (Kirschbaum et al., 2011; Bernier et al., 2011).

Our results should be valuable for future studies on the climatic impacts of LULUCF, especially for comparing and evaluating the results from climate models since our results are mainly based on satellite and field data. They should also be valuable for assessing the ecosystem (climate) service of forests in temperate mountains, i.e. for addressing the question of whether forest expansion in these regions is beneficial for climate or not. However, the interpretation of RF values has to be done carefully. First, the concept of Radiative Forcing has been developed to compare the impact of different forcing agents on the global mean temperature (Hansen et al., 2005). When applied at the regional and local scales one should keep in mind that the comparison of different forcing agents is far from being straightforward. For instance, the impact of albedo will remain mostly local while those from CO_2 will be globally distributed and therefore

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diluted. Furthermore, the Climate sensitivities of CO_2 RF and Albedo RF may differ (Davin et al., 2007).

Finally, it is important to note that our study does not account for all possible effects of forests on climate, such as changes in evapotranspiration, surface roughness, and impacts on aerosols and other gases than CO_2. The uptake of CH_4 during forest expansion in the Alps increased according to Hiltbrunner et al. (2012), which adds to a negative CO_2 RF. This effect is, however, one magnitude smaller than the effect of CO_2-sequestration. The effect of a changing aerosol concentration, providing cooling (through cloud formation), may be very important (Spracklen et al., 2008). Changes in evapotranspiration and surface roughness, due to forest expansion, have a cooling impact in many geographical contexts (Bonan, 2008; Luyssaert et al., 2014), but we did not include the impacts of these changes in our study. In general, the influence of evapotranspiration and surface roughness will be low in those areas where snow-cover plays an important role (Bonan, 2008; Bathiany et al., 2010; Gibbard et al., 2005; Lee et al., 2011). Hence, these effects will be more important at low elevations (e.g. on the Swiss Plateau) than at high elevations in the Alps. The gap between the benefits of forest expansion at low and high elevations may thus become even wider if evapotranspiration and surface roughness are also integrated.

5 Conclusions

In the temperate mountainous regions of Switzerland, the net RF associated with changes in forest cover varies greatly on small spatial scales. At low elevations, with low to moderate snow-cover, RF is strongly negative due to a dominance of CO_2 RF. At high elevations in continental regions with persistent snow-cover, a very high global radiation, low carbon sequestration and low albedos of mostly evergreen tree species, RF can be positive. As a consequence, both clearly negative and positive values of RF can be found within a horizontal distance of 5 km in alpine valleys. Therefore, the

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climatic benefits of changes in forest cover can only be properly assessed using data at a high spatial resolution.

Our results indicate that it is very important to include albedo RF when estimating the impact on climate of changes in forest cover. Maps of RF, such as those produced in this study, indicate where climatic benefits from changes in forest cover can be expected and where not. In the Swiss Alps, the relevance of albedo RF is especially high because most transitions from open land to forest occur in regions where albedo RF causes a strong offset of CO_2 RF. Practitioners and politicians who need information about ecosystem services on local and regional scales should take into account that RF in the Swiss Alps mainly depends on the persistence of snow-cover and the potential for carbon sequestration. Moreover, late successional forest cover changes from Open Forests to Closed Forests are more beneficial for climate than early successional changes.

Our results could be improved if changes in evapotranspiration, surface roughness, aerosols and other gases than CO_2 were included. To determine the impacts of RFs better, however, further advances in climate modeling are necessary. A promising approach could thus be the coupling of regional climate models with global climate models. Regional models are able to simulate all the effects of changes in land use on climate (including evapotranspiration, surface roughness and so on) on a small scale. Coupling regional models with global models allows the integration of feedbacks with the global circulation. This could help to close the gap between RF and temperature changes, and thus answer the question about where temperature changes caused by RF can be expected and how much change is likely.

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Table A1. Albedo of forest (snow, no snow) and Open Forest (snow, no snow) and corresponding standard errors of each biogeographical region. Values marked with * were derived using majority pixels and/or magnitude inversion (see chapter albedo RF), all other values have been derived using 92 % pixel cover and full inversion. Numbers 1–3 indicate the elevation level of each biogeographical region: Jura 1 = Jura below 600 m, Jura 2 = Jura between 600 and 1200 m and Jura 3 = Jura above 1200 m.

Region	Forest				Open Forest			
	Snow	Ste (%)	No Snow	Ste (%)	Snow	Ste (%)	No Snow	Ste (%)
Jura 1	0.263	1.30	0.139	0.08	NA	NA	NA	NA
Jura 2	0.221	0.50	0.133	0.04	0.303*	1.80*	0.141*	0.23*
Jura 3	0.175	0.64	0.109	0.12	0.232*	0.67*	0.117*	0.13*
Plateau 1	0.266	0.61	0.136	0.03	NA	NA	NA	NA
Plateau 2	0.251	0.53	0.134	0.05	NA	NA	NA	NA
Plateau 3	NA	NA	NA	NA	NA	NA	NA	NA
Pre-Alps 1	0.240	3.16	0.127	0.45	NA	NA	NA	NA
Pre-Alps 2	0.194	0.38	0.118	0.06	0.217*	2.36*	0.114*	0.49*
Pre-Alps 3	0.203	0.40	0.112	0.11	0.275*	0.42*	0.121	0.095
Alps 1	0.168*	2.1*	0.107	1.31	0.353*	15.7*	0.141*	0.58*
Alps 2	0.174	0.61	0.104	0.15	0.285*	3.09*	0.134*	0.18*
Alps 3	0.192	0.23	0.101	0.08	0.274*	0.33*	0.118*	0.068*
Southern Prealps 1	0.185*	4.9*	0.111	0.23	NA	NA	0.127*	0.78*
Southern Prealps 2	0.190	3.13	0.121	0.07	0.258*	3.28*	0.126*	0.27*
Southern Prealps 3	0.194	0.78	0.107	0.12	0.307*	0.50*	0.119	0.089

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Table A2. Carbon stocks of Closed Forests and Open Forests in biomass and soils. The standard errors (Stes) refer to the deviation from the sample mean in every biogeographical region. Not included are errors of the model parameters which have been used to derive carbon stocks from tree measurements.

	Forest biomass ($\mathrm{t\,C\,ha^{-1}}$)	Ste (%)	Open Forest biomass ($\mathrm{t\,C\,ha^{-1}}$)	Ste (%)
Jura 1	134.1	4.6	NA	NA
Jura 2	144.3	2.3	101.27	27.2
Jura 3	103.7	5.5	68.44	13.4
Plateau 1	140.4	2.7	21.08	51.0
Plateau 2	159.7	3.2	92.80	46.2
Plateau 3	137.58	14.1	71.26	33.6
Pre-Alps 1	169.8	9.5	NA	NA
Pre-Alps 2	166.8	2.7	85.60	22.7
Pre-Alps 3	152.5	4.5	72.21	11.0
Alps 1	122	11.2	NA	NA
Alps 2	124.7	4.0	70.41	29.8
Alps 3	115.5	2.3	57.90	7.9
Southern Prealps 1	95.2	6.8	NA	NA
Southern Prealps 2	94.7	4.7	37.40	39.3
Southern Prealps 3	100.6	4.5	41.60	11.6

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Table A3. Spatial variability and uncertainties applied in the sensitivity analysis.

	Spatial variability	Uncertainty (standard deviation)
Carbon sequestration [$\mathrm{t\,C\,ha^{-1}}$]	143–241	± 35 % (Hagedorn et al., 2010; Heldstab et al., 2012)
Snow-cover [$\mathrm{days\,year^{-1}}$]	10–240	± 10 % (Hüsler et al., 2012)
Global radiation [$\mathrm{W\,m^{-2}}$]	117–180	± 28 % (Durr et al., 2010)
Albedo snow-covered	0.208–0.375	± 36 % (Combined error of MODIS data and methods for assigning LULC specific albedos.)
Albedo snow-free	0.025–0.066	± 28 % (Combined error of MODIS data and methods for assigning LULC specific albedos.)
Carbon cycle	–	± 15 % (Joos et al., 2013)
Radiative transfer	–	± 10 % (Myhre et al., 1998)
Atmospheric absorption	–	± 30 % radiative transfer tests*

* For the uncertainty in atmospheric absorption, we relied on experiments with Fu and Liou online model (Fu and Liou, 2005). We tested different scenarios of cloudiness, aerosol concentration and elevation to determine how much atmospheric absorption could vary over Switzerland.

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Table A4. Forest expansion in each biogeographical region. Forest expansion was estimated as the sum of the transitions we used for calculating RF (see Sect. 2.2).

Biogeographical region	Forest expansion (ha)
Jura 1	386
Jura 2	1276
Jura 3	693
Plateau 1	1395
Plateau 2	531
Plateau 3	1
Pre-Alps 1	274
Pre-Alps 2	2473
Pre-Alps 3	4722
Alps 1	54
Alps 2	1294
Alps 3	6519
Southern Prealps 1	449
Southern Prealps 2	1189
Southern Prealps 3	2513

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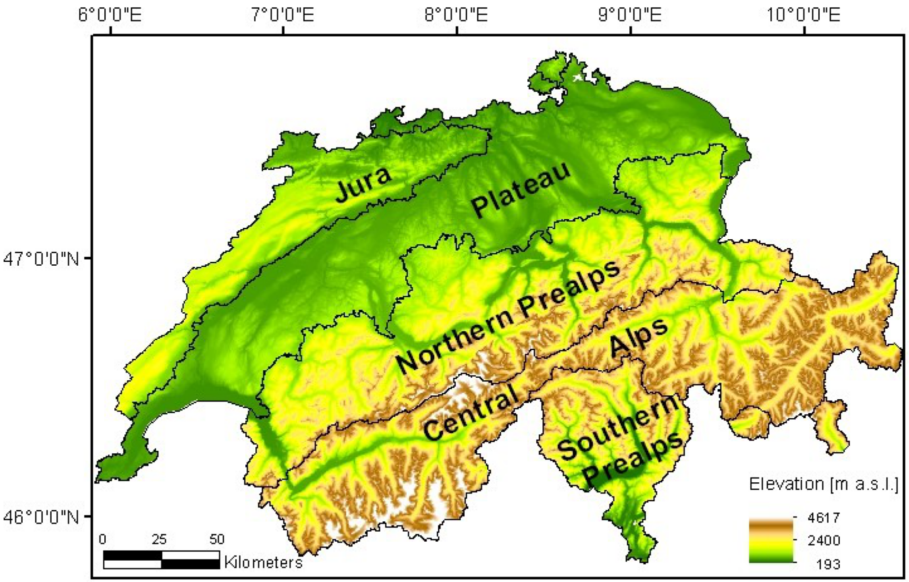

Figure 1. Digital elevation model and biogeographical regions of Switzerland.

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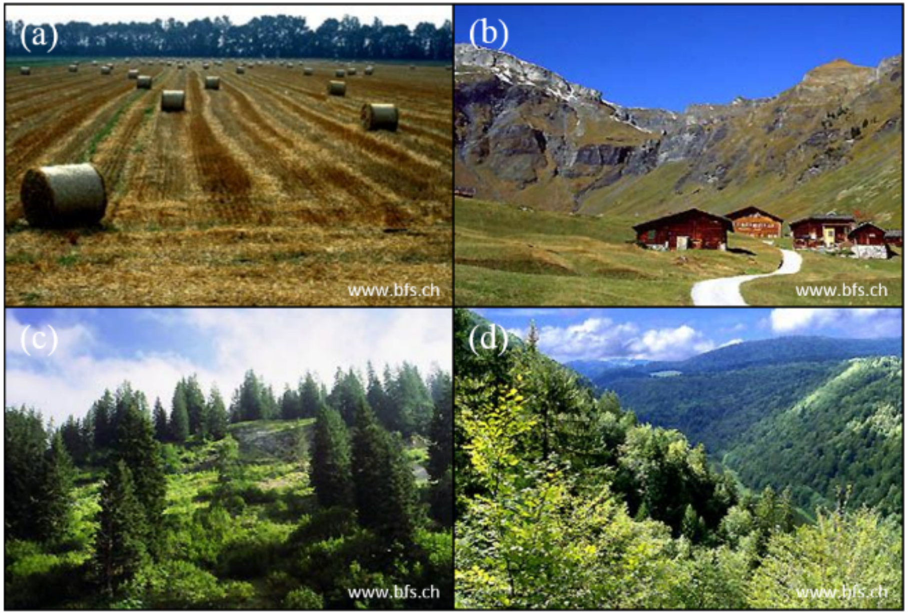

Figure 2. Examples of **(a)** Intensively Used Open Land **(b)** Extensively Used Open Land **(c)** Open Forest **(d)** Closed Forest.

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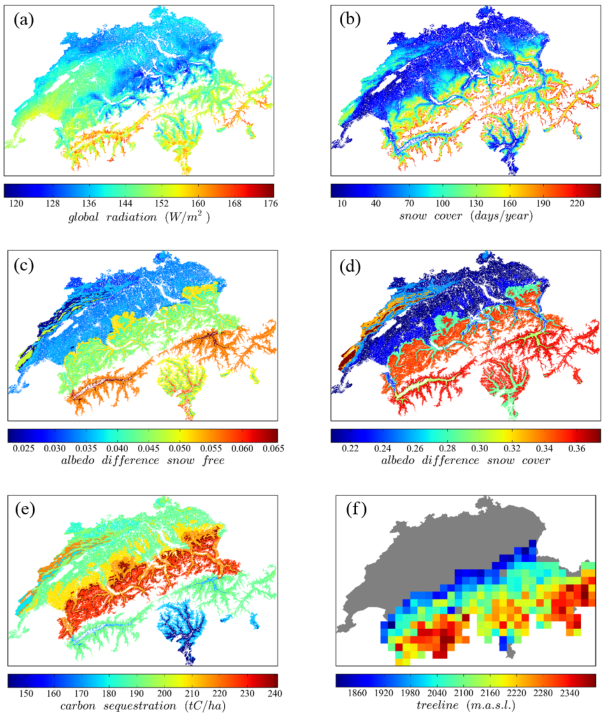

Figure 3. (a) Albedo difference without snow (difference between Intensively/Extensively Used Open Land and Closed Forest), **(b)** albedo difference with snow (difference between Intensively/Extensively Used Open Land and Closed Forest), **(c)** carbon sequestration (difference between intensively/Extensively and Closed Forest), **(d)** days with snow-cover per year. **(e)** Mean yearly global radiation. **(f)** Tree-line elevation calculated using the Swiss Area Statistics of 1997 and applying the method of Paulsen and Körner (2001).

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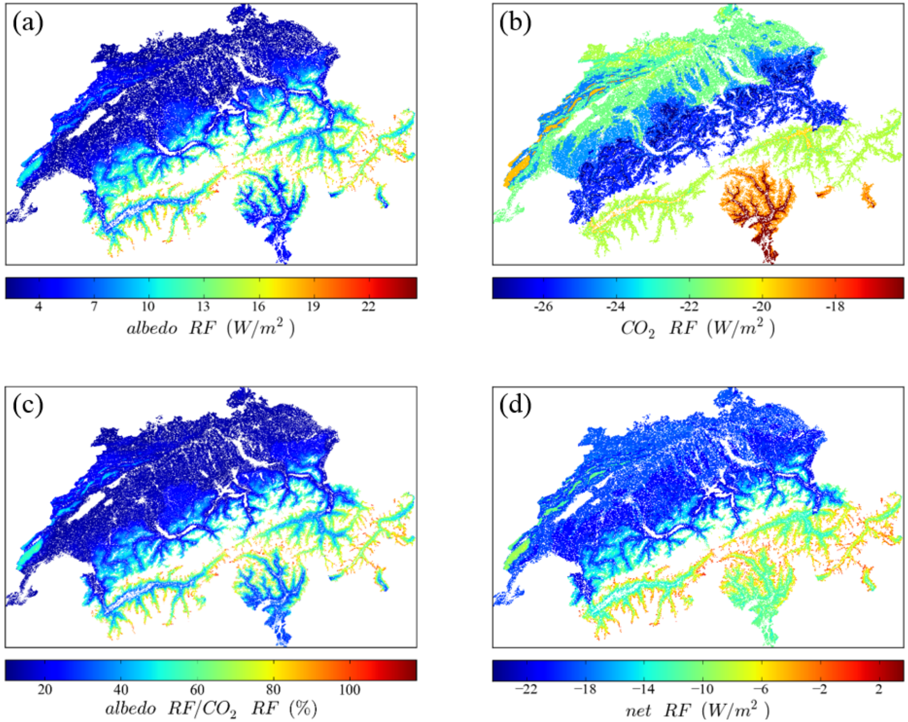

Figure 4. (a) Albedo RF, **(b)** CO_2 RF, **(c)** offset: albedo RF/CO_2 RF. **(d)** Net RF: albedo RF plus CO_2 RF. All datasets were derived for transitions from Intensively Used Open Land (< 1000 m) and Extensively Used Open Land (> 1000) to Closed Forest.

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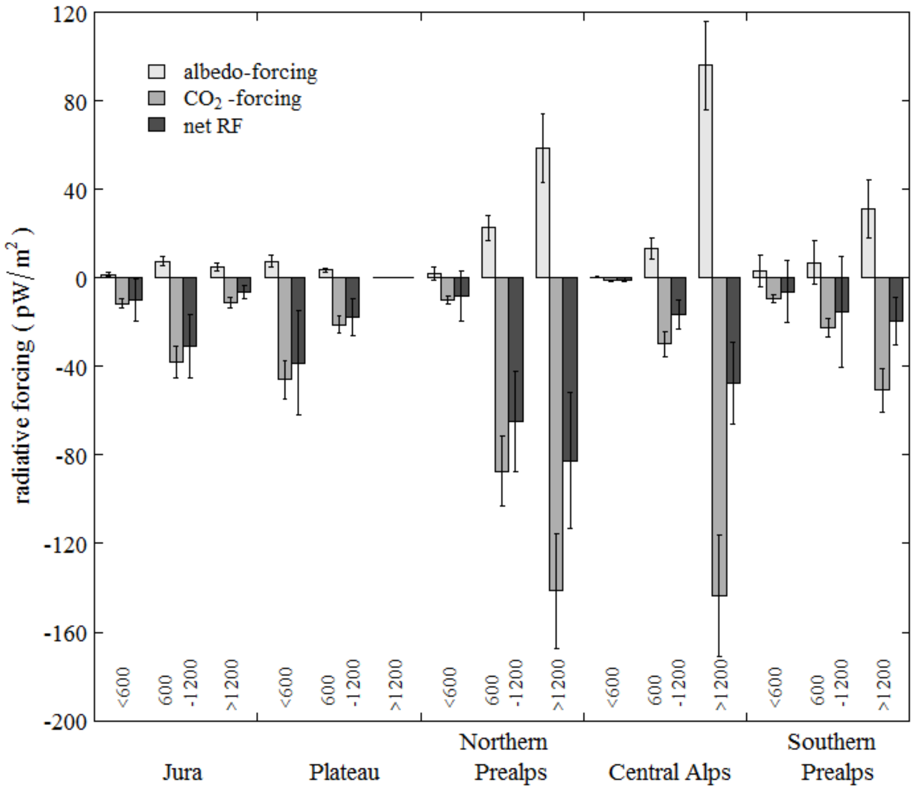

Figure 5. Radiative Forcings of the forest expansion between 1985 and 1997 for three elevations in the biogeographical regions Jura, Plateau, Northern Prealps, Central Alps, Southern Prealps.

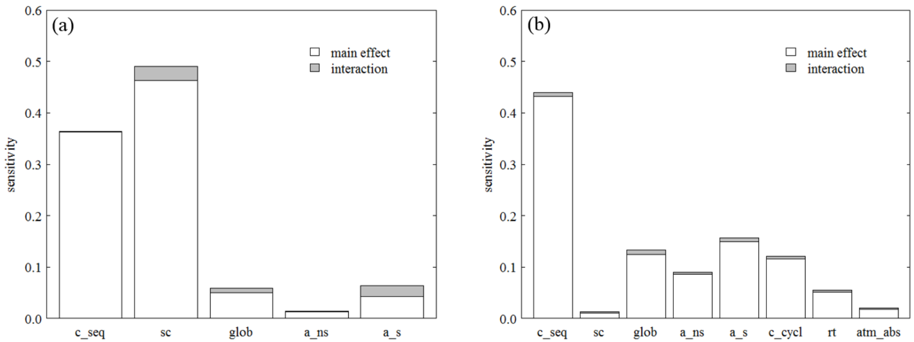

Figure 6. Global sensitivity analysis FAST **(a)** sensitivity analysis of spatial variability of c_seq (carbon sequestration), sc (snow-cover), glob (global radiation), a_ns (albedo difference no snow-cover) and a_s (albedo difference snow-covered) **(b)** sensitivity analysis of uncertainty for each pixel: c_seq, sc, glob, a_ns, a_s, c_cycle (carbon cycle), rt (radiative transfer) and atm_absorb (atmospheric absorption).

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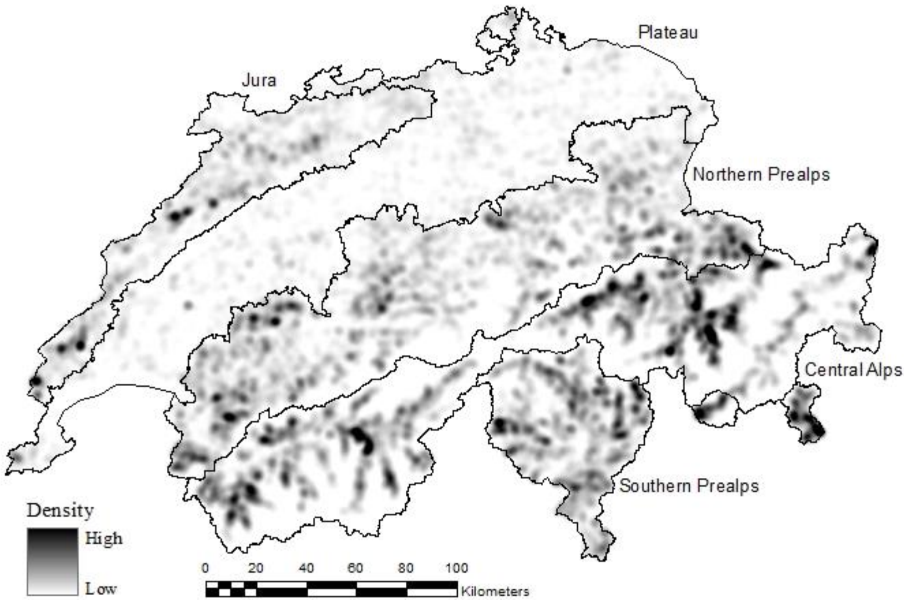

Figure A1. Spatial pattern of forest expansion. The pattern illustrates the density of forest expansion in Switzerland. The density was calculated including the area of all five transitions we used for calculating RF (see Sect. 2.2) and a kernel-density function in ArcGis 10.1 (ESRI).

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