Biogeophysical climate impacts of forest management in Switzerland

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1. Importance of biogeophysical processes for forest-climate interactions

1.1 Background and significance

Forests influence climate through biogeochemical and biogeophysical processes. Biogeochemical processes include greenhouse gas (GHG) exchange as well as emissions of other chemical compounds such as biogenic volatile organic compounds, which can act as aerosol precursors. The biogeophysical effect, on the other hand, refer to the alteration of land properties such as albedo, evapotranspiration and surface roughness (Davin and de Noblet-Ducoudré, 2010).

The climate impacts of land use activities such as forestry are routinely monitored in terms of GHG emissions under the United Nations Framework Convention on Climate Change (IPCC, 2016; FOEN, 2021). The associated biogeophysical impacts, however, are not accounted for as part of this framework despite the growing awareness that these effects matter regionally and should therefore be considered in the decision-making process (Bright et al., 2017; Windisch et al., 2021). In this report, we synthetizes the current state of knowledge concerning the biogeophysical effect of forestry activities with a special focus on Switzerland. Beside reviewing the existing literature we also present new results for Switzerland based on observation-driven estimates as well as process-based modelling.

1.2 Observational evidence of the biogeophysical impacts of forests

In recent years, the increasing availability of high resolution remote sensing data has enabled the emergence of new analysis strategies providing observation-based evidence of the influence of land cover change on climate conditions. Remotely sensed data, for instance, have been used to examine local differences in surface energy balance and Land Surface Temperature (LST) between different ecosystem types on a global scale (Mildrexler et al., 2011; Zhao and Jackson, 2014; Li et al., 2015; Duveiller et al., 2018). There is reasonably good agreement between these studies that, at the latitude of Switzerland, forests provide a cooling effect during daytime and a warming during nighttime in summer. In winter, a warming effect occurs. In other words, trees dampen seasonal and diurnal temperature variations compared to short vegetation. This also implies that the annual mean temperature effect is often small due to these seasonal and diurnal compensating effects, but in the context of summer extreme events the cooling effect of forest can be particularly large (Zaitchik et al., 2006; Renaud and Rebetez, 2009; Lejeune et al., 2018; Schwaab et al., 2020).

The type of forests also plays an important role. In-situ observations in Switzerland have for instance shown that coniferous trees provide less cooling effect than broadleaf trees in summer (Renaud and Rebetez 2009; Renaud et al. 2011). This is confirmed by remote-sensing-based estimates which indicate that broadleaf trees exhibit higher albedo and higher latent heat fluxes during summer, both contributing to colder temperatures over broadleaf forests compared to needleleaf (Bright et al., 2017; Duveiller et al., 2018; Schwaab et al., 2020). The situation during winter is less clear. Renaud et al. (2011) found that needleleaf forests are cooler and broadleaf forest warmer compared to open land. This is supported by Duveiller et al. (2018) and by Schwaab et al. (2020) who found a warming effect of deciduous broadleaf trees compared to evergreen needleleaf trees. On the other hand, the study of Bright et al. (2017) indicates that the transition from broadleaf to needleleaf results in warmer temperatures during winter related to the lower albedo of needleleaf forests.

1.3 Process-based modelling of the biogeophysical impacts of forest changes and forest management

A number of modelling studies have explored the biogeophysical effect of deforestation or reforestation from global to regional scales (e.g., Claussen et al., 2001; Davin and deNoblet-Ducoudré, 2010; Davin et al., 2020). One important finding is that this effect strongly varies across latitudes. In tropical regions, trees decrease temperature mainly due to their higher evapotranspiration and surface roughness, while in temperate regions the subtle balance between radiative (albedo) and non-radiative (evapotranspiration and surface roughness) processes depends on season and time of day thus leading to a more complex picture (Davin and de Noblet-Ducoudré, 2010). In temperate regions in particular, uncertainties are large as illustrated by the lack of agreement between individual model results (Pitman et al., 2009, Lejeune et al., 2017; Davin et al., 2020). Models usually agree about the warming effect of temperate forests in winter, but there is no consensus about the summertime effect. In addition models do not capture the nighttime warming effect of trees seen in observations (see previous section). This could be linked to the missing representation of biomass heat storage in climate models (Meier et al, 2019). Indeed, trees store heat in their trunks and leaves during the day and release it at night, thereby increasing nighttime temperature. The inclusion of this process in a climate model has been shown to resolve the nighttime mismatch between model and observations (Meier et al, 2019).

Concerning specifically the effect of forest management, only very few modeling studies exist. Naudts et al. (2016) argue that past forest management in Europe had a warming effect on the regional climate, mainly attributed to the replacement of broadleaf species with needleleaf species during the last 250 years. A logical consequence of this result is that reintroducing broadleaf species in Europe could reverse this effect and therefore lead to a cooling, but it might be offset by biogeochemical processes (Luyssaert et al., 2018). These studies have at least two limitations. The first one is that they rely on a single climate model with very limited observational evidence to establish the reliability of the results. This is particularly critical given the very strong model-dependency identified in previous land cover change experiments (Lejeune et al., 2017, 2018; Davin et al., 2020). A second limitation is the focus on daily mean temperature change, when in fact needleleaf-to-broadleaf conversion has a fundamentally different effect on daytime and nighttime temperatures (Schwaab et al., 2020). The potential biogeophysical benefit of broadleaf trees should therefore be assessed considering both seasonal and diurnal variations. In the next sections, we will address these two limitations by combining process-based modelling and observation-driven estimates with a focus on Switzerland.

Figure 1: Alpine study area over which both model-based and observation-based results are aggregated.

2. Potential biogeophysical effect of forest management in Switzerland

Here we combine observation-based and model-based estimates to assess the effect of forest management on temperature. We consider in particular the following types of management changes: conversion from open land to forest (section 2.1), forest density increase (section 2.2) and conversion from needleleaf to broadleaf trees (section 2.3). While we acknowledge that this does not represent the full portfolio of possible management changes, this selection is constrained by data availability and current model capabilities.

To provide observation-based estimates of the potential impact of forest management on surface temperature we employ a multiple linear regression approach. This approach was developed to extract the local sensitivity of Land Surface Temperature (LST) to forest and forest management considering possible confounding factors such as other land cover classes, elevation, slope and exposition (Schwaab et al., 2020). The statistical model relies on satellite remote sensing observations of LST from MODIS (Moderate Resolution Imaging Spectrometer) at 1 km resolution and that were taken at approximately 1:30 am and 1:30 pm and averaged over 8-day cycles. Satellite remote sensing data characterizing forest management (i.e. forest density and forest composition as proxies for forest management) are from the so-called High Resolution Layers (HRL) as part of the Copernicus Land Monitoring Service (EEA, 2017).

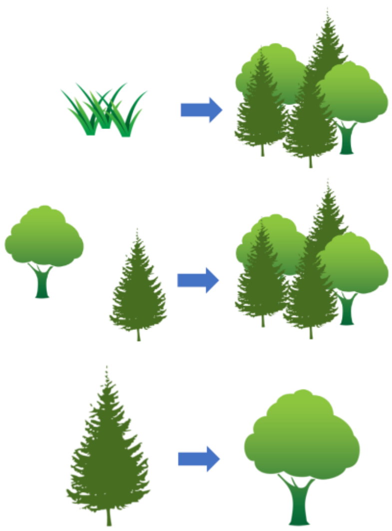
In addition, simulations with the Community Land Model (CLM5.1), a state-of-the-art process-based land surface model, are also presented. CLM5.1 includes a number of parameterization improvements (Meier et al., 2018; Meier et al., 2019; Meier et al., 2022) that have been shown to increase the model agreement with observations, in particular with respect to capturing seasonal and diurnal temperature variations in forests.

Results from the observation-based and model-based estimates are aggregated over an area encompassing the whole Alpine region (Fig. 1). Because elevation is a very important factor that can modulate the biogeophysical effect of forest changes and management (Schwaab et al., 2015), the results are also presented for different elevation classes (below 600m, between 600 and 1200m and above 1200m).

2.1 Open land to forest conversion

A conversion from open land (i.e., grassland or cropland) to forest has a pronounced effect on surface temperatures, which varies both seasonally and diurnally. Results from CLM5.1 over the Alpine region indicate that, during day, forests have a winter warming effect and a summer cooling effect (Table 1). This is well in line with observational evidence over Europe (Li et al., 2015; Vanden Broucke et al., 2015; Duveiller et al., 2018). The wintertime warming effect is related to a considerably lower albedo over forests compared to open land, as open land is covered more easily by snow than forests. Therefore, this winter warming is more pronounced at higher altitudes, where snow is more abundant (Table 1). The daytime cooling effect of forests in summer on the other hand can be attributed to (1) higher turbulent heat fluxes over forests due to their higher surface roughness and (2) a higher evaporative fraction over forests compared to open land (Davin and deNoblet-Ducoudré, 2010). Unlike winter, the summer effect is not strongly influenced by altitude.

Table 1: Summary of the local land surface temperature effect of forest management options as a function of elevation. The results are presented for winter and summer and for daytime (1:30 PM, in red) and nighttime (1:30 AM, in blue). Results from the observation-driven model in bold (Schwaab et al., 2020) and from the process-based model (CLM5.1) in italic (Meier et al., 2019; Meier et al., 2022). The uncertainty range is calculated as the standard deviation for CLM5.1 and as the standard error of the regression coefficients for the statistical model.



		Below 600 m		600 to 1200 m		Above 1200 m	
		DJF	JJA	DJF	JJA	DJF	JJA
Open land to forest		*0.43 ± 0.86* *1.18 ± 0.60*	*-1.58 ± 1.66* *0.23 ± 0.96*	*2.15 ± 1.72* *1.47 ± 1.83*	*-1.63 ± 1.84* *0.35 ± 1.47*	*3.12 ± 0.89* *2.24 ± 0.60*	*-0.98 ± 0.43* *0.89 ± 0.46*
Forest density increase	Management	**0.19 ± 0.02** **0.42 ± 0.02**	**-0.79 ± 0.02** **0.26 ± 0.02**	**0.34 ± 0.02** **0.71 ± 0.02**	**-0.95 ± 0.02** **0.41 ± 0.02**	**0.18 ± 0.02** **0.31 ± 0.04**	**-0.32 ± 0.03** **0.21 ± 0.02**
Needleleaf to broadleaf	Management	*-0.15 ± 0.52* *1.08 ± 0.45* **0.55 ± 0.04** **0.27 ± 0.04**	*-0.75 ± 0.29* *0.19 ± 0.10* **-0.45 ± 0.04** **0.39 ± 0.04**	*0.36 ± 0.42* *1.14 ± 0.71* **0.17 ± 0.04** **0.42 ± 0.04**	*-0.45 ± 0.44* *0.19 ± 0.10* **-0.47 ± 0.04** **0.54 ± 0.04**	*0.91 ± 0.43* *0.52 ± 0.79* **-0.12 ± 0.06** **0.12 ± 0.08**	*0.15 ± 0.47* *0.28 ± 0.21* **-0.55 ± 0.06** **0.11 ± 0.06**

The nighttime temperature signal of a conversion from open land to forest differs substantially from the daytime signal. Forests are warmer during the night throughout the year compared to open land. This has two possible explanations. Firstly, the sensible heat flux, which is often directed towards the land surface during night, is higher over forests because of the higher surface roughness thus contributing to the warming effect (Vanden Broucke et al., 2015). Secondly, the relatively large biomass of forests acts as an energy storage taking up energy during day and releasing it during night. This results in a strong nighttime temperature increase in forests. In CLM5.1, this nighttime warming effect of forests is captured becausebiomass energy storage has been implemented in the model (Meier et al., 2019). Overall, forests have thus a dampening effect on diurnal temperature variations, which is especially pronounced during summer (Table 1).

2.2 Forest density increase

Analysis of daytime (1:30 pm) MODIS land surface temperature indicates a strong seasonality of temperature sensitivity to forest density. In winter, a 20 % increase in tree cover density leads to a warming which is between 0.1-0.4°C (Fig. 2). This warming can be related to the low albedo of dense forests in comparison to less dense forests, in particular in the presence of snow. Surprisingly, the warming effect does not increase with elevation, despite the expectation that persistent snow cover at these altitudes would amplify the albedo effect. This absence of elevation-dependency may be related to the presence of larches at higher elevation. Larches, as opposed to evergreen coniferous trees found at lower elevations, can potentially combine high tree density with low snow-masking effect (because of the absence of needles in winter). In addition, satellite LST measurements over snow-covered areas are sometimes falsely defined as cloudy observations and removed, which leads to less observations under snow-covered conditions in high altitudes.

In summer, increasing tree cover density by 20% leads to a small cooling effect at high altitudes (0.3-0.5°C) and a larger cooling effect at lower altitudes (0.8-1°C). This cooling effect may be due to a higher evapotranspiration and higher surface roughness. The larger cooling effect at low elevations may be due to the more important role of evapotranspiration under higher temperatures leading to larger absolute evapotranspiration differences.

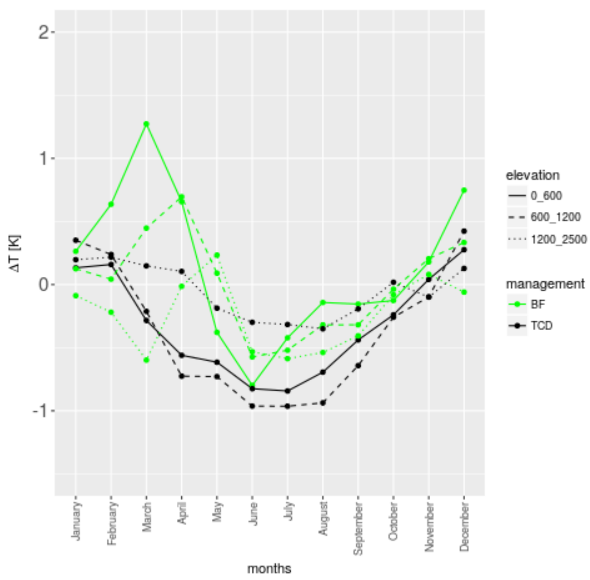


Figure 2: Daytime (1:30 pm) land surface temperature (MODIS) change due to increasing tree cover density (TCD) by 20% (averaged response over different forest types) and converting needleleaf to broadleaf trees. The effect is shown for different elevation classes over the Alpine domain shown in figure 1. Based on data from Schwaab et al. (2020).

2.3 Conversion from needleleaf to broadleaf trees

Converting needleleaf trees to broadleaf trees leads to warming in winter and spring at low elevations and a winter cooling mainly at higher elevations (Fig. 2). The low-elevation warming peaks in spring and can reach up to 1.5°C. The peak in spring occurs earlier at low elevations (March) and later at higher elevations (April, May).

During summer, the needleleaf to broadleaf conversion decreases temperatures by approximately 0.2-0.6°C. This cooling is consistent for different altitudinal levels. However, the cooling effect peaks in June at low elevations and decreases in July, August and September, whereas it remains more constant at higher elevations.

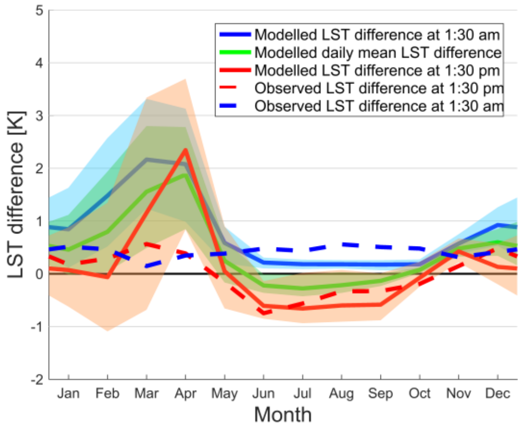


Figure 3: Land surface temperature difference between broadleaf trees minus needleleaf trees at 1:30 am (blue), 1:30 pm (red), and averaged over the day (green) as simulated by CLM5.1 (Meier et al., 2019; Meier et al., 2022). The shading depicts the range between the 10 % and 90 % percentile of these differences. The dashed lines indicate the corresponding observation-based estimates from the statistical model (Schwaab et al., 2020).

Model results obtained with CLM5 are in good agreement with these conclusions except for the much stronger springtime signal in CLM5 (Fig. 3), which might be related to a compensation effect over different altitude levels (Table 1). Because there is a good agreement between CLM5.1 and the observation-driven estimates (Fig. 3), the model can be used to get insights on the mechanisms behind the observed temperature sensitivity (Fig. 4). The analysis of the surface fluxes in CLM5.1 reveals that needleleaf trees have a lower albedo compared to broadleaf trees (except in autumn) resulting in higher absorbed shortwave radiation. This effect is counteracted by higher turbulent heat fluxes over needleleaf trees especially during spring, but also during summer and autumn. Latent heat flux is substantially higher over needleleaf forest during the spring months, hence being one of the drivers of the colder temperatures of needleleaf trees during these months. Once the leaves of broadleaf trees are fully developed, the latent heat flux is then higher over broadleaf forests, resulting in colder temperatures.

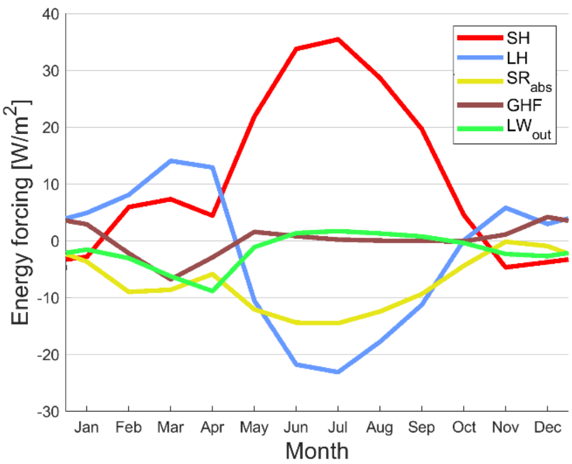


Figure 4: Seasonal variations of energy flux difference between broadleaf trees minus needleleaf trees (positive directed towards land surface) in CLM5.1 (Meier et al., 2019; Meier et al., 2022). Shown are the difference in sensible heat flux (red, SH), latent heat flux (blue, LH), absorbed solar radiation (yellow, SR_{abs}), ground heat flux (GHF) and outgoing longwave radiation (green, LW_{out}). Results are aggregated over the Alpine domain shown in figure 1.

3. Biogeophysical climate impacts of recent changes in forest cover

3.1 Recent forest cover changes in Switzerland (1995-2010)

Corine Land Cover (CLC) data (EEA, 2014) suggests that there was a slight decrease in forest area in Switzerland between 2000 and 2012 (approx. 0.74%). In contrast, the Swiss Area Statistic (SAS; BFS, 2017) shows an increase in forest area of about 1% between 1992-1997 and 2004-2009 when combining closed and open forests. Considering these two categories separately, there is a decrease in closed forest of approximately 2% and an increase in open forest of 3%. The seemingly contradictory results from the CLC data and the SAS data are most likely related to the different land-cover categorizations that were used when producing the two datasets. In addition, the SAS data is not only based on land-cover information, but indirectly includes land-use information. For instance, forest damages are categorized as forest (i.e. open forest) in the SAS and not in the CLC dataset. Results from the Swiss National Forest Inventory (NFI, Brändli, 2010; Brändli et al., 2020) are qualitatively in line with the SAS, suggesting an increase in forest area of 2.4%, although over a slightly more recent period.

According to CLC, the amount of broadleaf forest (i.e. more than 75% broadleaf trees) has decreased by 0.28% between 2000 and 2012. During the same period, the area covered by coniferous forest (i.e. more than 75% coniferous trees) decreased by 1.45%. Mixed forests, in which both coniferous and broadleaf species exceed 25% within the canopy closure, increased by approximatively 1%. Although the amount of purely broadleaf forests has decreased according to CLC, the overall amount of broadleaf trees may have increased resulting as indicated by the increase in mixed forests. NFI also indicates a decrease of needleleaf forests and mixed forests, but shows an increase in broadleaved forests in contradiction with CLC.

The intercomparison of these different datasets therefore does not provide a fully consistent picture about historical forest cover changes. First, none of the datasets allows a comprehensive monitoring of all changes in forest structure and composition (e.g. the SAS data lacks a differentiation between broadleaved and coniferous forests). Second, the different datasets cover different periods which complicates the comparison and makes a quantitative analysis of historical forest changes very challenging. Finally, NFI is the most comprehensive datasets in terms of monitored variables, including different tree species and different structural properties of forests, but it does not provide full spatial coverage over Switzerland, thus preventing its use for spatially explicit analysis. However, a qualitative analysis of recent observations of forest cover changes in Switzerland suggests that there was a small increase in the amount of forest areas paralleled by a slight increase in broadleaf trees.

Table 2: Forest cover area changes (%) in Switzerland based on the Swiss Area Statistics (SAS), Corine Land Cover (CLC) and the National Forest Inventory (NFI).

Dataset	SAS (92/97-04/09)				CLC (2000-2012)				NFI (NFI3: 04/06 – NFI4: 09/17)			
Altitude level	<600	600-1200	>1200	Total	<600	600-1200	>1200	Total	<600	600-1200	>1200	Total
Forest total	-0.05	0.07	1.11	1.13	0.07	-0.26	-0.55	-0.74	0.40	0.91^	4.02^^	2.4´
Open forest	1.12	1.53	0.46	3.18	x	x	x	x	x	x	x	x
Closed forest	-1.23	-1.47	0.65	-2.20	x	x	x	x	X	x	x	x
Coniferous forest/trees	x	x	x	x	-0.22	-0.63	-0.60	-1.45	x	X	x	-1.59
Broadleave d forest/trees	x	x-	x	x	0.07	-0.2	-0.15	-0.28	x	x	x	3.94
Mixed forest	x	x	x	x	0.22	0.58	0.20	1.0	x	x	x	3.51* /8.35 **

* Mixed (dominated by coniferous); ** Mixed (dominated by broadleaved)

^ Average of values of two elevation levels (601-1000, 1001-1400) ^^ Average of values of three elevation levels (1001-1400, 1401-1800, above 1800)

´NFI values for different altitudinal levels show the relative change of forest cover within each level and thus do not sum to the total.

3.2 Biogeophysical implications of recent forest cover changes

The considerable uncertainties in the magnitude and even the direction of forest management trends in Switzerland over the past decades (see previous section), hinders a quantitative analysis of associated biogeophysical impacts. However, some qualitative conclusions can be drawn based on knowledge of the potential biogeophysical effect of various forest changes in Switzerland (Table 1). First, the recent increase in forest areas (at least between 1992 and 2004) likely induced a local warming in winter and a cooling in summer during daytime. Since forest cover has increased mainly at high altitudes, the winter warming was more pronounced and the summer cooling less pronounced compared to what would have been expected at lower elevations. As a consequence, the annual mean effect was presumably close to zero or a slight warming. Second, an increase in broadleaved trees has happened mainly at lower elevations (at least over the last two decades, since there is no earlier data), most likely inducing a warming effect in winter and a cooling effect in summer. Third, an increase in forest carbon stocks (albeit with high regional variability) is also documented over the past two decades (Brändli et al., 2020), which may indicate an increase in forest density entailing a summer cooling effect particularly at lower altitudes (section 2.2).

4. Implications for adaptive forest management

Including the available knowledge about the biogeophysical effect of forests is essential when designing future mitigation strategies. For instance, the historical preference given to coniferous species came up with a number of biogeophysical trade-offs including lower albedo, lower evapotranspiration and higher summer daytime temperature (Fig. 5). Reintroducing native broadleaf species could therefore foster summer daytime biogeophysical cooling which could be particularly beneficial as an adaptive strategy to reduce the vulnerability of forest ecosystems to future increase in droughts and heatwaves. In addition, forest management aiming at restoring a higher forest density could complement this strategy by providing additional summer cooling, particularly at elevations below 1200 meters. It should be noted that both of these strategies would result in increased nighttime temperatures. While this is not a priori a negative aspect, the possible consequences on forest ecosystem functioning would be worth investigating in more details.

Furthermore, this type of management has the potential to combine other climate benefits such as increased drought tolerance (Lévesque et al. 2013), reduced fire risk (Astrup et al. 2018), increased carbon storage (Naudts et al. 2016; Astrup et al. 2018) and increased productivity and economic value (Liang et al., 2016). Adaptive forest management restoring both forest composition and density has therefore the potential to foster synergies between mitigation and adaptation benefits.

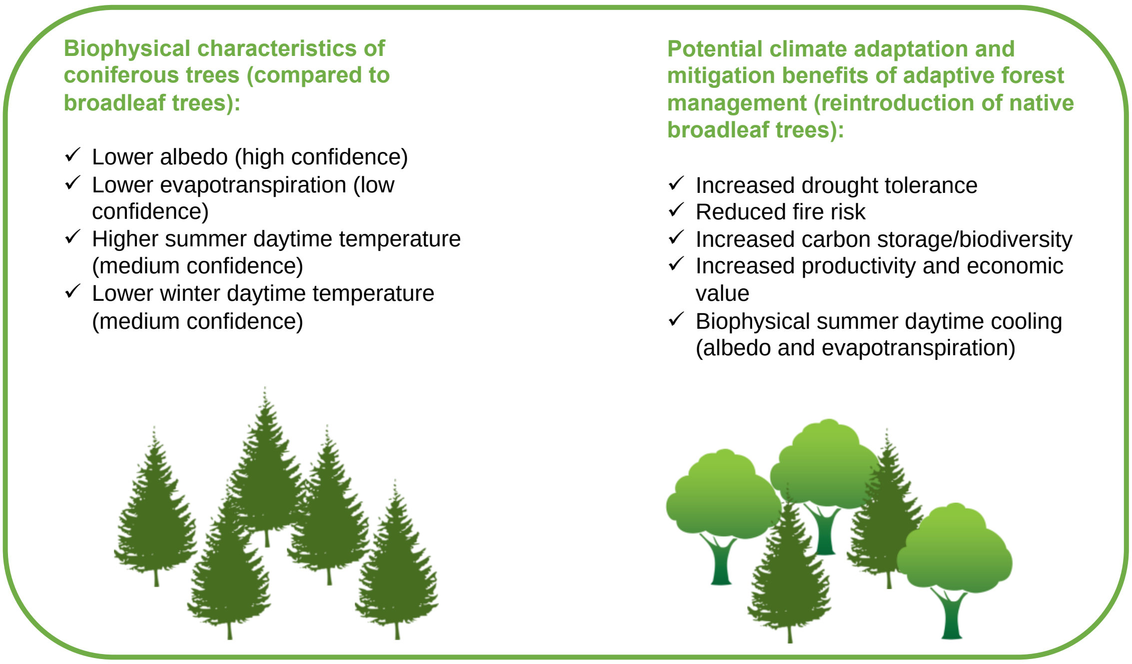


Figure 5: Overview of possible adaptive forest management benefits with a focus on reintroduction of broadleaf trees. The biogeophysical benefit is investigated in this report. Sources for other benefits not assessed in this report: Increased drought tolerance (Lévesque et al. 2013); Reduced fire risk (Astrup et al. 2018); Increased carbon storage and biodiversity (Naudts et al. 2016; Astrup et al. 2018); Increased productivity and economic value (Liang et al., 2016).

5. Knowledge gaps and future research needs

5.1 Historical forest changes reconstruction

Historical reconstructions of forest changes are essential in model-based assessment of the climatic impact of past land-cover changes. However, none of the existing datasets (SAS, CLC and NFI) allows a spatially comprehensive analysis of recent historical land-use and forest cover changes in Switzerland (section 3.1). This calls for the development of improved historical forest reconstruction for Switzerland combining high resolution, complete temporal and spatial coverage and distinguishing between different tree species and possibly even different management practices. Merging the different existing datasets may be a way forward to get a more comprehensive picture of past forest changes. Resolve the existing inconsistencies between these different datasets will, however, be challenging and require an in-depth analysis of the effect of methodological choices.

Incorporating different tree species in such reconstruction would be very valuable. One striking example are larches, which have very different properties in comparison to other coniferous species. Assessing their specific biogeophysical role would be essential in the Alpine context.

5.2 Limitations in observation-driven estimates

Estimating the biogeophysical impacts of different forest management strategies, based on satellite remote sensing data, is subject to a number of limitations. First, from this remote sensing perspective, the impact of forest management can only by approximated indirectly through proxies such as tree cover density and broadleaf tree fraction. Second, linking spatial differences in observed land surface temperature to differences in forest properties is a powerful approach, but since land surface temperature is also dependent on a number of other spatially varying variables (e.g. elevation) acting as confounding factors, extracting the actual effect of forest characteristics is necessarily subject to uncertainties. For instance we assumed a linear relationship between broadleaved tree fraction and temperature. However, non-linear effects may exist, e.g. an increase in broadleaf trees in a purely coniferous forest may have a different impact than the same increase in a forest already dominated by broadleaf trees.

Moreover, applying such remote sensing-based estimates to anticipate the effect of future forest management changes implies making use of a “space for time” analogy. This analogy may not always work perfectly if changes in the background climate occur. For instance, climate will reduce the amount of snow in some locations thus possibly reducing the albedo effect of some management strategies.

Finally, such estimates only quantify the local biogeophysical effect of forest changes. Possible atmospheric feedbacks or remote effects, which are more likely to arise if forest changes occur over relatively large areas, can be accounted for only through process-based climate modelling.

5.3 Process-based modelling

A major shortcoming in current models-based assessment of the role of forest on climate is the lack of agreement between individual model results (Lejeune et al., 2017, 2018). There is therefore an urgent need to better constrain process-based models using observations (Meier et al., 2018; Meier et al., 2019; Meier et al., 2022). This will help identify model deficiencies and important missing processes, potentially resulting in a new generation of models with more converging and reliable sensitivity to land cover changes. Further, land surface models need to be adapted to capture the full range of forest management processes, such as changes in forest density through harvesting and thinning which can have considerable biogeophysical impacts as seen based on remote sensing observations.

Finally there is a need for more integrated modelling approaches considering the full range of synergies and tradeoffs arising from forest management (biogeophysical and biogeochemical effects, biodiversity, productivity, etc). So far modelling studies are often one-sided, focusing on only one or a few of these aspects, thus leaving decision-makers and stakeholders with the task of assembling information from multiple sources. This also means that some potentially important interactions between processes are often ignored. An example is the possible consequences of biogeophysically-induced canopy temperature changes on carbon fluxes and forest productivity. More comprehensive modelling approaches could thus provide new scientific insights while supporting the decision-making process.

References

Astrup, R., R. M. Bright, P. Y. Bernier, H. Genet, and D. A. Lutz (2018), A sensible climate solution for the boreal forest. Nat. Clim. Chang.

BFS – Bundesamt für Statistik (2017). Arealstatistik nach Nomenklatur 2004 – Bodennutzung (Land Use). GEOSTAT-Datenbeschreibung, Version 1.1.

Brändli, U.-B. (Red.) (2010), Schweizerisches Landesforstinventar. Ergebnisse der dritten Erhebung 2004–2006. Birmensdorf, Eidgenössische Forschungsanstalt für Wald, Schnee und Landschaft WSL. Bern, Bundesamt für Umwelt, BAFU. 312 S.

Brändli, U.-B.; Abegg, M.; Allgaier Leuch, B. (Red.) (2020), Schweizerisches Landesforstinventar. Ergebnisse der vierten Erhebung 2009–2017. Birmensdorf, Eidgenössische Forschungsanstalt für Wald, Schnee und Landschaft WSL. Bern, Bundesamt für Umwelt. 341 S.

Bright, R. M., E. Davin, T. O'Halloran, J. Pongratz, K. Zhao, and A. Cescatti (2017), Local temperature response to land cover and management change driven by non-radiative processes. Nat. Clim. Chang., 40 7, 296–302, doi:10.1038/nclimate3250.

Claussen, M., Brovkin, V. & Ganopolski, A. (2001), Biogeophysical versus biogeochemical feedbacks of large-scale land cover change. Geophysical Research Letters, 28, 1011-1014, doi:10.1029/2000GL012471

Davin, E.L., N. de Noblet-Ducoudré and P. Friedlingstein (2007), Impact of land cover change on surface climate: Relevance of the radiative forcing concept, Geophys. Res. Lett., 34, L13702, doi:10.1029/2007GL029678.

Davin, E.L. and N. de Noblet-Ducoudré (2010), Climatic impact of global-scale deforestation: radiative versus non-radiative processes, J. Clim., 23, 97112, doi:10.1175/2009JCLI3102.1.

Davin, E. L., Rechid, D., Breil, M., Cardoso, R. M., Coppola, E., Hoffmann, P., Jach, L. L., Katragkou, E., de Noblet-Ducoudré, N., Radtke, K., Raffa, M., Soares, P. M. M., Sofiadis, G., Strada, S., Strandberg, G., Tölle, M. H., Warrach-Sagi, K., and Wulfmeyer, V (2020), Biogeophysical impacts of forestation in Europe : first results from the LUCAS (Land Use and Climate Across Scales) regional climate model intercomparison, Earth Syst. Dynam., 11, 183-200, https ://doi.org/10.5194/esd-11-183-2020

Duveiller, G., J. Hooker, and A. Cescatti (2018), The mark of vegetation change on Earth's surface energy balance. Nat. Commun., 9, 679, doi:10.1038/s41467-017-02810-8.

EEA - European Environmental Agency (2017), GIO Land High Resolution Layers (HRLs)—Summary of Product Specifications; EEA: Copenhagen, Denmark.

EEA - European Environmental Agency (2014), CLC2012 Addendum to CLC2006 Technical Guidelines - Final draft, V2. Copenhagen, Denmark.

FOEN (2021), Switzerland's Greenhouse Gas Inventory 1990–2019. Submission of April 2021 under the United Nations Framework Convention on Climate Change and under the Kyoto Protocol, Federal Office for the Environment FOEN, Climate Division, 3003 Bern, Switzerland.

IPCC (2006), 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Prepared by the National Greenhouse Gas Inventories Programme, Eggleston H.S., Buendia L., Miwa K., Ngara T. and Tanabe K. (eds). Published: IGES, Japan.

Liang, J., and Coauthors, 2016: Positive biodiversity-productivity relationship predominant in global forests. Science (80-.)., doi:10.1126/science.aaf8957.

Lejeune Q., S. I. Seneviratne, and E. L. Davin, 2017: Historical land-cover change impacts on climate: Comparative assessment of LUCID and CMIP5 multimodel experiments. J. Clim., 30, 1439–1459, 44 doi:10.1175/JCLI-D-16-0213.1.

Lejeune, Q., E. L. Davin, L. Gudmundsson, J. Winckler, and S. I. Seneviratne, 2018: Historical deforestation locally increased the intensity of hot days in northern mid-latitudes. Nat. Clim. Chang., 8, 386–390, doi:10.1038/s41558-018-0131-z.

Lévesque, M., M. Saurer, R. Siegwolf, B. Eilmann, P. Brang, H. Bugmann, and A. Rigling, 2013: Drought response of five conifer species under contrasting water availability suggests high vulnerability of Norway spruce and European larch. Glob. Chang. Biol., 19, 3184–3199, doi:10.1111/gcb.12268.

Li, Y., M. Zhao, S. Motesharrei, Q. Mu, E. Kalnay and S. Li (2015), Local cooling and warming effects of forests based on satellite observations. Nature communications 6, doi:10.1038/ncomms7603.

Luyssaert, S., and Coauthors, 2018: Trade-offs in using European forests to meet climate objectives. Nature, 562, 259–262, doi:10.1038/s41586-018-0577-1.

Meier, R., Davin, E. L., Lejeune, Q., Hauser, M., Li, Y., Martens, B., Schultz, N. M., Sterling, S., and Thiery, W. (2018), Evaluating and improving the Community Land Model's sensitivity to land cover, Biogeosciences, 15, 4731-4757, https://doi.org/10.5194/bg-15-4731-2018.

Meier, R., Davin, E. L., Swenson, S. C., Lawrence, D. M., and Schwaab, J. (2019), Biomass heat storage dampens diurnal temperature variations in forests, Environmental Research Letters, 14, 8.

Meier, R., Schwaab, J., Seneviratne, S.I., Sprenger, M., Lewis, E., and Davin, E. L. (2021), Empirical estimate of forestation-induced precipitation changes in Europe. Nat. Geosci. 14, 473–478, https://doi.org/10.1038/s41561-021-00773-6

Meier, R., Davin, E. L., Bonan, G. B., Lawrence, D. M., Hu, X., Duveiller, G., Prigent, C., and Seneviratne, S. I. (2022) Impacts of a revised surface roughness parameterization in the Community Land Model 5.1, Geosci. Model Dev., 15, 2365–2393, https://doi.org/10.5194/gmd-15-2365-2022.

Mildrexler, D. J., M. Zhao, and S. W. Running (2011), A global comparison between station air temperatures and MODIS land surface temperatures reveals the cooling role of forests, J. Geophys. Res., 116, G03025, doi:10.1029/2010JG001486.

Naudts K, Chen Y; McGrath MJ, Ryder J, Valade A, Otto J, and Luyssaert S. (2016), Europe's forest management did not mitigate climate warming. Science, 351, 597. DOI: 10.1126/science.aad7270

Pitman, A.J., N. de Noblet-Ducoudré, F.T. Cruz, E.L. Davin, G.B. Bonan, V. Brovkin, M. Claussen, C. Delire, V. Gayler, B.J.J.M. van den Hurk, P.J. Lawrence, M.K. van der Molen, C. Müller, C.H. Reick, S.I. Seneviratne, B.J. Strengers, and A. Voldoire (2009), Uncertainties in climate responses to past land cover change: first results from the LUCID intercomparison study, Geophys. Res. Lett., 36, L14814, doi:10.1029/2009GL039076.

Renaud, V., and M. Rebetez (2009), Comparison between open-site and below-canopy climatic conditions in Switzerland during the exceptionally hot summer of 2003. Agric. For. Meteorol., 149, 873–880, doi:10.1016/J.AGRFORMET.2008.11.006.

Renaud, V., J. L. Innes, M. Dobbertin, and M. Rebetez (2011), Comparison between open-site and below-canopy climatic conditions in Switzerland for different types of forests over 10 years (1998−2007). Theor. Appl. Climatol., 105, 119–127, doi:10.1007/s00704-010-0361-0.

Schwaab, J., M. Bavay, E.L. Davin, F. Hagedorn, F. Hüsler, M. Lehning, M. Schneebeli, E. Thürig, and P. Bebi (2015), Carbon storage versus albedo change : Radiative Forcing of forest expansion in temperate mountainous regions of Switzerland, Biogeosciences, 12, 467-487, doi :10.5194/bg-12-467-2015.

Schwaab, J., Davin, E.L., Bebi, P., Duguay-Tetzlaff A., Waser, L.T., Haeni, M., and Meier, R. (2020), Increasing the broad-leaved tree fraction in European forests mitigates hot temperature extremes. Scientific Reports, 10, 14153, https ://doi.org/10.1038/s41598-020-71055-1

Vanden Broucke, S., Luyssaert, S., Davin, E. L., Janssens, I., and van Lipzig, N.: New insights in the capability of climate models to simulate the impact of LUC based on temperature decomposition of paired site observations, J. Geophys. Res.-Atmos., 120, 5417–5436, https://doi.org/10.1002/2015JD023095, 2015.

Wan, Z., Hook, S. and Hulley, G. (2015). MOD11A2 MODIS/Terra Land Surface Temperature/Emissivity 8-Day L3 Global 1km SIN Grid V006 [Data set]. NASA EOSDIS LP DAAC. doi: 10.5067/MODIS/MOD11A2.006

Windisch, M.G., Davin, E.L., and Seneviratne, S.I. (2021), Prioritizing forestation based on biogeochemical and local biogeophysical impacts. Nat. Clim. Chang. 11, 867–871, https://doi.org/10.1038/s41558-021-01161-z

Zaitchik, B. F., A. K. Macalady, L. R. Bonneau, and R. B. Smith (2006), Europe’s 2003 heat wave: a satellite view of impacts and land–atmosphere feedbacks. Int. J. Climatol., 26, 743–769, doi:10.1002/joc.1280. http://doi.wiley.com/10.1002/joc.1280.

Zhao, K., and Jackson, R. (2014), Biophysical forcings of land-use changes from potential forestry activities in North America. Ecol. Monogr. 84, 329–353