

FORREG: Forest regeneration in Switzerland analyzing and modelling LFI regeneration data: Final report in the FOEN/WSL program forest and climate change

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FORREG Final Report

Forest regeneration in Switzerland

analyzing and modelling LFI regeneration data

A project funded by the BAFU-WSL program on
“Forests and Climate Change” in Switzerland

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Project Summary

We successfully fitted models for mapping the binary regeneration success of two important tree species in Switzerland, namely *Fagus sylvatica* (beech) and *Picea abies* (spruce). This is expressed by high scores in repeated split-sample tests (AUC of all models >0.8) and by high agreements between observed and predicted regeneration success under current climate and stand structural conditions. In fact, we did not fully expect such a good result, since we were not able to include some of the important drivers of regeneration success (e.g. forest management history or browsing intensity). Yet, the models are very successful in capturing the general patterns of observed forest regeneration, and they also map well the rather patchy distribution, which results both from stochastic processes and specific canopy structural conditions.

We were not able to calibrate specific drought conditions of the upper soil layer due to lack of availability in suitable data. Such data was not available readily, and still is not available for all three climate models used in this project. In addition, we were not able to calibrate the effect of longer-term climate variability. We used climate extremes as measured over shorter or longer time periods. Because of some problems in single-day extreme values in the data used, we decided to abstain from using annual absolute extremes of these layers as predictive variables. Rather, we used 30-year annual or period means of extremes.

In general, the results project that under future climates spruce will largely fail to regenerate on the Swiss Plateau and in the Southern half of the Ticino. It will also only remain viable by means of regeneration on the highest sites of the Jura Mountains. In the Alps, however, the species will continue to do well, and will likely expand its regeneration to areas above the current treeline. We were not able to model this effect, since we did not obtain the climate data from Meteotest as requested (1 km raster of daily data across all of Switzerland), and only obtained daily data for the LFI 2 plots (ca. 6'500 plots). For beech, there is uncertainty as to where on the Swiss Plateau the species will remain viable for regeneration. Most likely, it will no longer regenerate well on the warmest and driest parts of the Plateau (mostly to the West) and of the valleys interior and south of the Alps, but might possibly remain regenerating in valleys north of the Alps and on the more mesic and cooler sites on the Plateau. Opening forests for natural regeneration, and protecting saplings from browsing will support the regeneration there.

For the final report, we attempted to update the existing models with 2-4 additional tree species, for which we thought to have sufficient data. Unfortunately, the models are quite data hungry due to the many variables that affect regeneration and due to the stochastic nature of the regeneration process. We were not successful in generating regeneration models for the additional 4 species we had envisioned, and did not include these results in the final report.

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Introduction

Forest regeneration is a limiting factor in the dynamics of species that ultimately define the geographic range of forest trees. Regeneration is strongly limited by inter- and intraspecific competition (competition for light with seedlings from other species; intraspecific density dependent regulation; shading by taller individuals and trees, facilitation by taller trees through sheltering from climate extremes) and is regulated and constrained by a range of climatic (frost, drought, evaporation) and soil (chemistry and physics) properties. While there is a rich experimental literature on factors that may influence seed regeneration, there is considerably less information on other important aspects that influence the likelihood that trees successfully can establish.

First, there have been only few attempts to model the regeneration of trees in a spatially explicit manner. This is likely due to the different nature of experimental and natural settings, with detailed soil water potential information in experiments and the difficulty to translate such physical information to the forests at large. Existing attempts that can e.g. be applied to relatively large landscapes include the work by Wimberly & Spies (2001) who statistically modeled and analyzed tree regeneration at the landscape scale in Oregon using Landsat TM, aerial photographs, digital elevation and stream network data as predictors. Therefore, this model primarily includes stand structural, but little to no climatic information. In a similar approach Weisberg *et al.* (2003) assessed to what degree the overstory diameter structure can predict the understory vegetation cover, an indication of tree establishment. Similar research has been published by Clark *et al.* (1996), Lookingbill *et al.* (2000), Brang *et al.* (2003; 2005), or by Camarero *et al.* (2005). Other studies have focused on seedling or sapling growth, rather than (only) on regeneration or establishment (Cunningham *et al.* 2006a, b; Hunziker & Brang 2005). A spatially explicit regeneration modelling study that is similar to the approach used in ForRegCH has recently been published for the North-Western US forests (Dobrowski *et al.* 2015).

Gap dynamics models (Bugmann 2001) that simulate the temporal stand dynamics of forests under the influence of a fluctuating or changing climate, as well as under other important drivers, such as FORECE (Kienast 1987), ForClim (Bugmann 1994), or DiscForm (Lischke *et al.* 1998) implicitly have a model for tree establishment (indicating under what climatic conditions trees can establish into simulated stands). However, such routines are usually not specifically addressing the seed germination or the whole tree regeneration process explicitly, although some refinements and specific implementations have recently been made to improve the realism of tree establishment modeling (e.g., Wehrli *et al.* 2007). Finally, very few models only exist to date that have a full tree regeneration and establishment process implemented that are also operable at the landscape scale. TreeMig (Lischke *et al.* 2006) is e.g. one of them, while many others rather operate in a single stand mode only. However, since such spatially explicit modeling of stand dynamics is computationally very demanding, no easy simulation for many different model realizations at high spatial resolution is currently feasible.

Therefore, a simple statistical model that is able to predict to what degree single tree species may regenerate and finally establish as young trees in a stand as a function of stand structure, climate and soil conditions is desirable. Calibrating such a

model requires (1) the availability of statistically sufficient (many hundred, if not thousand) sites with observations on regeneration and establishment, (2) the availability of stand structural information, and (3) the availability of high-resolution (spatially and temporally) climate and soil information relevant to regeneration and establishment. Such data is readily available for all of Switzerland with the exception of sufficiently well resolved soil characteristics (mostly soil physical properties), although minimal data on soils are already available. Therefore, it seems feasible and desirable to model the regeneration niche of trees and their establishment into stands at the scale of Switzerland, at least for the forest inventory sites at which regeneration success is monitored. In order to transfer such models to the whole landscape of Switzerland, a transfer of stand structural measurements from forest inventory plots to remote sensing-based assessments of stand structures would be required, but was not envisioned to be developed for this project.

One of the difficulties in modelling regeneration is that the success of regeneration is a highly stochastic process. Trees produce millions of seeds and many of them also germinate. But only very few of them make it to the sapling stage. There are many reasons why regeneration can fail. Yet, it is statistically challenging to extract the information of why regeneration fails here or there and under what conditions it then finally can succeed, if the ratio of prevalence of success is so low. It means that detailed models with many variables are not likely successful, specifically also because too many variables would start to interact with the stochastic spatial patterns that exist (partly due to specific management histories that are not well known in forest inventory stands).

Tree species have started to respond to climate change both by changes in regeneration but also in mortality, the two important stand dynamic processes. While we observe significant changes at the (usually drought-constrained) trailing edge (i.e. primarily mortality) in some species and some locations (Allen *et al.* 2010), there is only a weak signal (of increased regeneration) currently observable at the upper or northern range edge (Gehrig-Fasel *et al.* 2007; Woodall *et al.* 2009). The reason for this slow upward and northward movement likely originates from a slow release in cold-temperature related extremes and means. In order to better understand the effect of temperature on upward or poleward movement of trees, and to understand the change in habitat suitability just north of (or at higher elevation than) the current range, it is important to track the temperature related variability and extremes. Zimmermann *et al.* (2009) have demonstrated that climate (including temperature) extremes significantly influence species ranges. Having such variables at hand for analyses allows for a better assessment of the likely consequences of climate change on tree species ranges.

While the rear edge of a species' distribution is often related to drought effects (Allen *et al.* 2010; Dobbertin *et al.* 2004; Rigling *et al.* 2013) and often associated with mortality events accompanied by a lack of regeneration (Rigling *et al.* 2013), the front edge of a species' range is more often controlled by temperature, notably low temperature constraints during the leaf flush phase (Körner *et al.* 2016).

Here, we developed a range of temperature related maps and indicators of temperature extremes. These were used to judge what areas might become suitable to the regeneration of beech (*Fagus sylvatica*) and spruce (*Picea abies*). We attempted to build regeneration models for other than these two most abun-

dant tree species, such as fir or oaks. Yet, the data structure is too sparse and we were not able to build sufficiently good models. In addition, we had some problems with extreme values in the climate data obtained. While for average temperature-based measures these few possibly erroneous daily values did not really matter, they obviously have more influence when long-term extremes are calculated (which we intended for better understanding the effect of climate extremes on regeneration success and failure). Therefore, we decided not to use single-day absolute extremes and standard deviations (reflecting variabilities) in our regeneration models in order to avoid spurious effects. This may also have had an effect on the failure to fit successful regeneration models for the species with fewer observations of regeneration.

Project objectives

Research objectives

The following two research questions were addressed:

- (1) What are the spatial patterns of tree regeneration and establishment in Swiss Forests under current and potential future climate conditions for beech and spruce.
- (2) How do climate (mean, variability and extremes), stand structure (conifer/broadleaf mixing, canopy density) and soil properties (base saturation,) combine to explain the spatial variation and future (21 Century) pace of tree regeneration and establishment for these two species.

RESULTS 1: Model summary and evaluation

All binary models of regeneration success for the two species (*Fagus sylvatica*, *Picea abies*), one each for smaller (10-40 cm in size) and larger (40-130 cm) seedlings/saplings provided similar calibration strengths (adj. D²) model accuracies (AUC, PCC, Sensitivity) in repeated (5x) split sample tests against observed regeneration patterns (Table 1). For smaller and larger saplings, AUC values reached 0.834 (± 0.007) und 0.828 (± 0.009) for beech and 0.804 (± 0.010) und 0.828 (± 0.008) for spruce, respectively. These measures can be considered credible for the fitted models to capture the distribution patterns of tree regeneration, especially given the fact that regeneration is a quite stochastic process, and given that the models capture effects of climate, stand structure and site conditions, but lack otherwise important aspects, such as e.g. of browsing (densities), mast seeding, or forest management history (due to lack of spatial data). The models include variables representing extremes of climate parameters, but not their frequency or temporal variability, because the data obtained by Meteotest showed very strange patterns for these variability metrics. It also showed partly very strange individual values, but these were probably infrequent enough (at least in the third edition) to not disturb the models too much. Also, good soil-adjusted drought data was not available for this project.

Models of the regeneration density (saplings per hectare) were also calibrated originally. However, these models were only marginally better, partly even worse, than the binary models representing the probability of presence of regeneration.

Table 1: Calibration strengths of GLM models for the regeneration smaller (10-40cm) and larger (40-130 cm) saplings of *Fagus sylvatica* (beech) and *Picea abies* (spruce) for either binary presence/absence of regeneration or the (log of) abundance of regeneration (individuals per hectare) on LFI plots.

	<i>Fagus sylvatica</i>		<i>Picea abies</i>	
	small 10-40cm	large 40-130cm	small 10-40cm	large 40-130cm
adj. D ²	0.31	0.24	0.28	0.28
AUC	0.83	0.83	0.80	0.83
Cut-level	0.60	0.59	0.52	0.62
PCC	0.77	0.74	0.75	0.74
Sensitivity	0.80	0.78	0.73	0.71

adj.D²: GLM model calibration strength; AUC: Area under the ROC curve; Cut-level: optimized cut level of probabilistic output for presence/absence mapping; PCC: percent correctly classified presences and absences; Sensitivity: true positive rate.

Because these abundance models did not really improve the information and usefulness of the models, we only provide information on binary model outcomes.

Table 2 summarizes the variables retained in the four different regeneration models. See the methods section for more details on model building, variable preparation and analysis. An initial, large set of predictors was reduced to avoid the presence of highly correlated variables, and was meant to contain a mix of soil, stand structural and climate (including extremes) variables. While standard deviations were prepared, we abstained from using them because of the remaining presence of strange patterns originating from some data layers in the obtained data.

Table 2: Summary of used variables (X) in the 4 models. The climate variables and the species-specific basal areas were selected individually per model, while all other variables were used in all models. Lowercase x denotes a variable that was insignificant and thus removed in the stepwise variable selection. The variables are explained below the table and in the method section.

Explanatory Var.	<i>Fagus sylvatica</i>		<i>Picea abies</i>	
	small	large	small	large
<i>Prec_me.Yr_4</i>	–	–	X	–
<i>Prec_me.SH_0-6</i>	X	–	–	–
<i>Prec_me.Su_0-10</i>	–	X	–	–
<i>Prec_me.SH_0-10</i>	–	–	–	X
<i>Tave_me.WH_0-2</i>	X	–	–	–
<i>Tave_me.WH_0-10</i>	–	–	–	X
<i>Tmax_me.Su_0-10</i>	–	X	–	–
<i>Tmin_me.Wi_0-6</i>	–	–	X	–
<i>Sp.10</i>	–	–	X	X
<i>Sp.50</i>	X	X	–	–
<i>avDia</i>	X	X	X	X
<i>VegCov</i>	X	X	X	X
<i>LeafCov140</i>	x	X	X	X
<i>PropNeedle</i>	X	X	X	X
<i>BS</i>	X	X	X	X
<i>AWC</i>	X	x	x	x

Prec=precipitation sum; *Tave*=daily mean temperature; *Tmax*=daily max temperature; *Tmin*=daily minimum temperature; *me*=mean; *sd*= standard deviation; *Yr*=Year; *SH*=summer halfyear; *WH*=winter halfyear; *Su*=summer; *Wi*=winter; *0-n*=mean calculated over last *n* years; *n*=value of *n* years ago; *Sp.10*=proportion of beech basal area on stand basal area per plot; *Sp.50*=proportion of spruce basal area on stand basal area per plot; *avDia*= mean diameter; *VegCov*=cover proportion of herb layer; *LeafCov140* =leaf cover proportion above 140 cm; *PropNeedle*=proportion of needleleaf trees on plot; *BS*=base saturation; *AWC*=available water capacity.

RESULTS 2: Regeneration under current climate

Forest regeneration is a patchy process, and only occurs if conditions are optimal for regeneration. If e.g. the canopy is closed then regeneration is often impossible due to a lack of light. On the other hand, in drier environments, partial shade may protect seedlings and saplings from severe drought in direct sunlight. As a result, not all LFI plots on which a target tree is growing in the canopy, will exhibit regeneration of that same tree species. Figure 1 illustrates the currently observed (Figure 1A) and the simulated distribution of regeneration under current canopy conditions (Figure 1B) on LFI plots summarized at ca. 2.0 x 2.5 km across Switzerland for beech saplings (10-40 cm in size) under actual canopy and site conditions.

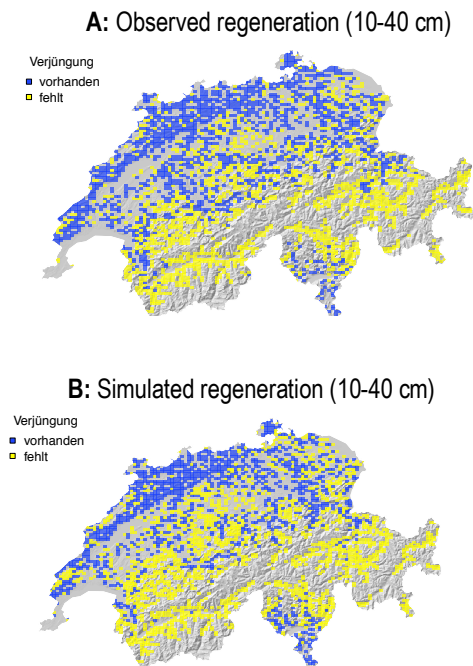


Figure 1: Summary of observed (A) and simulated (B) forest regeneration on LFI plots for beech (*Fagus sylvatica*) saplings (10-40 cm in size) under current stand structure and site conditions across Switzerland mapped at ca. 2.0 x 2.5 km pixels for better visibility.

The two maps in Figure 1 (A & B) reveal very similar patterns, indicating that the model is well able to capture the general distribution of beech regeneration in Switzerland. Notably, the model captures the regions suitable for regeneration under current climates well, indicating that the Jura, the Swiss Plateau, and the mid-to-low altitudes of the Ticino are mostly suitable, given that the stand structure and site conditions are optimal. Under strong canopy closure (*LeafCov140*), and especially under high needleleaf canopy cover (*PropNeedle*) and low base saturation (*BS*), the species does not regenerate (well). Therefore, several pixels are mapped as currently unsuitable, despite having an otherwise suitable climate.

For spruce, we find similar patterns (Figure 2). Regeneration is abundant in almost all parts of the Alps except in some of the driest and lowest (warmest) parts. It is also available abundantly on the highest parts of the Jura range (mostly the western and more elevated part). On the Swiss Plateau, regeneration is very patchy, most abundantly on the higher elevated parts of

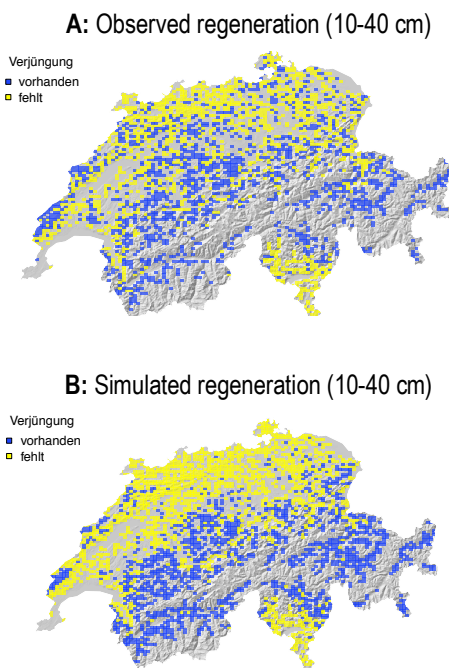


Figure 2: Summary of observed (A) and simulated (B) forest regeneration on LFI plots for spruce (*Picea abies*) saplings (10-40 cm in size) under current stand structure and site conditions across Switzerland mapped at ca. 2.0 x 2.5 km pixels for better visibility.

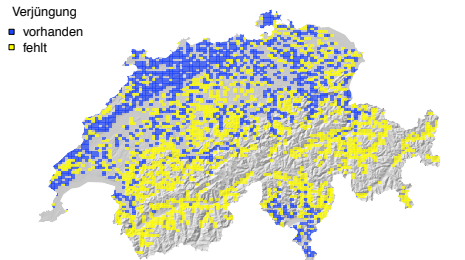
the Napf and Säntis regions. Otherwise, regeneration is observed very patchily throughout the Plateau, with many unsuitable sites. This originates likely from the fact that spruce is largely planted on the Plateau, and is regenerating if competition from other species is not too severe and if local site conditions are optimal (low base saturation). The simulations under current site conditions (climate, stand structure, soils) represent the observed distribution generally well. Here, the suitability for regeneration on the Plateau is mapped to be less suitable than is visible from the observed patterns. This may originate from the fact that the important base saturation map may not capture all local site conditions perfectly, and partly overestimate the percent base saturation per plot, which reduces the likelihood of spruce regeneration.

RESULTS 3: The effect of stand structure

Stand structure has a strong influence on the regeneration success on a site. Therefore, forest managers often open up stands in order to facilitate natural regeneration in forests. It is therefore meaningful, not only to simulate forest regeneration under current stand structural conditions, but rather also under conditions that are more optimal for natural regeneration. Figure 3 and 4 compare the current canopy and site conditions for beech and spruce, respectively, with the assumptions that on each LFI plot canopies are semi-open (40% cover only) and have more optimal base saturation (80% for beech, 20% for spruce) and ground vegetation cover (only 20%). Canopy cover and ground vegetation cover can be managed, while we varied base saturation as well, because spruce plantations may strongly alter base saturation locally. By varying base saturation, we can check if the climate or canopy conditions would allow beech regeneration otherwise.

In both simulations for beech and spruce we observe that when canopy (and some site) conditions are kept constant across all sites, we find a less patchy, more homogenous distribution of regeneration success, indicating the climatic potential of the process. Now, many more sites are generally suitable on the Swiss Plateau, both for beech and spruce.

A: Simulated regeneration (10-40 cm), current canopy



B: Simulated regeneration (10-40 cm), semi-open canopy

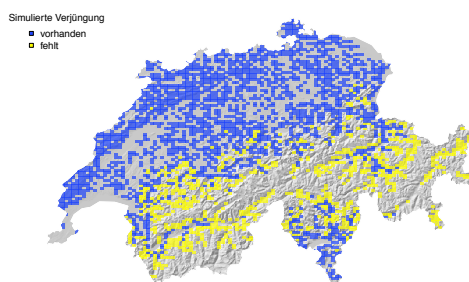


Figure 3: Comparison of simulated binary regeneration success under current (A) or semi-opened canopy conditions (B) for *Fagus sylvatica* (beech).

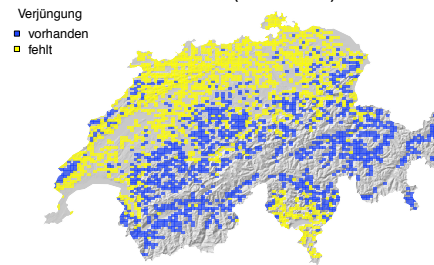
RESULTS 4: Regeneration under future climates

Under future climate conditions, we only compare predictions using standardized, semi-open canopy conditions as outlined in the methods section. This allows for comparing the effect of climate on regeneration success across Switzerland for both, beech and spruce saplings of smaller or larger size. Here, only data for 2080 (+/- 15 years) are presented. More material for 2050 and for more open (20%) canopy cover are presented in appendix A1 for beech and in appendix A2 for spruce.

In Figure 5, the simulated regeneration success of smaller (10-40 cm) and larger (40-130 cm) saplings is presented for projected future (2050 & 2080) climate conditions. The projections are based on three RCM simulations, which had been down-scaled to LFI points as daily climate time series by Meteotest (Remund *et al.* 2016). Smaller and larger saplings reveal very similar patterns under 2050 climates for both species, with the larger saplings showing a bit higher regeneration success on the Swiss Plateau for beech. Smaller saplings thus are more likely to fail in regenerating than larger ones, a fact that is known from forest management.

Under projected 2080 climates, similar difference occurred for spruce, but not for beech. By 2080, the Swiss Plateau is likely no longer harboring a climate for regenerating smaller saplings of beech, but larger ones, still seem to regenerate to a certain degree (at least for some of the three RCM climate scenarios used). This means that beech regeneration is becoming uncertain for beech by 2080, but that this is specifically true for smal-

A: Simulated (10-40 cm), current canopy



B: Simulated (10-40 cm), semi-open canopy

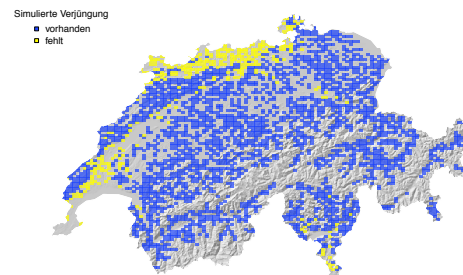


Figure 4: Comparison of simulated binary regeneration success under current (A) or semi-opened canopy conditions (B) for *Picea abies* (spruce).

ler, but not so much for larger saplings. In a similar way, the simulations differ in the Ticino between smaller and larger saplings for beech. For spruce, the patterns look quite different. First, there is strong agreement between smaller and larger saplings, and second, the smaller saplings seem to cover more or less the same span of regeneration success across the Swiss landscape by 2080. Slight differences are visible in the western Jura, Western Prealps and in the Napf region north of the Alps. In the Central part of the Alps, the two models agree to a very high degree.

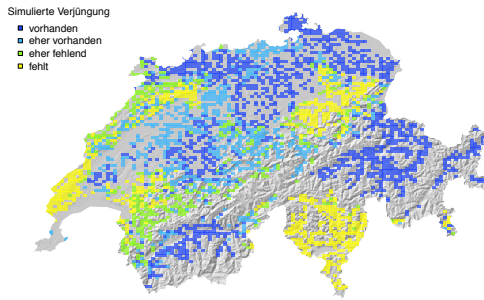
In summary, the results are in good agreement with the results from the species distribution modelling of forest tree species in Switzerland¹ (Zimmermann *et al.* 2014; Zimmermann *et al.* 2016). *Picea abies* can be expected to fail regenerating (and finally disappear growing) on the Swiss Plateau, and retreating to the higher elevations in the Alps, and to the highest in the Jura Mountains. Also, the southern Ticino is no longer harboring suitable conditions for regeneration (and distribution) of spruce. For *Fagus sylvatica*, there is agreement that the warmest parts of the Plateau and of the interior and southern valleys are no longer suitable for regeneration and distribution. However, there is comparably high uncertainty, as to whether beech can still regenerate and distribute on cooler parts of the Plateau. In locations with sufficient water supply or sufficiently mesic soil conditions, the species will likely still persist. In other regions, it might slowly (probably not rapidly) be outcompeted by oaks. The driver behind this uncertainty is most likely the frequency and severity of future droughts, and not so much of future heat. Under severe and frequent drought events, beech might disappear relatively rapidly, and be replaced by oaks.

¹ <http://www.wsl.ch/lud/portree>

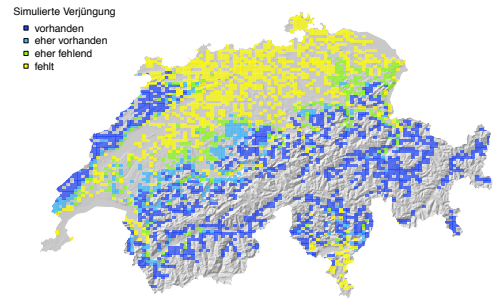
Fagus sylvatica

Picea abies

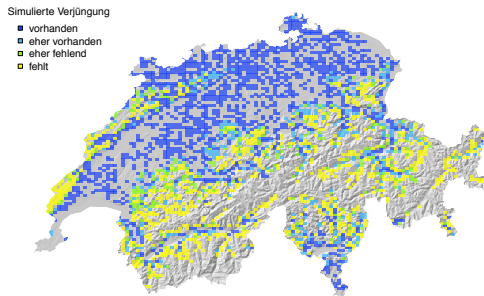
A: Simulated smaller (10-40 cm), semi-open, 2050



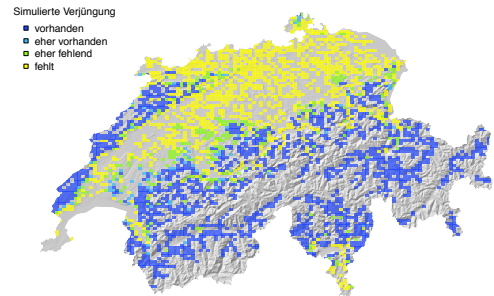
B: Simulated smaller (10-40 cm), semi-open, 2050



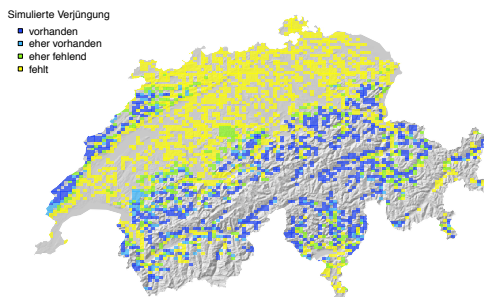
C: Simulated larger (40-130 cm), semi-open, 2050



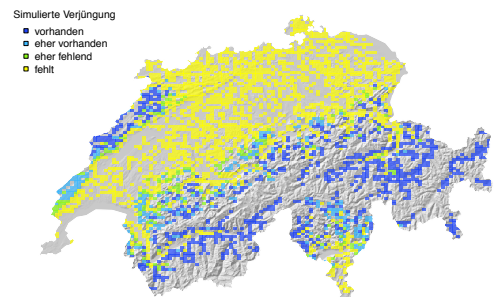
D: Simulated larger (40-130 cm), semi-open, 2050



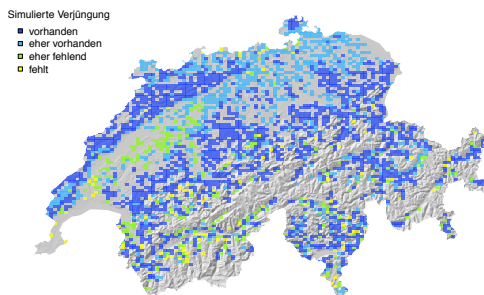
E: Simulated smaller (10-40 cm), semi-open, 2080



F: Simulated smaller (10-40 cm), semi-open, 2080



G: Simulated larger (40-130 cm), semi-open, 2080



H: Simulated larger (40-130 cm), semi-open, 2080

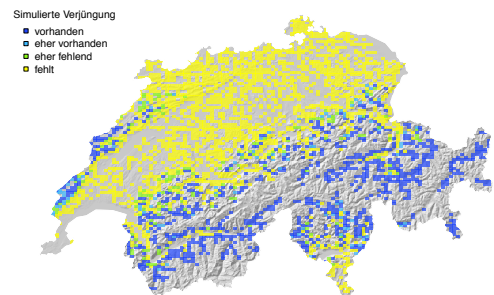


Figure 5: Comparison of simulated, binary regeneration success for *Fagus sylvatica* and *Picea abies* under projected 2050 (A-D) and 2080 (E-H) future climate conditions and standardized, semi-open canopy conditions. Simulations are mapped onto LFI plots, and aggregated to ca. 2.5 x 2.0 km cells for better readability. Future climate projections are averaged across 3 RCMs so that values between 0 and 1 indicate the level of agreement of regeneration success among climate models. Simulations for both time periods are done for both smaller (10-40 cm; panels A,B,E,F) and larger (40-130 cm; panels C,D,G,H) saplings. Left panels (A,C,E,G) are for *Fagus sylvatica*; right panels (B,D,F,H) are for *Picea abies*.

Management implications

For beech there is a tendency to lose regeneration capacity on the Swiss Plateau around and after 2050 (see appendix A1). This loss is much reduced for larger (40-130 cm) saplings, meaning that plantation of such saplings has the potential to sustain beech in many (mostly cooler and more mesic) sites to the end of the 21st Century. Keeping stands from getting too dense will additionally increase natural regeneration and will additionally avoid too heavy effects from drought events. Mixing stands with high proportion of conifers will not be a good strategy, as beech does not regenerate well if base saturation is decreased due to high fractions of needle litter. Low proportions of spruce or fir do not much affect natural regeneration. However, in many regions of the Swiss Plateau and in the Ticino, natural regeneration might be hampered by the fact the smaller saplings (10-40 cm) might not survive the increasing drought and heat levels (appendix A1).

At higher elevations, beech will likely sustain and increase its regeneration and growth capacity. New locations that are currently colonized by spruce will become suitable for beech regeneration, at least from a climatic perspective. However, regeneration might be difficult in many sites, if stands are too dense and dark from sustaining spruce trees, and because of low base saturation due to needle litter. Planting larger saplings will help overcoming this problem and create stepping-stones for beech regeneration.

For spruce, there most is likely no future potential for regeneration or growth on the Swiss Plateau. Until 2050, there is still a reasonable potential for regeneration, at least for smaller saplings (10-40 cm), but obviously already much reduced for larger saplings, meaning that they might not survive and grow to adult trees. At higher elevations, spruce will likely sustain and grow well. It already colonizes all forested areas up to the treeline in many (more mesic) parts of the Alps. Here, new areas can be expected to become suitable above the current treeline. Colonization of these newly suitable areas is not always easy (nor wanted). Where colonization is wanted, removal of dense canopy cover of the ground vegetation (especially of dense dwarf shrub layers) accompanied with local plantations for creating regeneration stepping stones will assist the upward movement of the treeline.

Concluding remarks

The models are successful in mapping the regeneration success of two important tree species in Switzerland. This becomes especially evident from figures 1 and 2, which simulate the distribution of binary regeneration success under current climate and site conditions. In fact, we did not fully expect such a result, since we are not able to include some of the important drivers of regeneration success (e.g. forest management history, browsing intensity or climate extremes). Yet, the models are very successful in capturing the general patterns of observed forest regeneration, and they also map the rather patchy distribution, which results both from stochastic processes and specific canopy structural conditions.

We were not able to calibrate specific drought conditions of the upper soil layer due to lack of availability in suitable data. Such data was not available readily for all LFI sites, and are neither for all three climate models used in this project. In addition, we

were not able to calibrate the effect of longer-term climate variability (extremes). We had intended to use climate extremes as measured over shorter or longer time periods. Yet, the maps of the variability in extremes (across years to decade) were obviously partly erroneous. We therefore decided to use only climate data on shorter- or longer-term means and no measures of variability (st.dev) or extremes, so as not to be dependent on possible remaining errors that may more strongly affect variabilities and extremes than means.

In agreement with the program coordinators, we switched from using remotely sensed predictors to using the LFI stand structural variables, and therefore we predicted only to LFI sites. Because we had data only available for LFI sites, these models cannot be projected easily to sites other than the LFI plots. *Picea abies* – and to a certain degree even *Fagus sylvatica* – is therefore underestimated in its response to climate change, since we cannot predict to sites above the current treeline that will become suitable by the end of the 21st Century. Since the LFI points are scattered at >1km distance, and partly much farther, where no forest is available, we decided to map the response of our models at a ca. 2.5 x 2.0 km resolution for better visibility of the model results.

In accordance with the program coordination, we added base saturation and nitrogen deposition as predictive layers to the models. We had to remove nitrogen deposition during the analysis phase. It tended to explain regeneration well, specifically the abundance of regeneration. Yet, we didn't have nitrogen deposition available under projected future conditions, and the models only lost less than 0.02 of R² when removing N-deposition from the models. Also, some projections under future climate became more realistic when dropping N-deposition, due to the fact that in our projections, we were not able to use future deposition values, and thus had to keep depositions constant. Under such conditions (future climate but current nitrogen deposition), there was obviously an interaction effect between Ndep and climate that resulted in very weird projections. Finally, we dropped the regeneration abundance models, since they did not improve the modelled output compared to binary predictions and projections. Measures of abundance were not easy to compare anyway due to the change in measurement between LFI inventorying periods.

It was our ambition for the final report to update the existing models with 2-4 additional tree species, for which we thought to have sufficient data. Unfortunately, the regeneration models are quite data hungry due to the many variables that affect regeneration and due to the stochastic nature of the regeneration process. We tested regeneration models for additional species such as *Quercus robur*, *Quercus petraea*, *Acer pseudoplatanus* or *Abies alba*, but failed to build models that were sufficiently accurate and predictive. We therefore did not include them in the final report.

Methods

We had already delivered a preliminary report and a first development of the basic data and an initial model from own financial sources. Based on feedbacks from the program committee, we had adjusted the proposal according to the input from the committee, and submitted an interim report (M1). The final report (which included additional tests, optimizations of the existing models also for the scientific programme synthesis) is

based on the same general procedure for finalizing the model development and application as was presented in the M1 report. The main difference was that we decided to drop the climate extremes variables, after spotting continued errors and data inconsistencies on single days. These single days did not affect (much) the mean statistics, yet had strong influences on the extremes statistics. We adopted the following procedure:

- (1) All LFI data was prepared (regeneration and establishment as binomial and ordinal predictor), and no NDVI or 3D stand structural data (mean and variability per plot) is calculated, but rather LFI structural variables are used; in addition, all climate and soil data is compiled (available water capacity (AWC) (0-100cm), base saturation (BS) (0-40cm), and N-deposition (Ndep), according to requests from the program committee). BS was provided by Braun *et al.* (2015), NFK was provided Remund & Augustin (2015), while Ndep, BS and AWC was provided by Meteotest as raster layers.
- (2) Models were trained by taking daily temperature and precipitation data from Meteotest (Remund *et al.* 2016). These data have been aggregated to monthly seasonal means and extremes over the periods preceding (at various lengths) the regeneration measurements. The model uses a regression-based approach with a binomial (for the presence-absence of regeneration) and a Poisson (for regeneration density measured as saplings per hectare) distribution of the dependent variable. We explored GLM, GAM and randomForest as statistical model alternatives to optimally fit models. Because of data errors and inconsistencies, we dropped the climate extremes variables from the model calibration and only used means instead.
- (3) Input from the drought mapping (current and future; Walther *et al.*) was envisioned to use, but was not available for this project for all LFI sites in Switzerland.
- (4) The final regeneration (Verjüngung) was modelled at two different size classes, namely 10-40 cm size (smaller saplings) and 40-130 cm size (larger saplings). Instead of using only the regeneration data from one LFI period, we combined all available LFI measurement periods in order to have more data available for modelling. This is crucial as the models are very data hungry due to the very stochastic nature of the regeneration process.
- (5) The model was then applied to future climate conditions in an ENSEMBLE mode originating from 3 RCMs (representing climate uncertainty) applied to all LFI data points. Since we do not know the stand structure of the future, we applied standardized stand structural sets for each species, in order to allow assessing the climate effect on regeneration. Therefore, we set the same stand structural and some other non-climatic variables to constant values at every LFI point. Final results were averaged across all climate models used, which allows for mapping the model uncertainty of regeneration success.
- (6) This protocol was explored and worked out in detail for the two most abundant tree species, namely: *Fagus sylvatica* (beech) and *Picea abies* (spruce). The intermediate report aims at exploring what additional species might be modelled given the frequency of available data.

The results provide maps of regeneration success for two size classes of the two most important tree species at the scale of Switzerland (LFI points), sensitive to important stand structural

variables, climate, and site parameters. This allows forest managers to decide on the level of risk they are experiencing with regards to these two major tree species under future climates, and on the impact of canopy structure under a range of climate and site conditions on regeneration success.

General method

The proposed research builds on a spatially explicit, statistical analysis of tree regeneration (Jungwald LFI) and establishment (Baumdaten LFI) in response to a set of spatial predictors. The built model then predicts regeneration and establishment of important tree species as a function of these predictors in a spatially explicit manner and allows for exploring the effect of climate change on tree regeneration and establishment. Tree regeneration success (*Regen*) of species *T* can be summarized as follows (eqn. 1):

$$Regen_T = f(Struct, Env, Soil) \quad (1)$$

where: *Struct* is a matrix of stand structural variables such as canopy cover density, ground vegetation cover, or, average diameter of all trees on the plot; *Env* is a matrix of temperature and precipitation related variables expressed in the form of means and extremes and *Soil* is a matrix of soil-based variables, such as base saturation or N-deposition (where the latter was dropped as it was not available for future projections). These three sets of variables serve as predictors of regeneration success in our model analyses. *Habitat* is a simple description of the proportion of coniferous trees on the regeneration success of individual species.

Dependent Variables

The dependent variable for “regeneration” is taken from the “Jungwald” data set, a specific data set measured since LFI2 at >5000 sites across Switzerland with every inventory period. Seven classes of juveniles are distinguished, the first 4 being measured as numbers per species and height class ranging in sapling height from 10 to 130 cm, and the latter being measured as diameter at breast height (dbh at 130cm of height) ranging from 0.1cm to 11.9 cm, which is just below establishment size. However, every inventory period has measured the different size classes of regeneration slightly differently, with different borders between neighboring size classes and with different spatial settings of the measurement plots. We then first decided to use only two size classes (small = 10-40 cm; large = 40-130 cm) that could be derived +/- clearly and consistently from all three inventories (LFI2, LFI3, and LFI4), and to scale the number of regeneration saplings to numbers per hectare in order to avoid effects from differing plot sizes. We distinguish the two variables in order to explore if there are strong environmental differences between regeneration of smaller (10-40 cm) and larger (40-130 cm) saplings on LFI plots, and to better understand what variables are driving the spatial structure of the tree establishment process. To this end, we pooled all LFI2, LFI3 and LFI4 data of regeneration. Table 3 lists the number of plots with observed data for the 11 most abundant regenerating species across the three inventory periods used. It becomes clear that next to the here used two most abundant species, we can easily calibrate models also for *Acer pseudoplatanus* and *Abies alba*. Yet, for the other species there are only comparably few observations plots available, considerably less than 500, which we consider a minimum to build credible models of regeneration success.

Table 3: The 11 most abundant species that potentially can be used or come close to being used for calibration of regeneration models.

	Size class	
	10-40 cm	40-130 cm
<i>Fagus sylvatica</i>	8265	8587
<i>Picea abies</i>	6334	8187
<i>Acer pseudoplatanus</i>	4445	2088
<i>Abies alba</i>	2440	1319
<i>Quercus robur</i>	360	90
<i>Quercus petraea</i>	315	69
<i>Castanea sativa</i>	301	201
<i>Carpinus betulus</i>	273	194
<i>Larix decidua</i> (& <i>kaempferi</i>)	267	485
<i>Quercus pubescens</i>	79	40
<i>Pinus sylvestris</i>	60	77

Because these abundance models did not really improve the information and usefulness of the models, we only provide information on binary model outcomes. We first had tested both binary models of regeneration success (number of regenerating individuals >1) as well as models with log(abundance) as dependent variables. Table 1 lists the model qualities (R², which represents the calibration strength, as well as AUC, cut level, sensitivity and PCC, representing model accuracies and model characteristics). Due to the very similar results, we decided to pursue only the use of binary regeneration success models. These are more useful for management purposes than the log(abundance) models, since for the latter, it is not clear what value stands for success.

Predictor variables

Climate data: We used daily climate data originating from three RCMs (CLM, RCA, RegCM3) and downscaled by MeteoTest (Remund *et al.* 2016) to the LFI sites. From these daily climate time series spanning from 1961-2100, we extracted aggregated value of means and extremes for periods of various length. Yet, the maps of the variability in extremes (across years to decade) generated from the originally obtained data were obviously partly erroneous. They showed a very strange pattern of north to south striping (with individual cells of very extreme values). The second delivery of the data was not improved and still contained heavily erroneous data in some days and for some regions (see also Appendix A5 in Zimmermann *et al.* 2016b), which strongly affects variabilities and extremes statistics. We therefore decided to exclude these layers of variabilities and extremes as predictive variables.

Once all climate layers were ready, we then tested in preliminary analyses, which sets of parameters best explained the regeneration of smaller or larger saplings. Yet, aggregations were not simply calculated for a longer period of climate Normals (such as e.g. 1981-2010), but rather for many different periods relative to the recording of regeneration. This way, climate extremes and means were calculated for the period of recordings, and for the period covering the last $n = 2, 4, 6, 8, 10$ years prior to the recording, and in addition we calculated the means and extremes of exactly 2, 4, 6, 8, 10 years before the regeneration measurements took place. This latter, in order to check if specific events in the past had a specific influence on the regeneration success. For each calculation period (e.g. $n = 4$), we calculated annual means and extremes, but also half years (SH=summer half for months 4-9; WH=winter half for months 10-3) and quarters (Sp=spring, Su=summer, Fa=fall and Wi=winter for months 3-5, 6-8, 9-11 and 12-2, respectively), and we calcu-

lated means and standard deviation (as variability and expression of extremes) of minimum, mean and maximum temperature (TMIN, TAVE, TMAX) and of precipitation sum (PRCP). As reported above, we dropped the standard deviation layers later, due to missing trust in extremes statistics from the available data.

From these many variables, we extracted a set of climate variables for each of the dependent variables (2 size classes per tree species), so that none of the selected variables correlated more than 0.7 with any other of the selected variables. This is necessary to avoid multi-collinearity problems during model calibration. The selected climate variables used (and retained) in the models are summarized in table 3.

Stand structure data: Stand density and canopy closure have been identified as important predictors of tree regeneration in variably dense stands (Dobrowski *et al.* 2015). Here, we use four different stand structural variables for modelling the regeneration success of trees. First, the leaf density above 140 cm from the ground (*LeafCov140*) was expressed as percent cover, expressing the amount of shade saplings experience from the tree and tall shrub layers. Second, the average stem diameter of all trees on a plot (*avDia*) expresses the mean stand age. The ground vegetation cover (*VegCov*) expresses the amount of competition for regeneration at the forest floor, while the proportion of needleleaf trees on a plot (*PropNeedle*) expresses the amount of needle litter on the ground, which changes the pH of the uppermost soil layer and hinders broadleaf tree species more or less (depending on spp) from successful regeneration. An additional variable was used to express the availability of seed trees of the target model species. This was expressed as the average, species-level stand basal area of the seed trees (*Sp.xx*), where xx stands for the code of the species in the LFI data structure (50 for beech, 10 for spruce). All variables were entered into the regeneration models (see table 3).

Soil-related variables: We added several soil-related variables that were expected to affect tree regeneration in forests. First, we included the available water capacity (AWC) as an important soil physical variable. Second, we used base saturation (*BS*) as important soil chemistry variables. In addition, we explored the effects of nitrogen deposition on regeneration success. Yet, the latter was discarded due to partly strange effects under future climates, and due to the fact that they were not very predictive for binary regeneration success. AWC and BS were used as is under projected future climates.

Statistical Analyses

Several statistical models were evaluated for modelling the binary and the log(abundance) regeneration success of trees. We compared generalized linear models (GLMs; McCullagh & Nelder 1989) with linear and quadratic terms), generalized additive models (GAMs; Hastie & Tibshirani 1986), and random forests (RFs; Breiman 2001). All methods provide similar results when tested in repeated split-sample tests. However, the more tightly fitting methods (GAMs and RFs) tended to generate interactions and overfitting that caused problems when projecting the models to future conditions, where not all used variables were projected as such (e.g. BS, NFK, etc.). We therefore decided to use GLMs only for modelling forest regeneration success. As explained earlier, we fitted models for both dependent variables, binary and log(abundance), but again decided

to stick with the more parsimonious model type, the binary regeneration success for final analyses. These were of almost the same quality as the log(abundance) models (and partly even better). We fitted all models by using the selected variables that are summarized in table 3. We first fitted a full model, and then applied a backward-forward variable selection procedure and retained and dropped variables are explained in table 2. As test measure, we used the area under the curve (AUC; Swets 1988), applied in a 5-times repeated split sample test. This test measure takes a value of 1.0 if observed and simulated binary regeneration success are in perfect agreement, a value of 0.5 for random agreement and value <0.5 for systematically wrong predictions (Fielding & Bell 1997). In addition, we determined the importance of the individual variables in the final

models, and the optimal cut level to split the probabilistic output of regeneration success (probability of regeneration) into a binary presence and absence response of regeneration.

The final models were projected to all LFI points across Switzerland for a range of conditions, namely current and projected future climate, and to current stand structural parameters, as well as to two different sets of standardized stand structural and site parameters. The latter allow for better comparison of climate change effects. Therefore, we defined “semi-open” canopy structure such that *LeafCov140* is set to 40%, while an “open” canopy structure uses a value of 20% for the same variable. We finally mapped all LFI predictions to cells of 2.5 x 2.0 km for better visibility of the model results.

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Appendix A1 – Simulation results for *Fagus sylvatica*

Table of A1 content¹:

- A1.1: Observed (LFI) distribution of regeneration success
- A1.2: Simulated binary regeneration success; current stand and site conditions; current climate
- A1.3: Simulated binary regeneration success; semi-open stand structure; current climate
- A1.4: Simulated binary regeneration success; open stand structure; current climate
- A1.5: Simulated binary regeneration success; current stand and site conditions; 2050 climate
- A1.6: Simulated binary regeneration success; semi-open stand structure; 2050 climate
- A1.7: Simulated binary regeneration success; open stand structure; 2050 climate
- A1.8: Simulated binary regeneration success; current stand and site conditions; 2080 climate
- A1.9: Simulated binary regeneration success; semi-open stand structure; 2080 climate
- A1.10: Simulated binary regeneration success; open stand structure; 2080 climate
- A1.11: Simulated probability of binary regeneration success; current stand and site conditions; current climate
- A1.12: Simulated probability of binary regeneration success; semi-open stand structure; current climate
- A1.13: Simulated probability of binary regeneration success; open stand structure; current climate
- A1.14: Variable importance in final models

¹ see also www.wsl.ch/lud/forreg

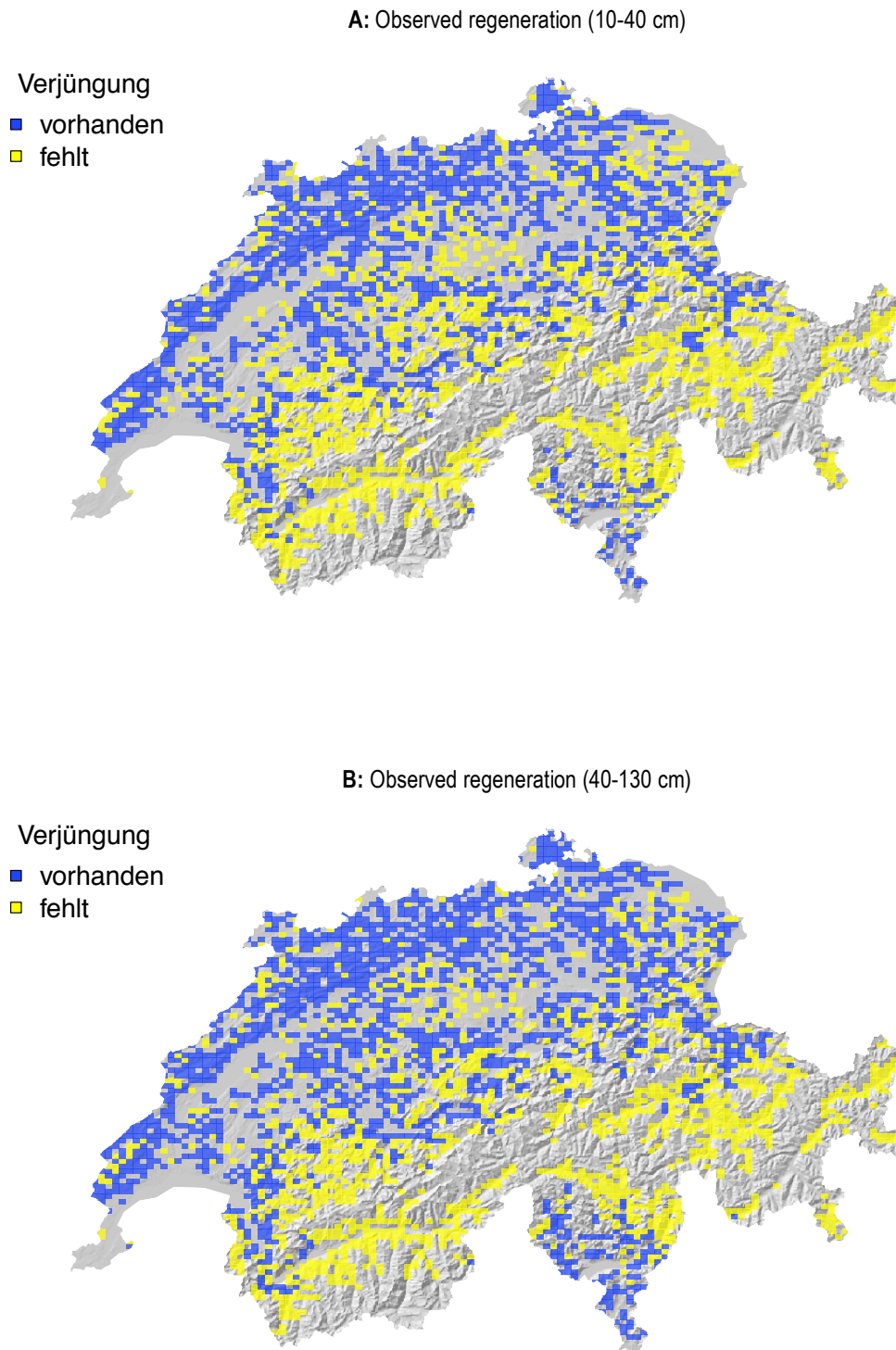
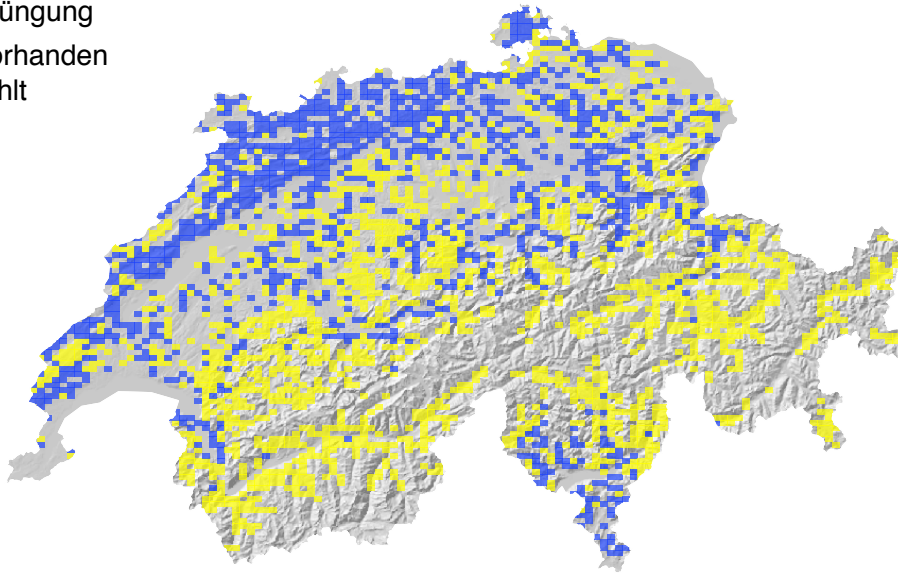


Figure A1.1: Observed distribution of regeneration in *Fagus sylvatica* (beech) for A: smaller (10-40 cm) and B: larger (40-130 cm) saplings in Switzerland, summarized from LFI plot observations to ca. 2.0 x 2.5 km resolution for better visibility.

A: Simulated binary regeneration success (10-40 cm); actual stand and site conditions; current climate

Verjüngung
■ vorhanden
■ fehlt



B: Simulated binary regeneration success (40-130 cm); actual stand and site conditions; current climate

Verjüngung
■ vorhanden
■ fehlt

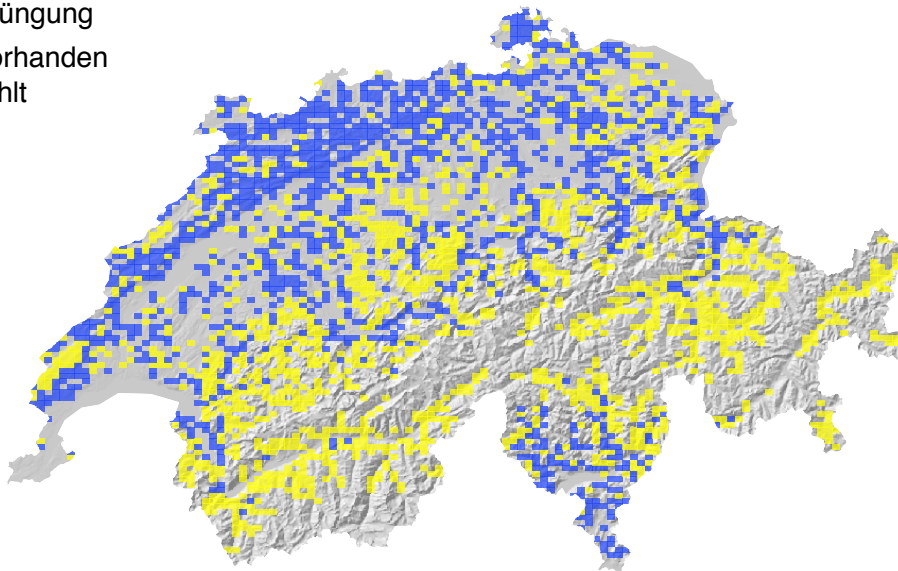
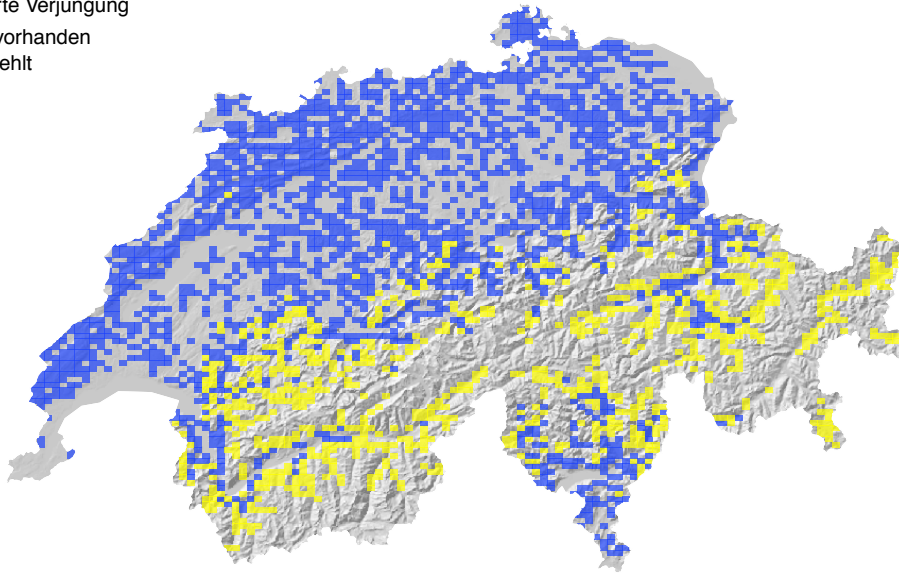


Figure A1.2: Simulated binary regeneration success in *Fagus sylvatica* (beech) for A: smaller (10-40 cm) and B: larger (40-130 cm) saplings in Switzerland under current climate and current canopy structure and site conditions, summarized from LFI plot observations to ca. 2.0 x 2.5 km resolution for better visibility. The binary threshold indicates the cut-level to optimally split probabilities into presence and absence of regeneration per LFI plot.

A: Simulated binary regeneration success (10-40 cm); semi-open stand structure; current climate

Simulierte Verjüngung

- vorhanden
- fehlt



B: Simulated binary regeneration success (40-130 cm); semi-open stand structure; current climate

Simulierte Verjüngung

- vorhanden
- fehlt

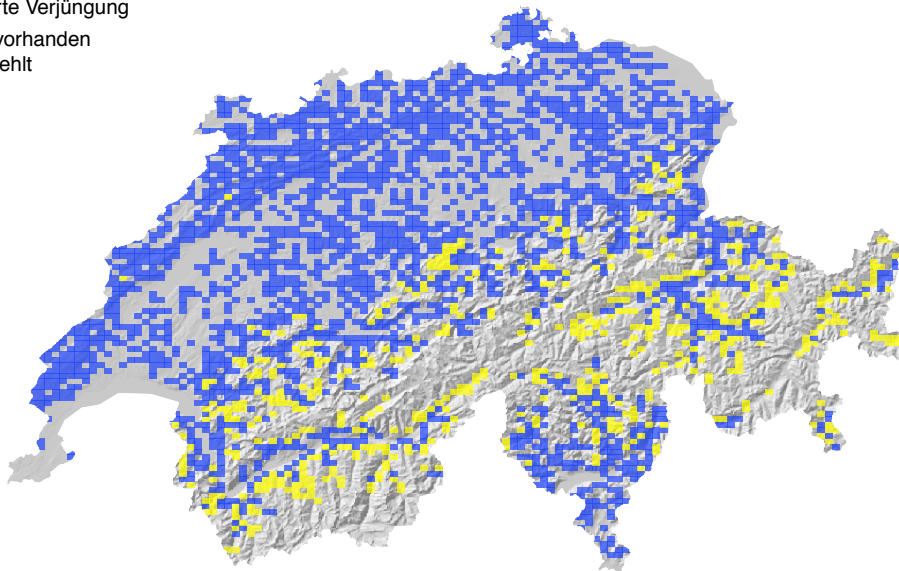
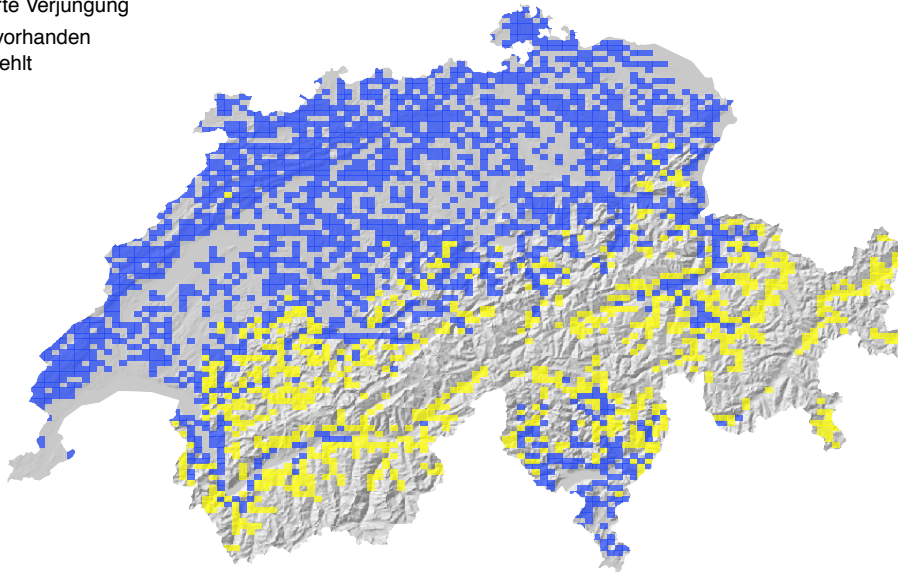


Figure A1.3: Simulated binary regeneration success in *Fagus sylvatica* (beech) for A: smaller (10-40 cm) and B: larger (40-130 cm) saplings in Switzerland under current climate and semi-open (40% cover) canopy structure, summarized from LFI plot observations to ca. 2.0 x 2.5 km resolution for better visibility. The binary threshold indicates the cut-level to optimally split probabilities into presence and absence of regeneration per LFI plot.

A: Simulated binary regeneration success (10-40 cm); open stand structure; current climate

Simulierte Verjüngung

- vorhanden
- fehlt

**B:** Simulated binary regeneration success (40-130 cm); open stand structure; current climate

Simulierte Verjüngung

- vorhanden
- fehlt

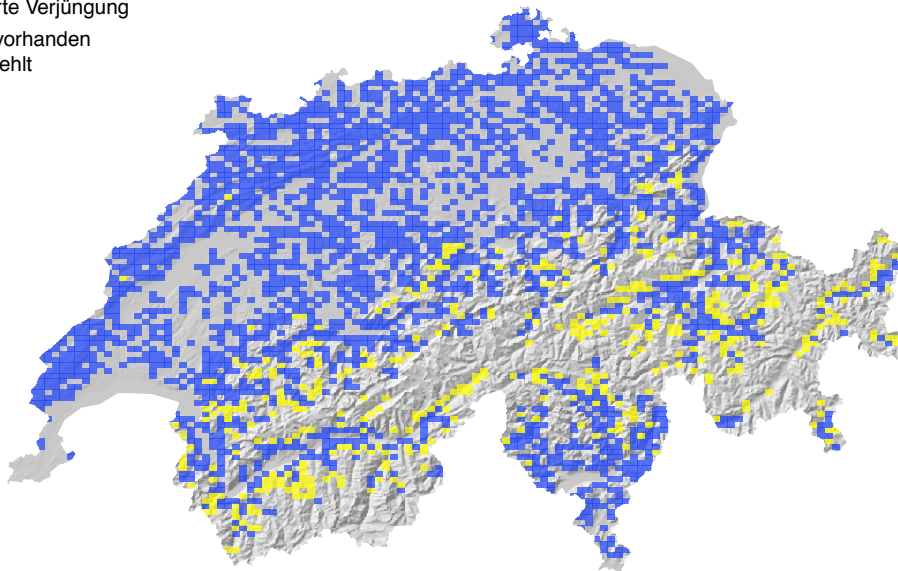
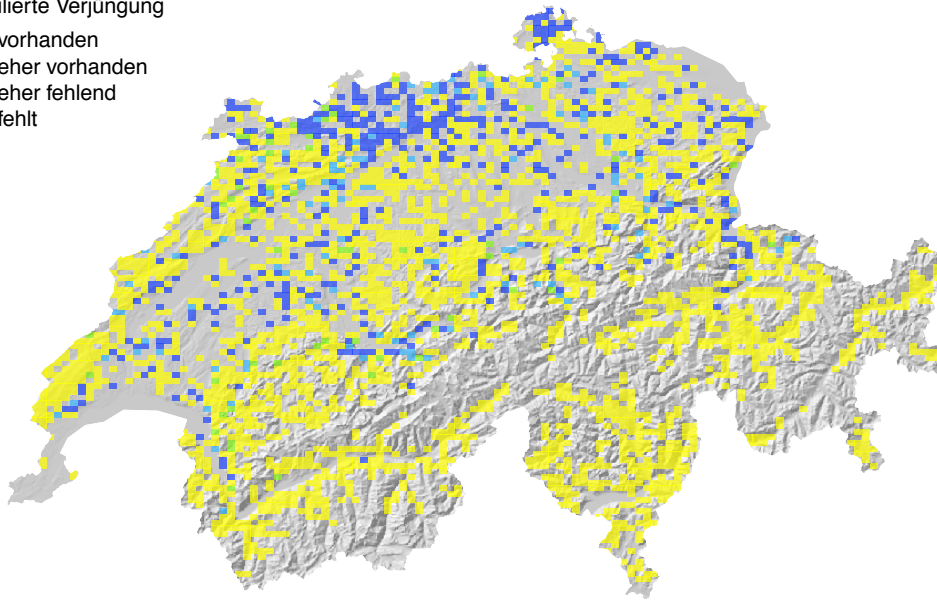


Figure A1.4: Simulated binary regeneration success in *Fagus sylvatica* (beech) for A: smaller (10-40 cm) and B: larger (40-130 cm) saplings in Switzerland under current climate and open (20% cover) canopy structure, summarized from LFI plot observations to ca. 2.0 x 2.5 km resolution for better visibility. The binary threshold indicates the cut-level to optimally split probabilities into presence and absence of regeneration per LFI plot

A: Simulated binary regeneration success (10-40 cm); actual stand and site conditions; 2050 climate

Simulierte Verjüngung

- vorhanden
- eher vorhanden
- eher fehlend
- fehlt



B: Simulated binary regeneration success (40-130 cm); actual stand and site conditions; 2050 climate

Simulierte Verjüngung

- vorhanden
- eher vorhanden
- eher fehlend
- fehlt

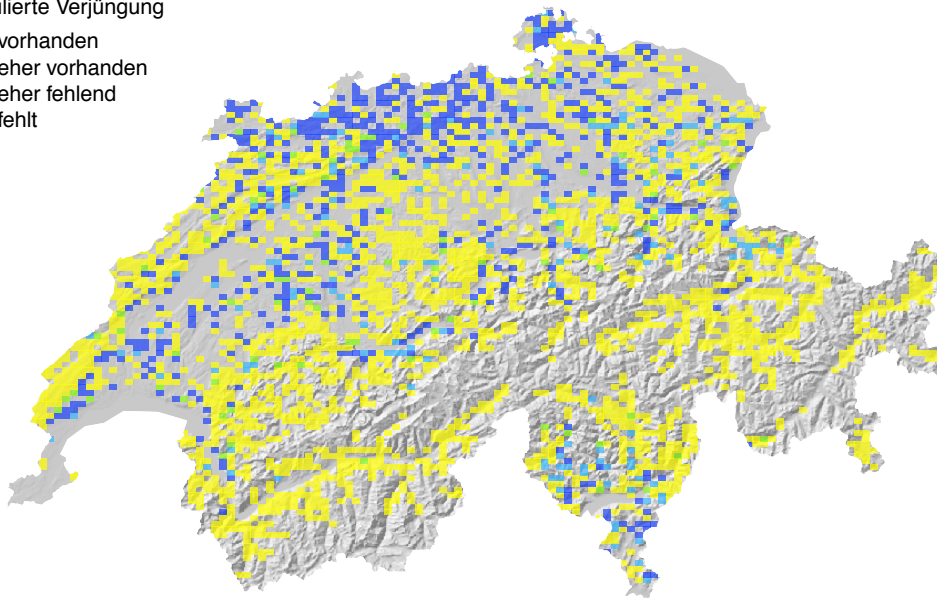
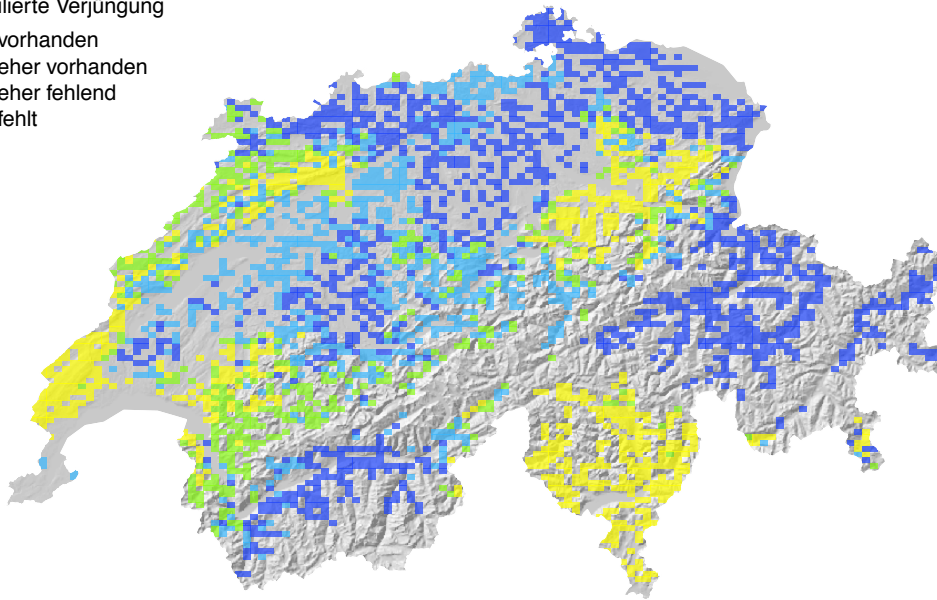


Figure A1.5: Mean simulated binary regeneration success in *Fagus sylvatica* (beech) for A: smaller (10-40 cm) and B: larger (40-130 cm) saplings in Switzerland under 3 different RCMs around 2050 and current canopy structure and site conditions, summarized from LFI plot observations to ca. 2.0 x 2.5 km resolution for better visibility. The binary threshold indicates the cut-level to optimally split probabilities into presence and absence of regeneration per LFI plot.

A: Simulated binary regeneration success (10-40 cm); semi-open stand structure; 2050 climate

Simulierte Verjüngung

- vorhanden
- eher vorhanden
- eher fehlend
- fehlt



B: Simulated binary regeneration success (40-130 cm); semi-open stand structure; 2050 climate

Simulierte Verjüngung

- vorhanden
- eher vorhanden
- eher fehlend
- fehlt

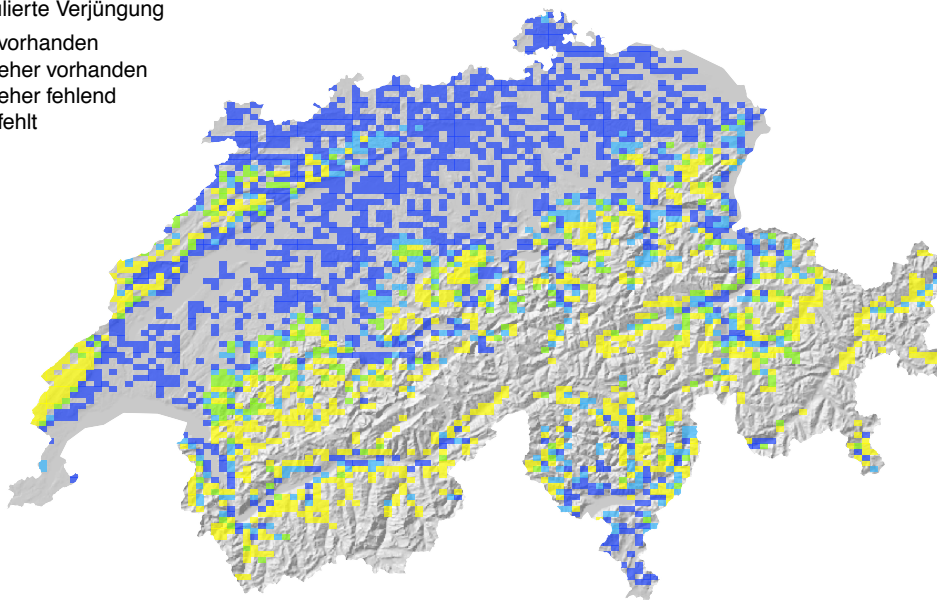
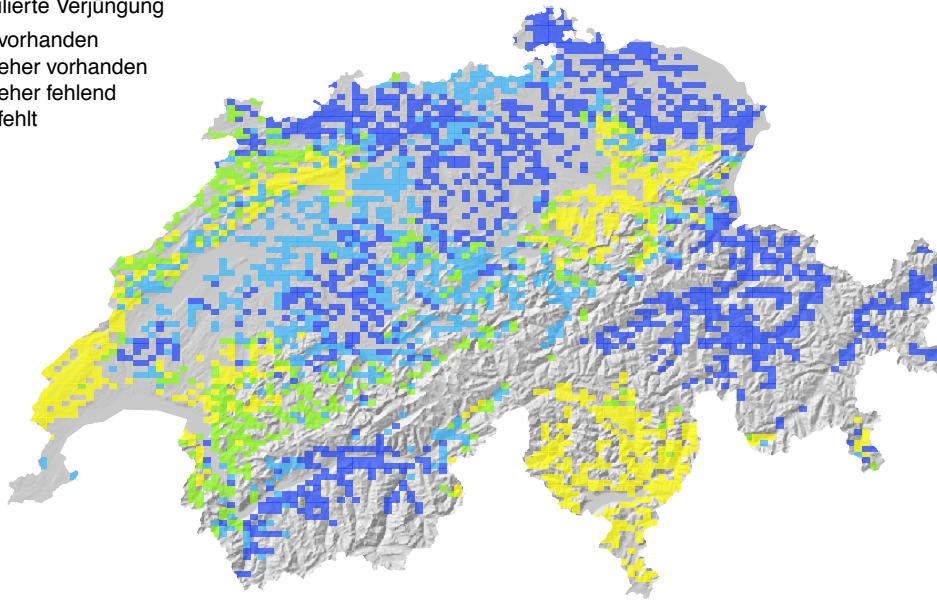


Figure A1.6: Mean simulated binary regeneration success in *Fagus sylvatica* (beech) for A: smaller (10-40 cm) and B: larger (40-130 cm) saplings in Switzerland under 3 different RCMs around 2050 and semi-open (40% cover) canopy structure, summarized from LFI plot observations to ca. 2.0 x 2.5 km resolution for better visibility. The binary threshold indicates the cut-level to optimally split probabilities into presence and absence of regeneration per LFI plot

A: Simulated binary regeneration success (10-40 cm); open stand structure; 2050 climate

Simulierte Verjüngung

- vorhanden
- eher vorhanden
- eher fehlend
- fehlt



B: Simulated binary regeneration success (40-130 cm); open stand structure; 2050 climate

Simulierte Verjüngung

- vorhanden
- eher vorhanden
- eher fehlend
- fehlt

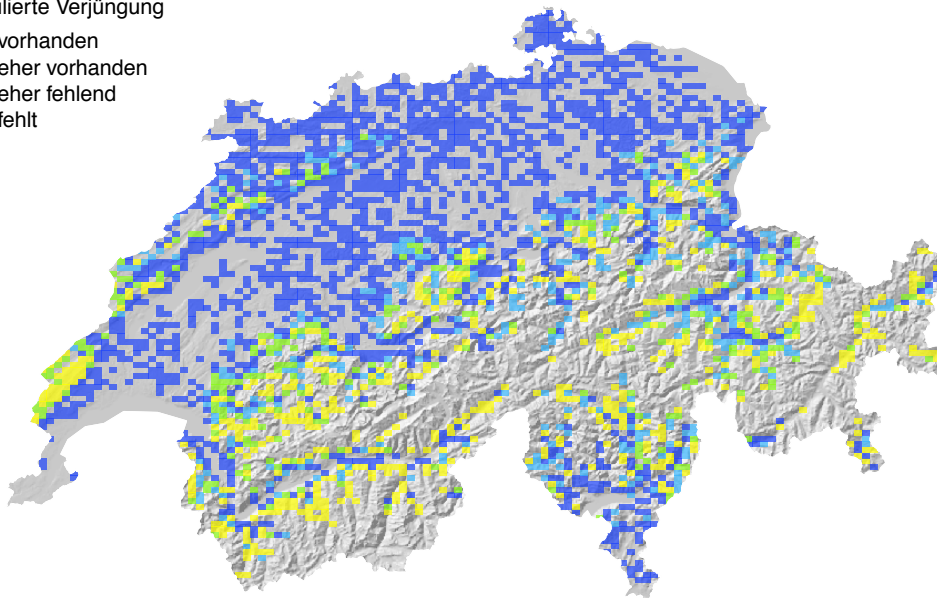
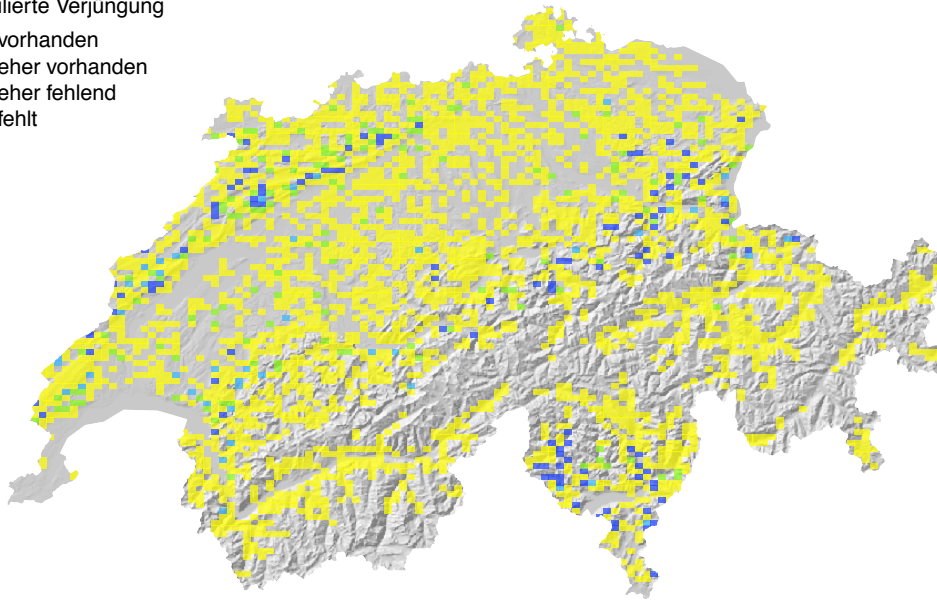


Figure A1.7: Mean simulated binary regeneration success in *Fagus sylvatica* (beech) for A: smaller (10-40 cm) and B: larger (40-130 cm) saplings in Switzerland under 3 different RCMs around 2050 and open (20% cover) canopy structure, summarized from LFI plot observations to ca. 2.0 x 2.5 km resolution for better visibility. The binary threshold indicates the cut-level to optimally split probabilities into presence and absence of regeneration per LFI plot

A: Simulated binary regeneration success (10-40 cm); actual stand and site conditions; 2080 climate

Simulierte Verjüngung

- vorhanden
- eher vorhanden
- eher fehlend
- fehlt



B: Simulated binary regeneration success (40-130 cm); actual stand and site conditions; 2080 climate

Simulierte Verjüngung

- vorhanden
- eher vorhanden
- eher fehlend
- fehlt

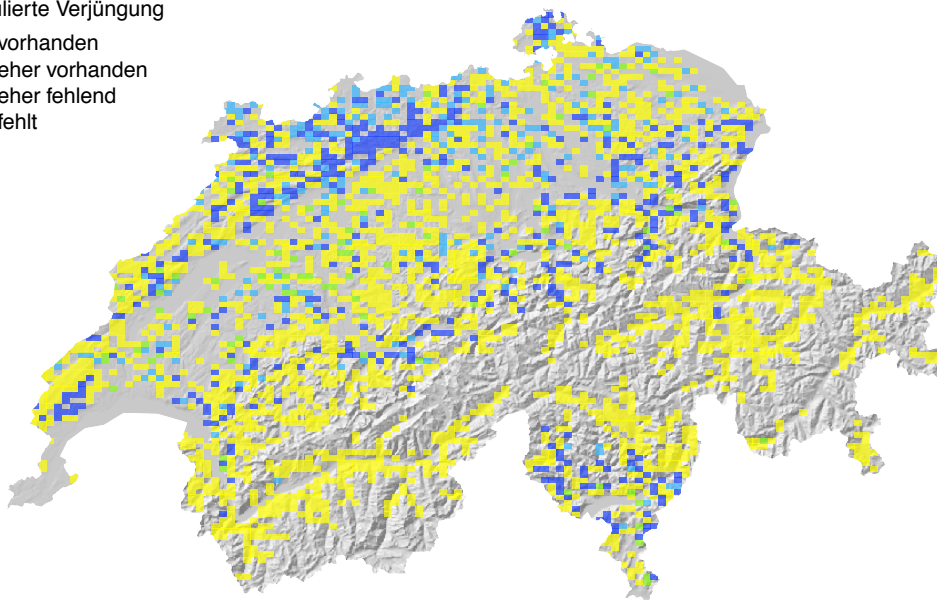
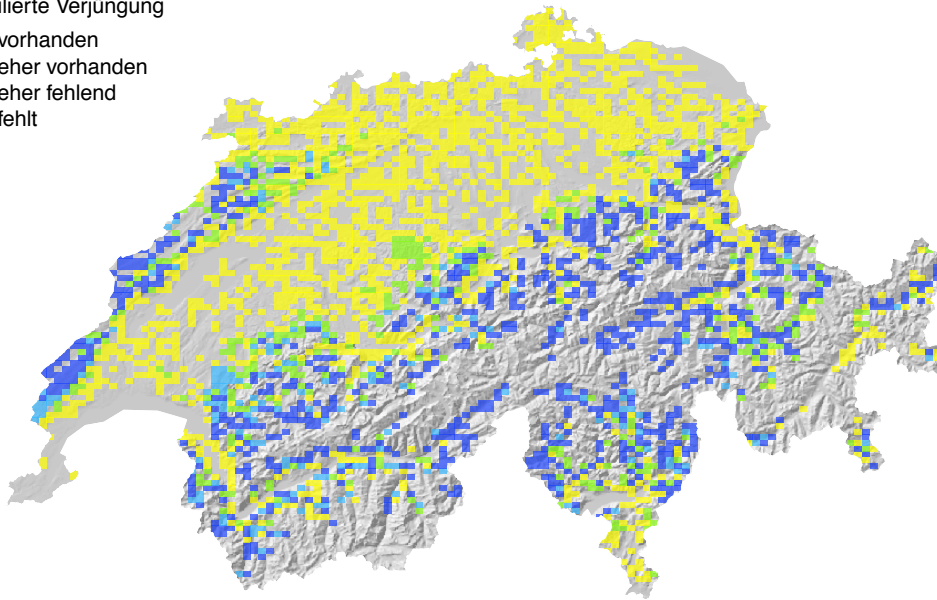


Figure A1.8: Mean simulated binary regeneration success in *Fagus sylvatica* (beech) for A: smaller (10-40 cm) and B: larger (40-130 cm) saplings in Switzerland under 3 different RCMs around 2080 and current canopy structure and site conditions, summarized from LFI plot observations to ca. 2.0 x 2.5 km resolution for better visibility. The binary threshold indicates the cut-level to optimally split probabilities into presence and absence of regeneration per LFI plot.

A: Simulated binary regeneration success (10-40 cm); semi-open stand structure; 2080 climate

Simulierte Verjüngung

- vorhanden
- eher vorhanden
- eher fehlend
- fehlt



B: Simulated binary regeneration success (40-130 cm); semi-open stand structure; 2080 climate

Simulierte Verjüngung

- vorhanden
- eher vorhanden
- eher fehlend
- fehlt

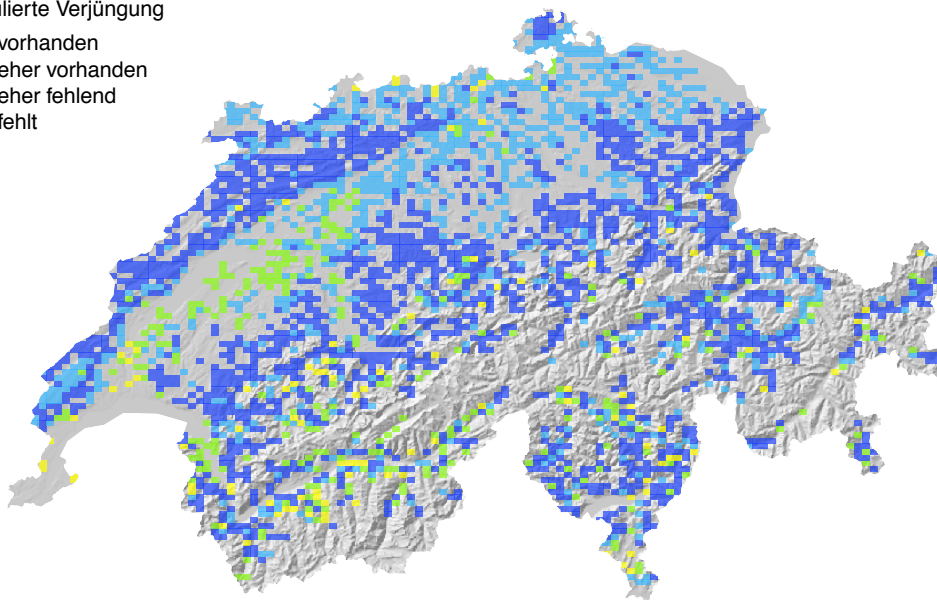
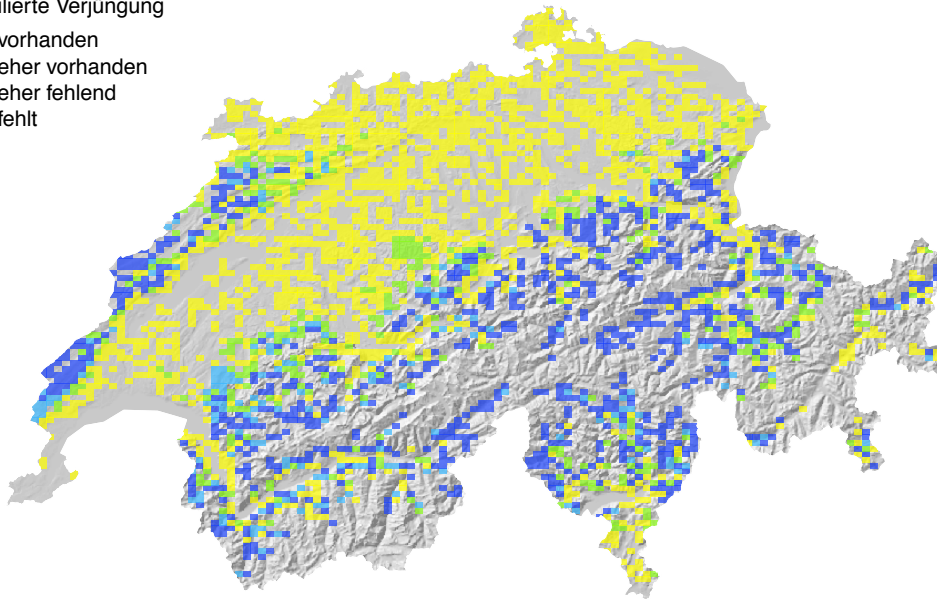


Figure A1.9: Mean simulated binary regeneration success in *Fagus sylvatica* (beech) for A: smaller (10-40 cm) and B: larger (40-130 cm) saplings in Switzerland under 3 different RCMs around 2080 and semi-open (40% cover) canopy structure, summarized from LFI plot observations to ca. 2.0 x 2.5 km resolution for better visibility. The binary threshold indicates the cut-level to optimally split probabilities into presence and absence of regeneration per LFI plot

A: Simulated binary regeneration success (10-40 cm); open stand structure; 2080 climate

Simulierte Verjüngung

- vorhanden
- eher vorhanden
- eher fehlend
- fehlt

**B:** Simulated binary regeneration success (40-130 cm); open stand structure; 2080 climate

Simulierte Verjüngung

- vorhanden
- eher vorhanden
- eher fehlend
- fehlt

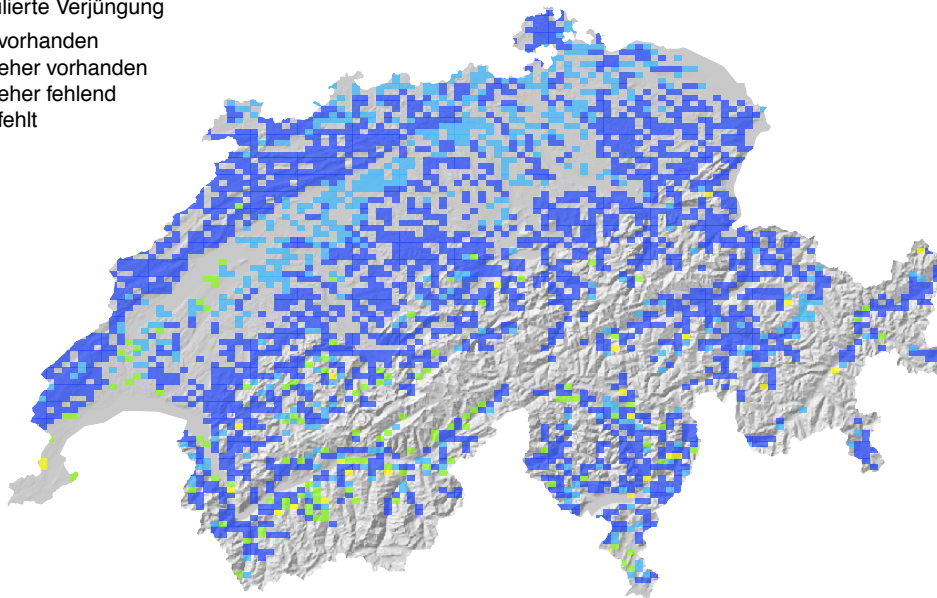
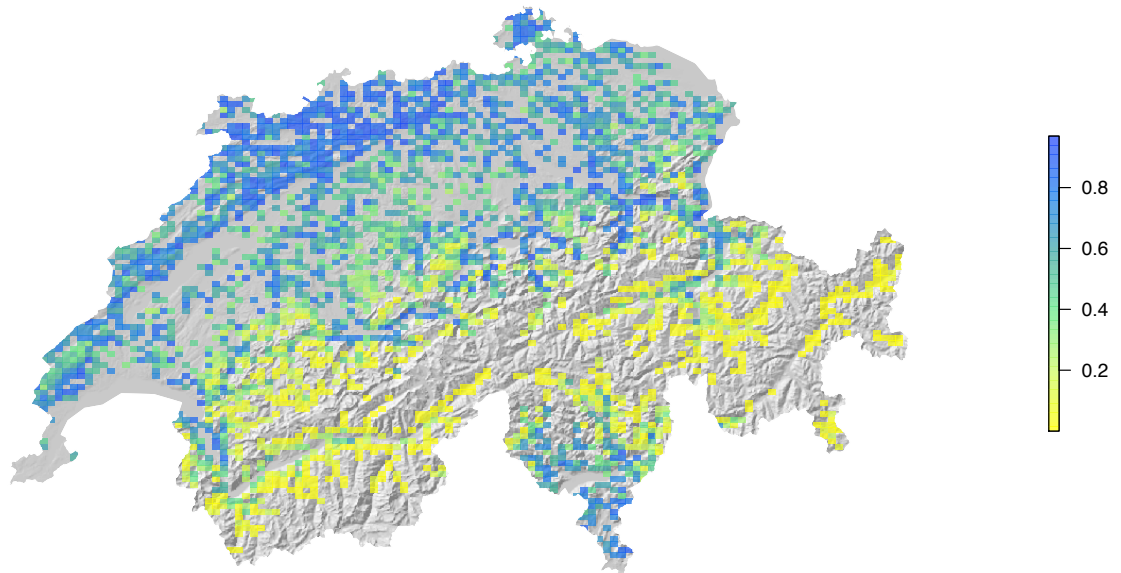


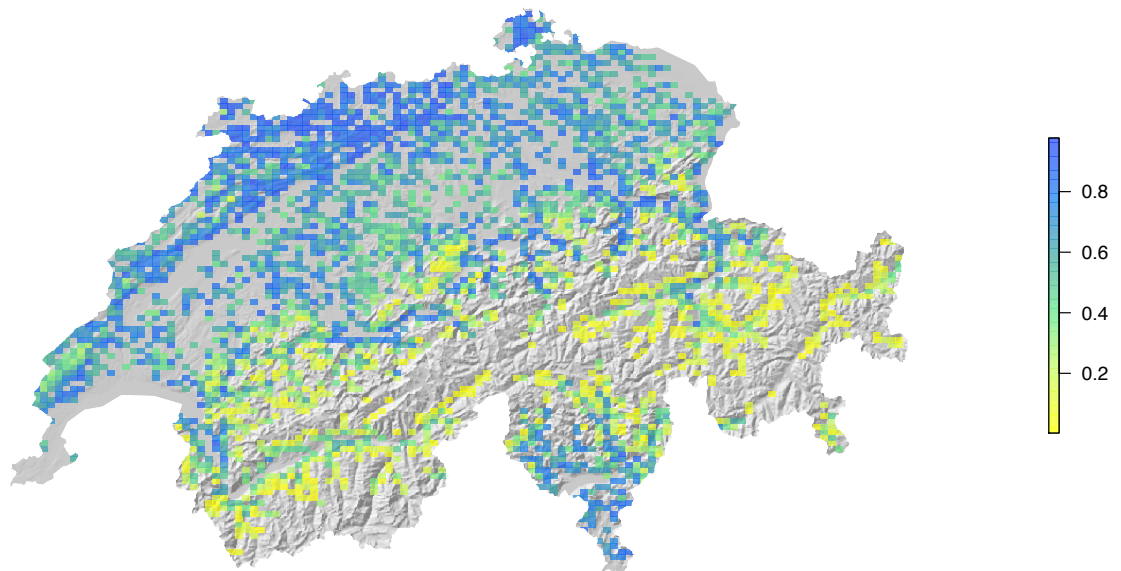
Figure A1.10: Mean simulated binary regeneration success in *Fagus sylvatica* (beech) for A: smaller (10-40 cm) and B: larger (40-130 cm) saplings in Switzerland under 3 different RCMs around 2080 and open (20% cover) canopy structure, summarized from LFI plot observations to ca. 2.0 x 2.5 km resolution for better visibility. The binary threshold indicates the cut-level to optimally split probabilities into presence and absence of regeneration per LFI plot

A: Simulated probability of regeneration success (10-40 cm); actual stand and site conditions; current climate



Grenzwert: 0.6

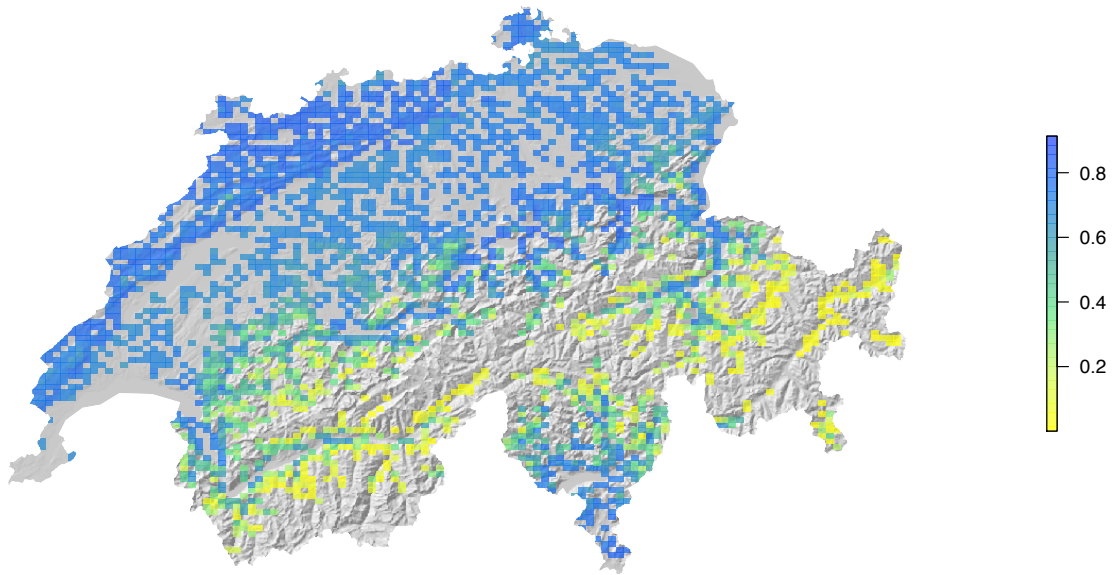
B: Simulated probability of regeneration success (40-130 cm); actual stand and site conditions; current climate



Grenzwert: 0.59

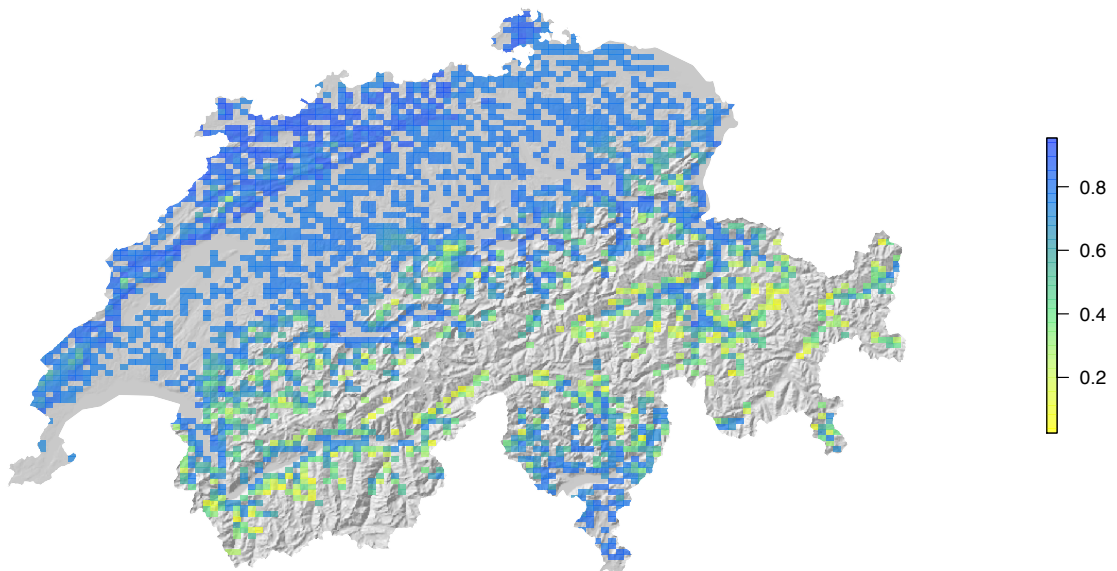
Figure A1.11: Simulated probability of regeneration success in *Fagus sylvatica* (beech) for A: smaller (10-40 cm) and B: larger (40-130 cm) saplings in Switzerland under current climate and current canopy structure and site conditions, summarized from LFI plot observations to ca. 2.0 x 2.5 km resolution for better visibility. The binary threshold indicates the cut-level to optimally split probabilities into presence and absence of regeneration per LFI plot.

A: Simulated probability of regeneration success (10-40 cm); semi-open stand structure; current climate



Grenzwert: 0.6

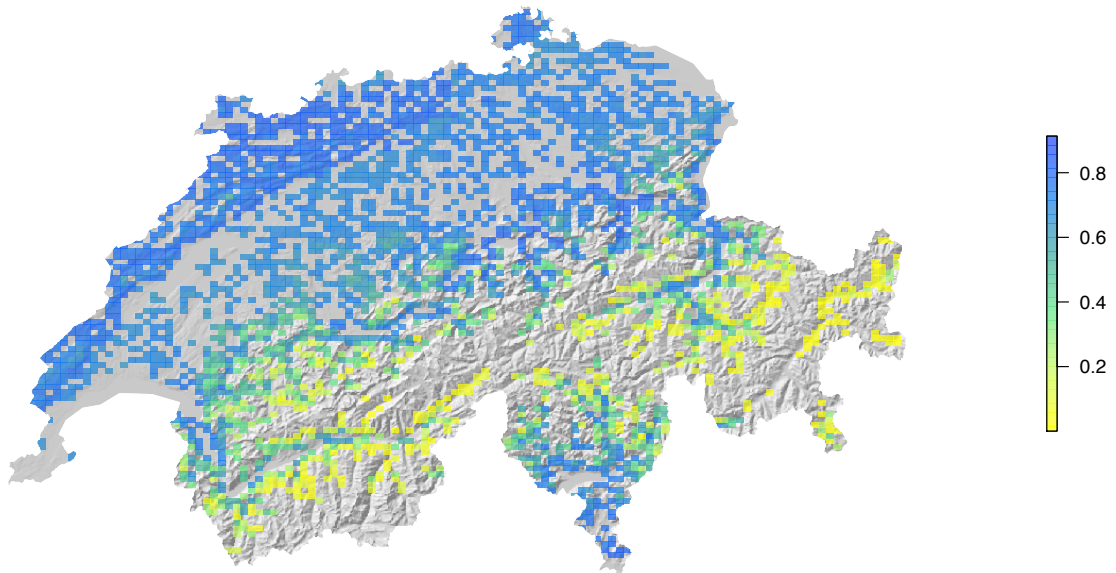
B: Simulated probability of regeneration success (40-130 cm); semi-open stand structure; current climate



Grenzwert: 0.59

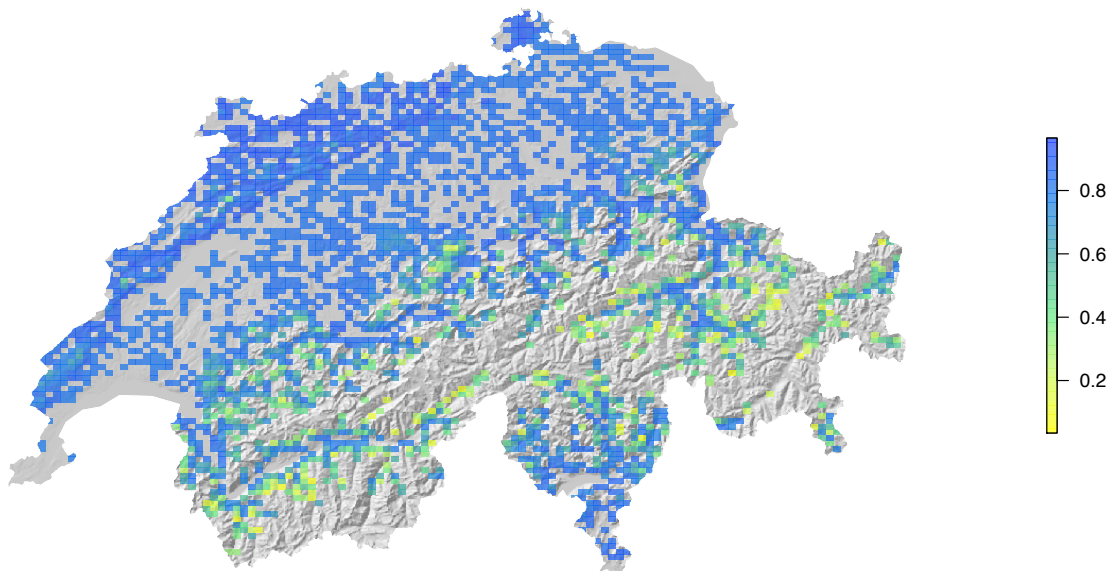
Figure A1.12: Simulated probability of regeneration success in *Fagus sylvatica* (beech) for A: smaller (10-40 cm) and B: larger (40-130 cm) saplings in Switzerland under current climate and semi-open (40% cover) canopy structure, summarized from LFI plot observations to ca. 2.0 x 2.5 km resolution for better visibility. The binary threshold indicates the cut-level to optimally split probabilities into presence and absence of regeneration per LFI plot.

A: Simulated probability of regeneration success (10-40 cm); open stand structure; current climate



Grenzwert: 0.6

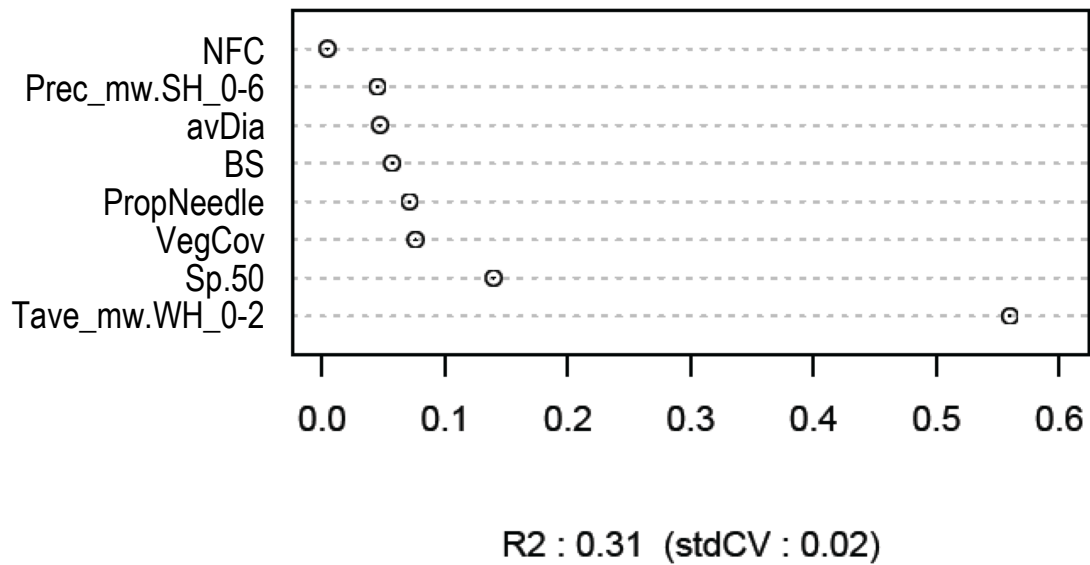
B: Simulated probability of regeneration success (40-130 cm); open stand structure; current climate



Grenzwert: 0.59

Figure A1.13: Simulated probability of regeneration success in *Fagus sylvatica* (beech) for A: smaller (10-40 cm) and B: larger (40-130 cm) saplings in Switzerland under current climate and open (20% cover) canopy structure, summarized from LFI plot observations to ca. 2.0 x 2.5 km resolution for better visibility. The binary threshold indicates the cut-level to optimally split probabilities into presence and absence of regeneration per LFI plot.

Variable importance *Fagus* (50) juveniles



Variable importance *Fagus* (50) older

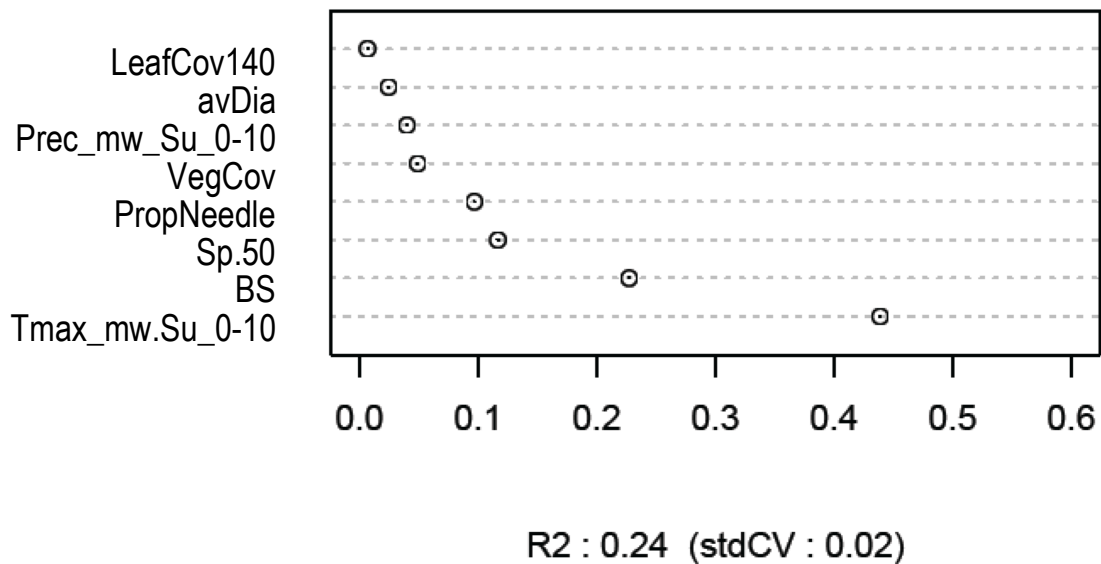


Figure A1.14: Variable importance for modelling the binary regeneration success of smaller (juveniles) and larger (older) saplings of beech (*Fagus sylvatica*). Values on the X-axis indicate the % importance in terms of contribution to the full model.

Appendix A2 – Simulation results for *Picea abies*

Table of A2 content¹:

- A2.1: Observed (LFI) distribution of regeneration success
- A2.2: Simulated binary regeneration success; current stand and site conditions; current climate
- A2.3: Simulated binary regeneration success; semi-open stand structure; current climate
- A2.4: Simulated binary regeneration success; open stand structure; current climate
- A2.5: Simulated binary regeneration success; current stand and site conditions; 2050 climate
- A2.6: Simulated binary regeneration success; semi-open stand structure; 2050 climate
- A2.7: Simulated binary regeneration success; open stand structure; 2050 climate
- A2.8: Simulated binary regeneration success; current stand and site conditions; 2080 climate
- A2.9: Simulated binary regeneration success; semi-open stand structure; 2080 climate
- A2.10: Simulated binary regeneration success; open stand structure; 2080 climate
- A2.11: Simulated probability of binary regeneration success; current stand and site conditions; current climate
- A2.12: Simulated probability of binary regeneration success; semi-open stand structure; current climate
- A2.13: Simulated probability of binary regeneration success; open stand structure; current climate
- A2.14: Variable importance in final models

¹ see also www.wsl.ch/lud/forreg

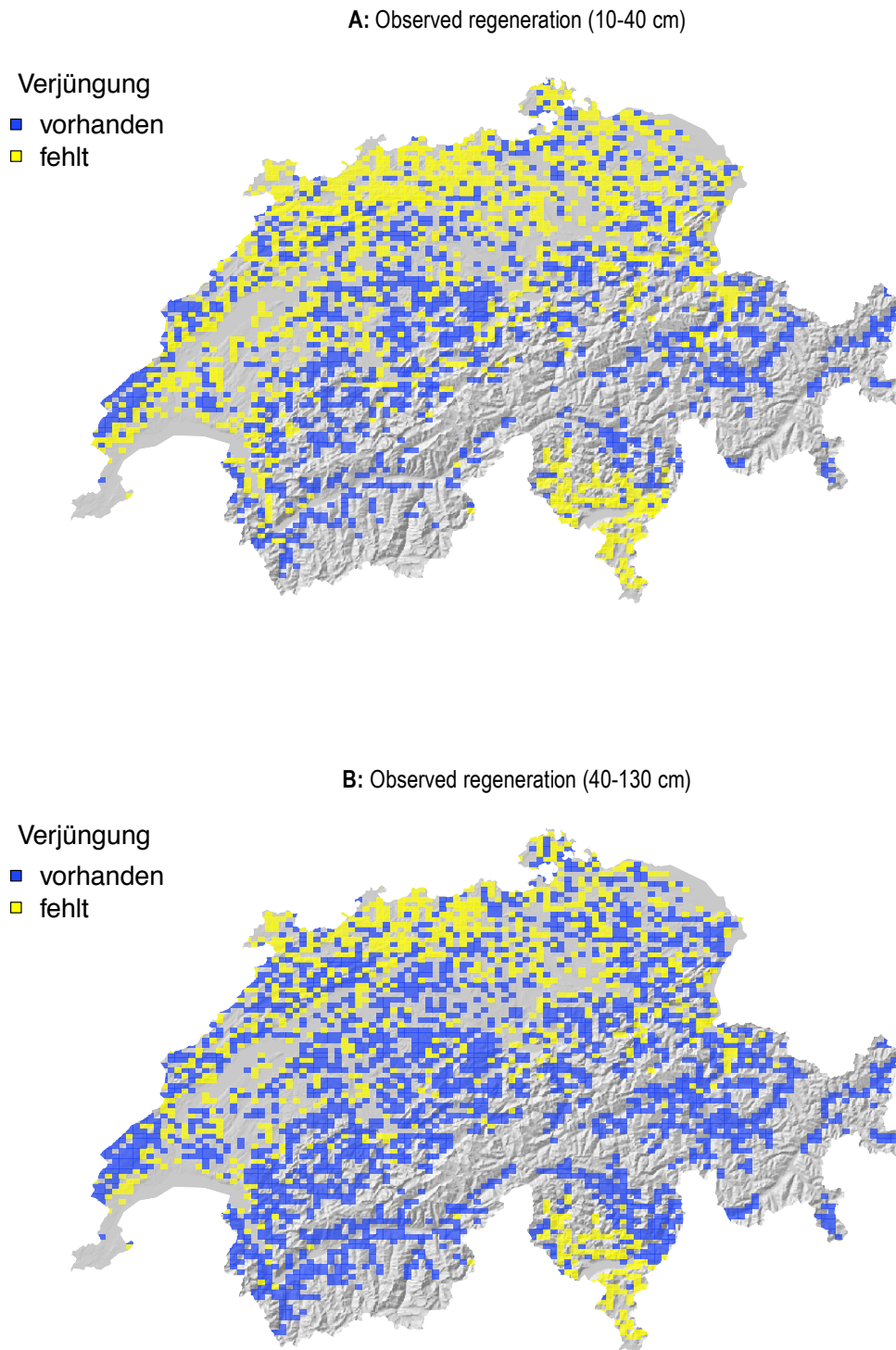
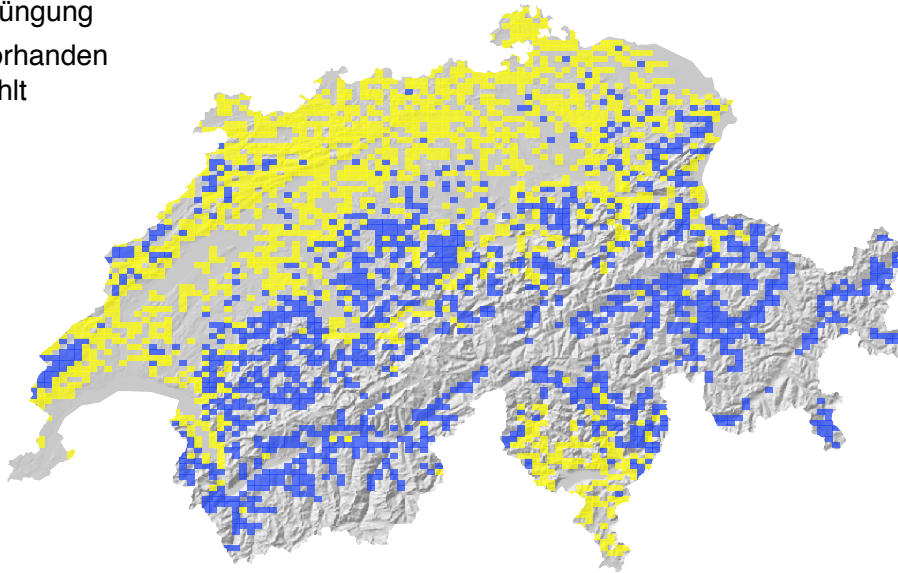


Figure A2.1: Observed distribution of regeneration in *Picea abies* (spruce) for A: smaller (10-40 cm) and B: larger (40-130 cm) saplings in Switzerland, summarized from LFI plot observations to ca. 2.0 x 2.5 km resolution for better visibility.

A: Simulated binary regeneration success (10-40 cm); actual stand and site conditions; current climate

Verjüngung
■ vorhanden
■ fehlt



B: Simulated binary regeneration success (40-130 cm); actual stand and site conditions; current climate

Verjüngung
■ vorhanden
■ fehlt

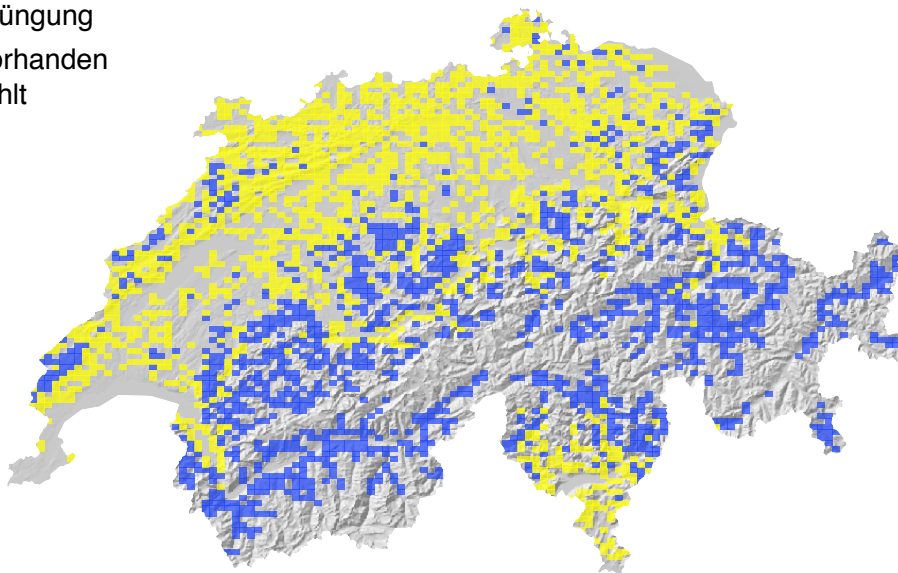


Figure A2.2: Simulated binary regeneration success in *Picea abies* (spruce) for A: smaller (10-40 cm) and B: larger (40-130 cm) saplings in Switzerland under current climate and current canopy structure and site conditions, summarized from LFI plot observations to ca. 2.0 x 2.5 km resolution for better visibility. The binary threshold indicates the cut-level to optimally split probabilities into presence and absence of regeneration per LFI plot.

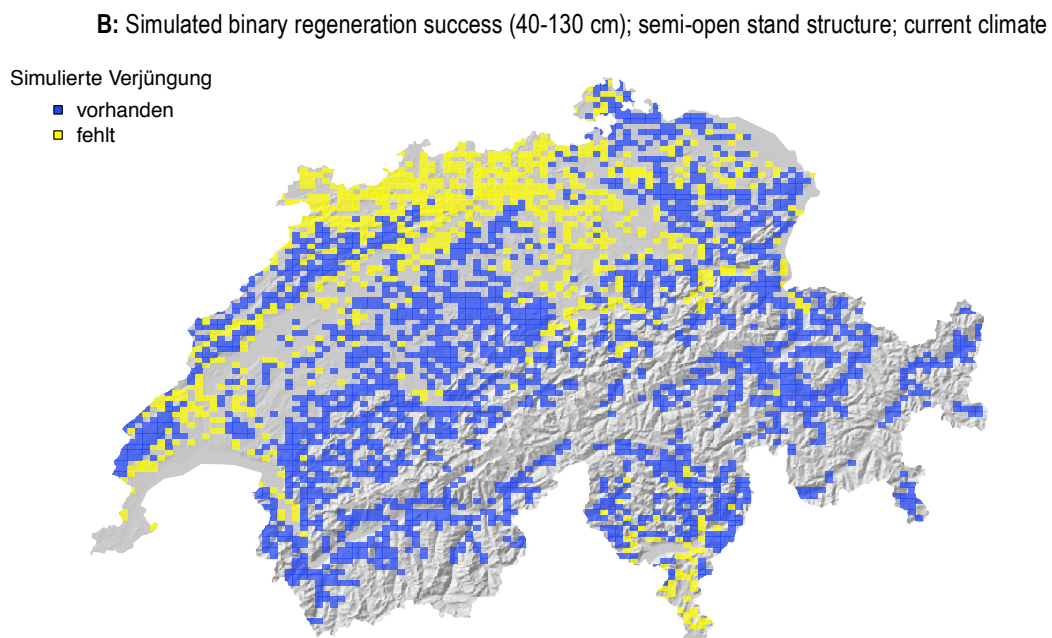
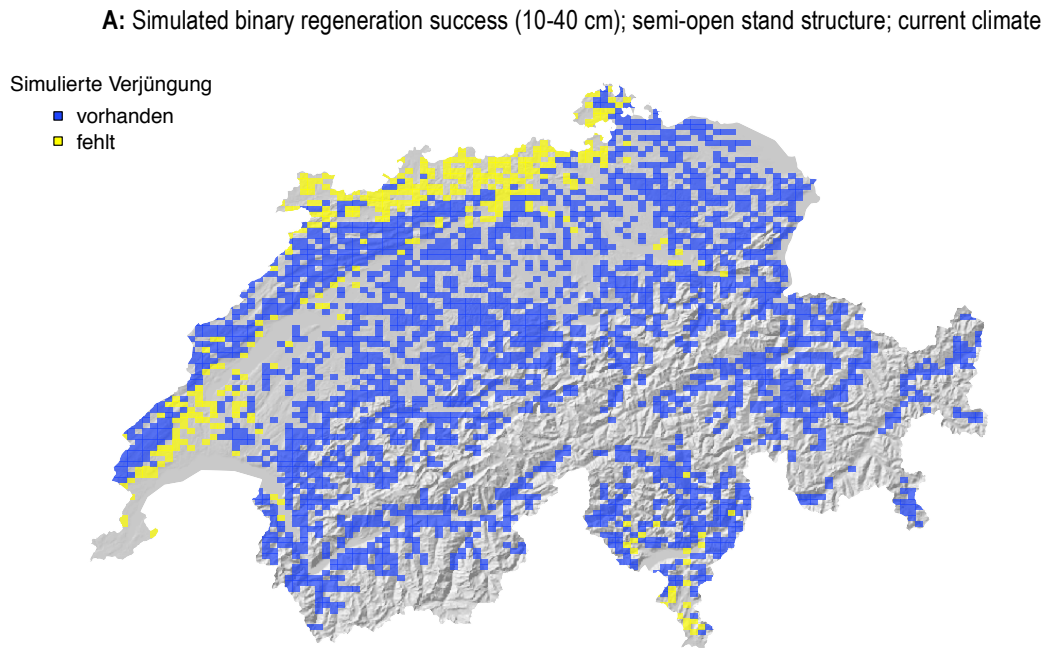
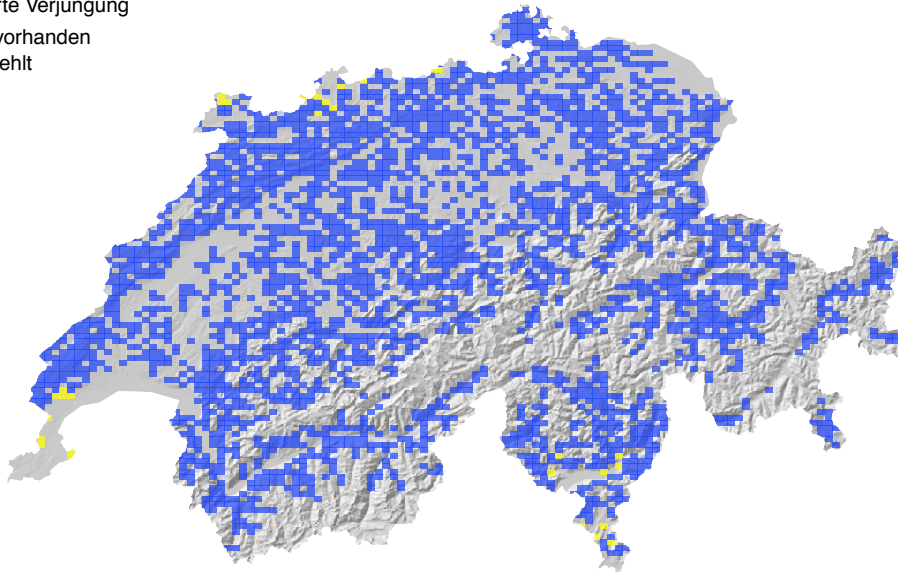


Figure A2.3: Simulated binary regeneration success in *Picea abies* (spruce) for A: smaller (10-40 cm) and B: larger (40-130 cm) saplings in Switzerland under current climate and semi-open (40% cover) canopy structure, summarized from LFI plot observations to ca. 2.0 x 2.5 km resolution for better visibility. The binary threshold indicates the cut-level to optimally split probabilities into presence and absence of regeneration per LFI plot.

A: Simulated binary regeneration success (10-40 cm); open stand structure; current climate

Simulierte Verjüngung

- vorhanden
- fehlt

**B:** Simulated binary regeneration success (40-130 cm); open stand structure; current climate

Simulierte Verjüngung

- vorhanden
- fehlt

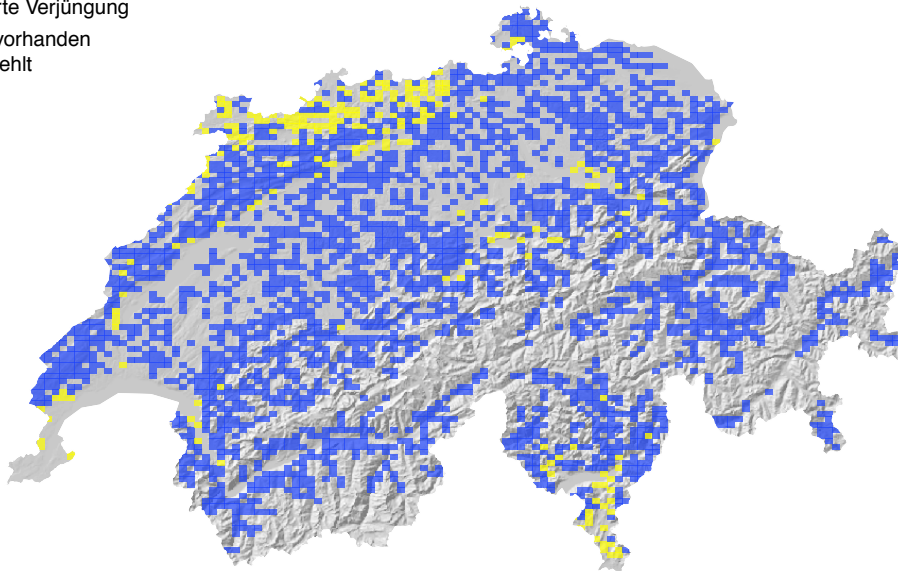
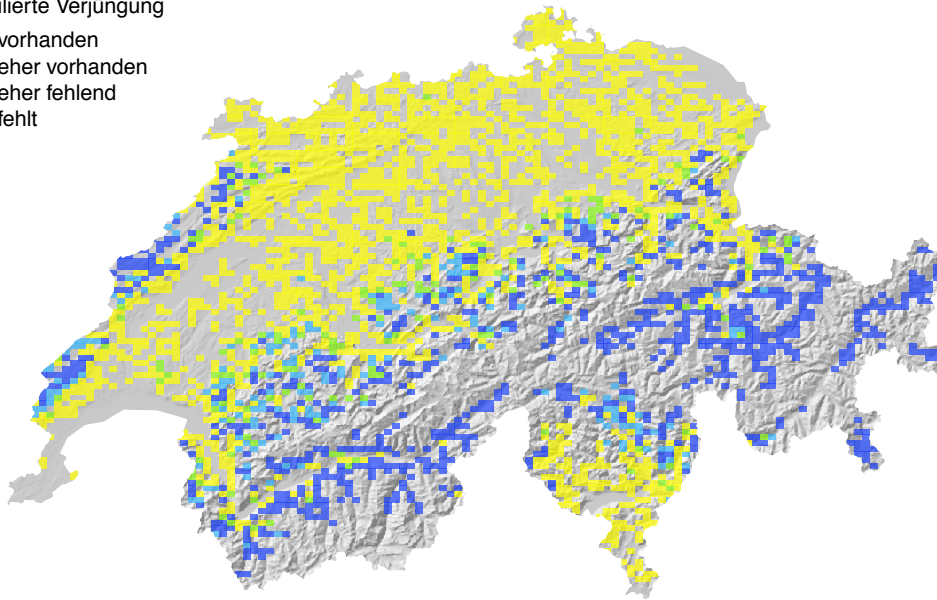


Figure A2.4: Simulated binary regeneration success in *Picea abies* (spruce) for A: smaller (10-40 cm) and B: larger (40-130 cm) saplings in Switzerland under current climate and open (20% cover) canopy structure, summarized from LFI plot observations to ca. 2.0 x 2.5 km resolution for better visibility. The binary threshold indicates the cut-level to optimally split probabilities into presence and absence of regeneration per LFI plot

A: Simulated binary regeneration success (10-40 cm); actual stand and site conditions; 2050 climate

Simulierte Verjüngung

- vorhanden
- eher vorhanden
- eher fehlend
- fehlt



B: Simulated binary regeneration success (40-130 cm); actual stand and site conditions; 2050 climate

Simulierte Verjüngung

- vorhanden
- eher vorhanden
- eher fehlend
- fehlt

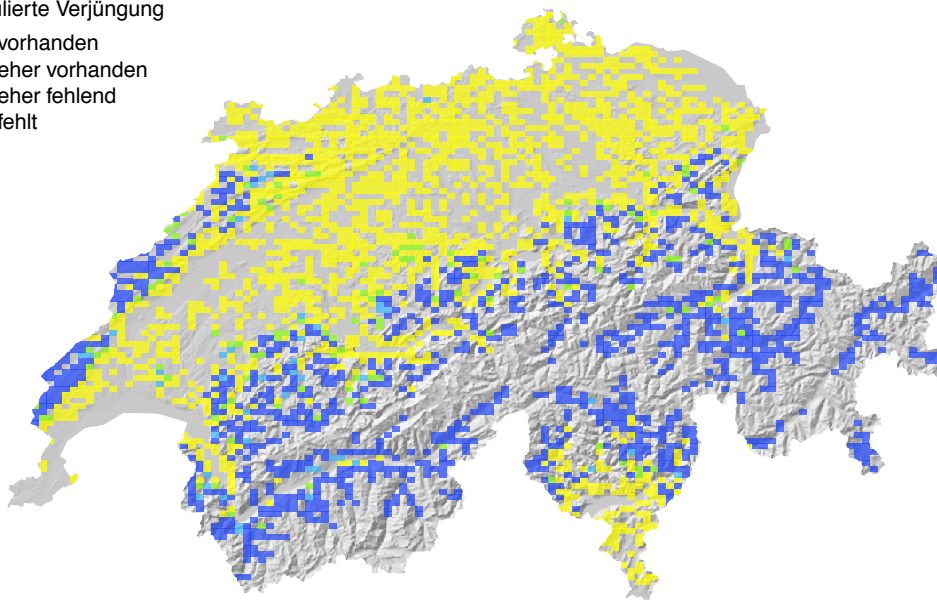
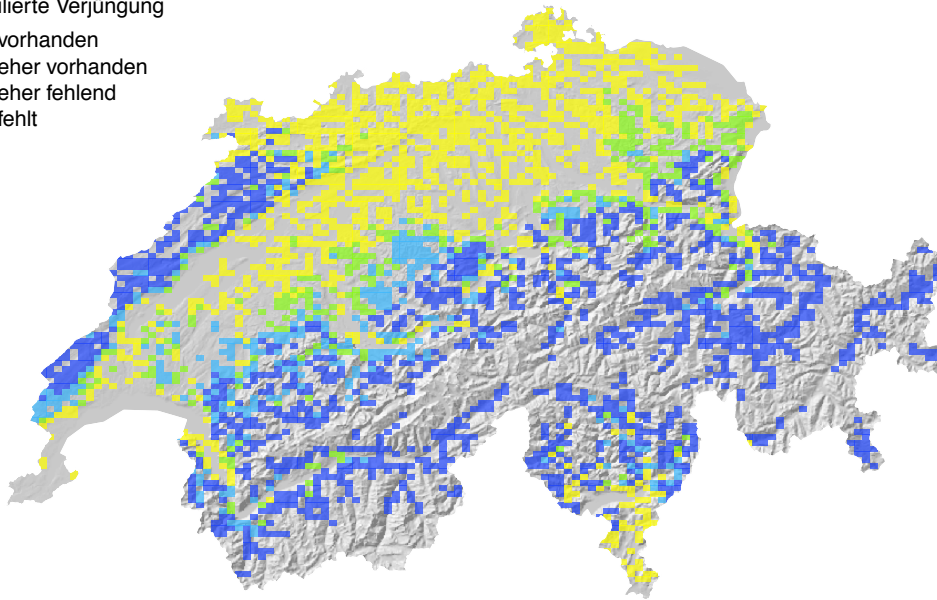


Figure A2.5: Mean simulated binary regeneration success in *Picea abies* (spruce) for A: smaller (10-40 cm) and B: larger (40-130 cm) saplings in Switzerland under 3 different RCMs around 2050 and current canopy structure and site conditions, summarized from LFI plot observations to ca. 2.0 x 2.5 km resolution for better visibility. The binary threshold indicates the cut-level to optimally split probabilities into presence and absence of regeneration per LFI plot.

A: Simulated binary regeneration success (10-40 cm); semi-open stand structure; 2050 climate

Simulierte Verjüngung

- vorhanden
- eher vorhanden
- eher fehlend
- fehlt



B: Simulated binary regeneration success (40-130 cm); semi-open stand structure; 2050 climate

Simulierte Verjüngung

- vorhanden
- eher vorhanden
- eher fehlend
- fehlt

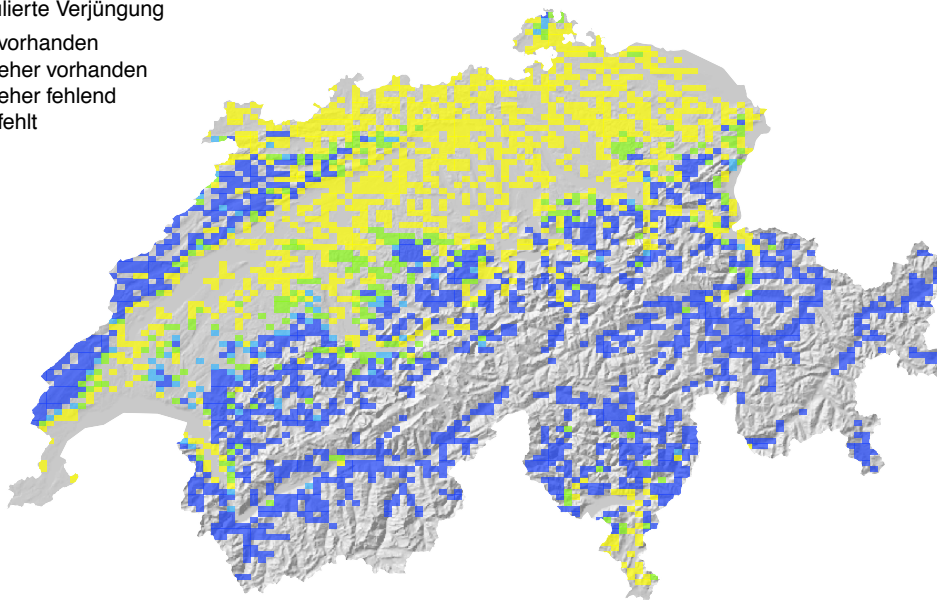
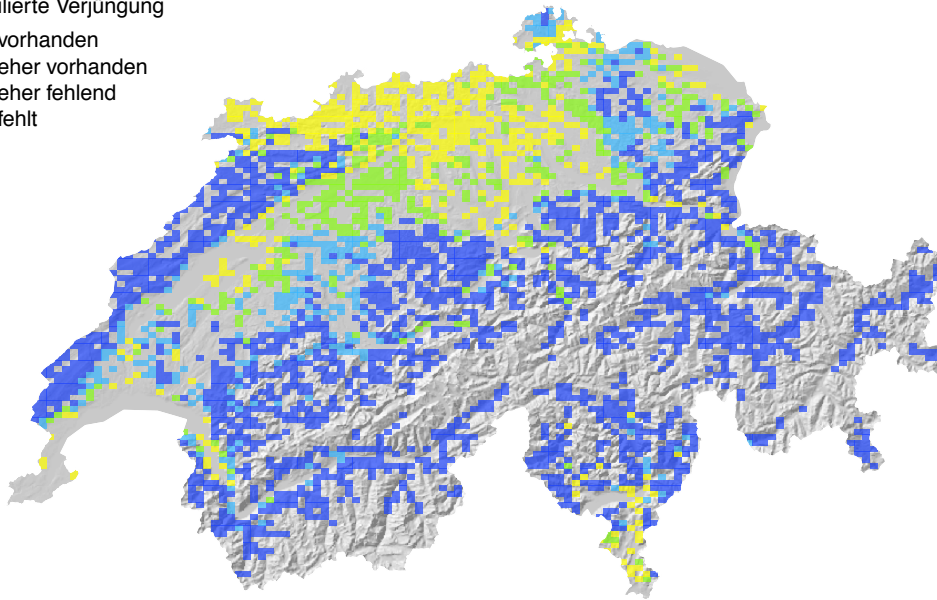


Figure A2.6: Mean simulated binary regeneration success in *Picea abies* (spruce) for A: smaller (10-40 cm) and B: larger (40-130 cm) saplings in Switzerland under 3 different RCMs around 2050 and semi-open (40% cover) canopy structure, summarized from LFI plot observations to ca. 2.0 x 2.5 km resolution for better visibility. The binary threshold indicates the cut-level to optimally split probabilities into presence and absence of regeneration per LFI plot

A: Simulated binary regeneration success (10-40 cm); open stand structure; 2050 climate

Simulierte Verjüngung

- vorhanden
- eher vorhanden
- eher fehlend
- fehlt

**B:** Simulated binary regeneration success (40-130 cm); open stand structure; 2050 climate

Simulierte Verjüngung

- vorhanden
- eher vorhanden
- eher fehlend
- fehlt

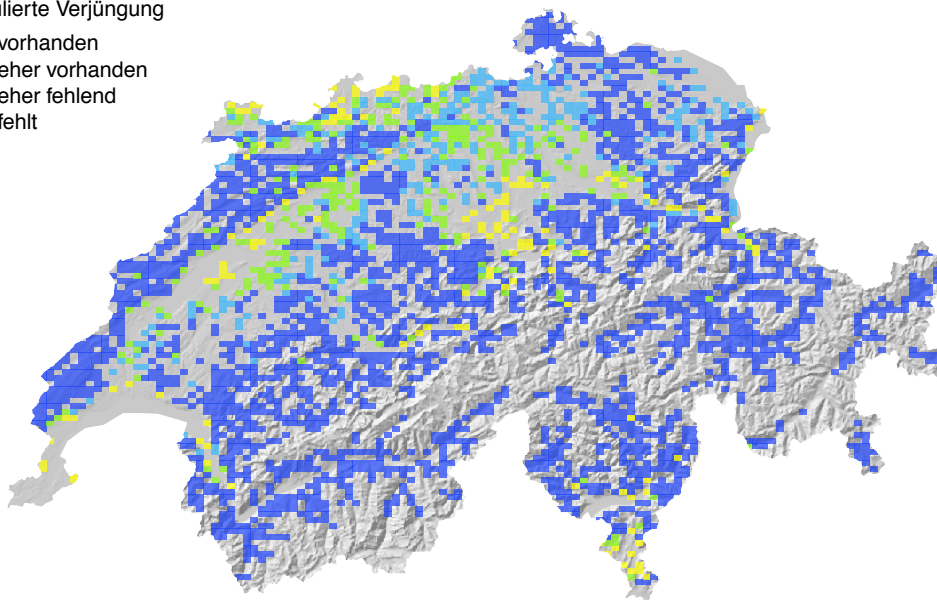
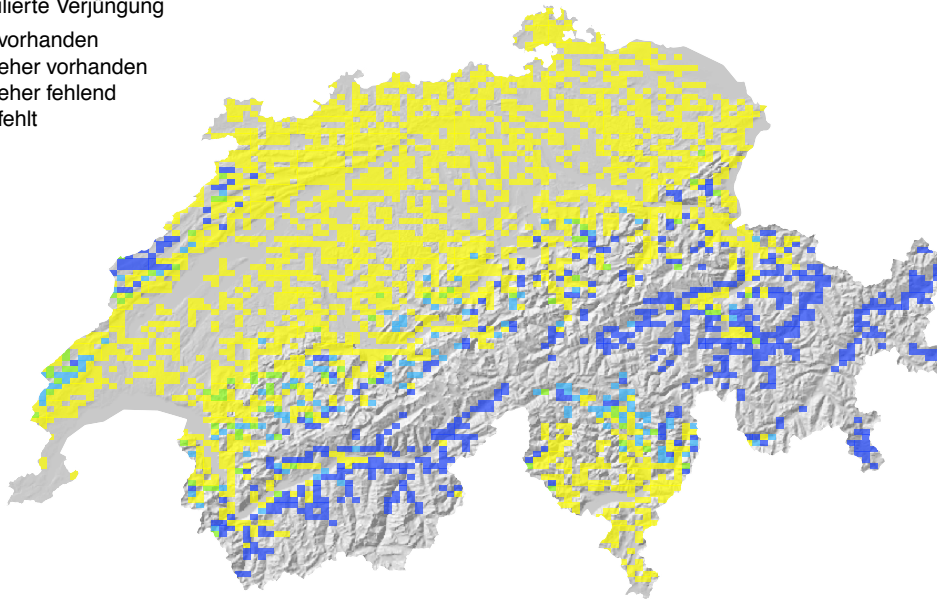


Figure A2.7: Mean simulated binary regeneration success in *Picea abies* (spruce) for A: smaller (10-40 cm) and B: larger (40-130 cm) saplings in Switzerland under 3 different RCMs around 2050 and open (20% cover) canopy structure, summarized from LFI plot observations to ca. 2.0 x 2.5 km resolution for better visibility. The binary threshold indicates the cut-level to optimally split probabilities into presence and absence of regeneration per LFI plot

A: Simulated binary regeneration success (10-40 cm); actual stand and site conditions; 2080 climate

Simulierte Verjüngung

- vorhanden
- eher vorhanden
- eher fehlend
- fehlt



B: Simulated binary regeneration success (40-130 cm); actual stand and site conditions; 2080 climate

Simulierte Verjüngung

- vorhanden
- eher vorhanden
- eher fehlend
- fehlt

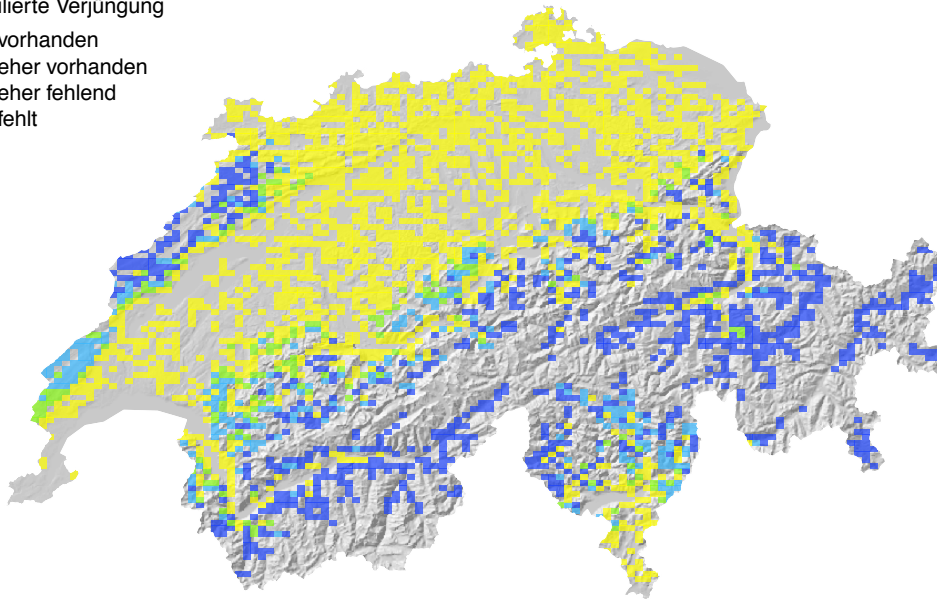


Figure A2.8: Mean simulated binary regeneration success in *Picea abies* (spruce) for A: smaller (10-40 cm) and B: larger (40-130 cm) saplings in Switzerland under 3 different RCMs around 2080 and current canopy structure and site conditions, summarized from LFI plot observations to ca. 2.0 x 2.5 km resolution for better visibility. The binary threshold indicates the cut-level to optimally split probabilities into presence and absence of regeneration per LFI plot.

A: Simulated binary regeneration success (10-40 cm); semi-open stand structure; 2080 climate

Simulierte Verjüngung

- vorhanden
- eher vorhanden
- eher fehlend
- fehlt

**B: Simulated binary regeneration success (40-130 cm); semi-open stand structure; 2080 climate**

Simulierte Verjüngung

- vorhanden
- eher vorhanden
- eher fehlend
- fehlt

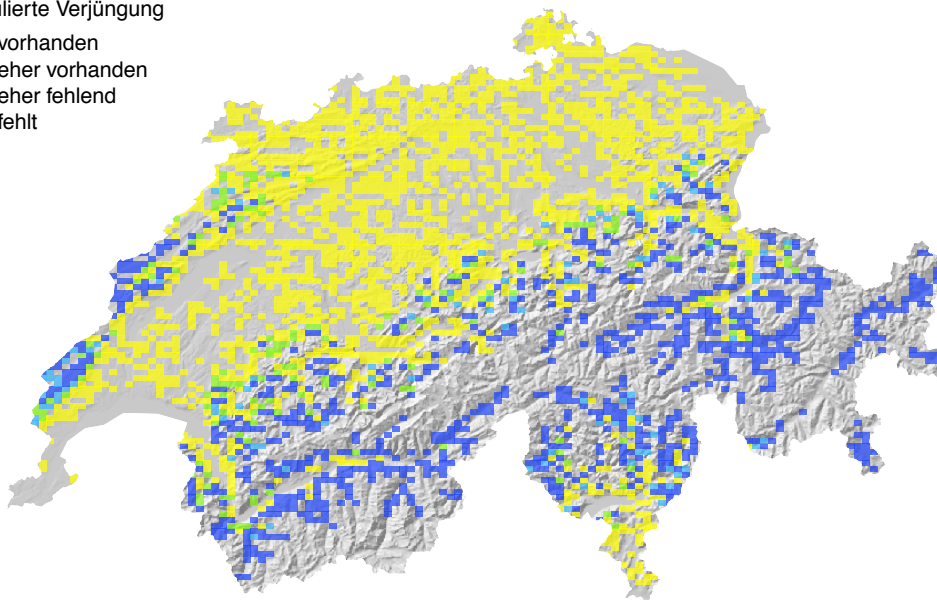
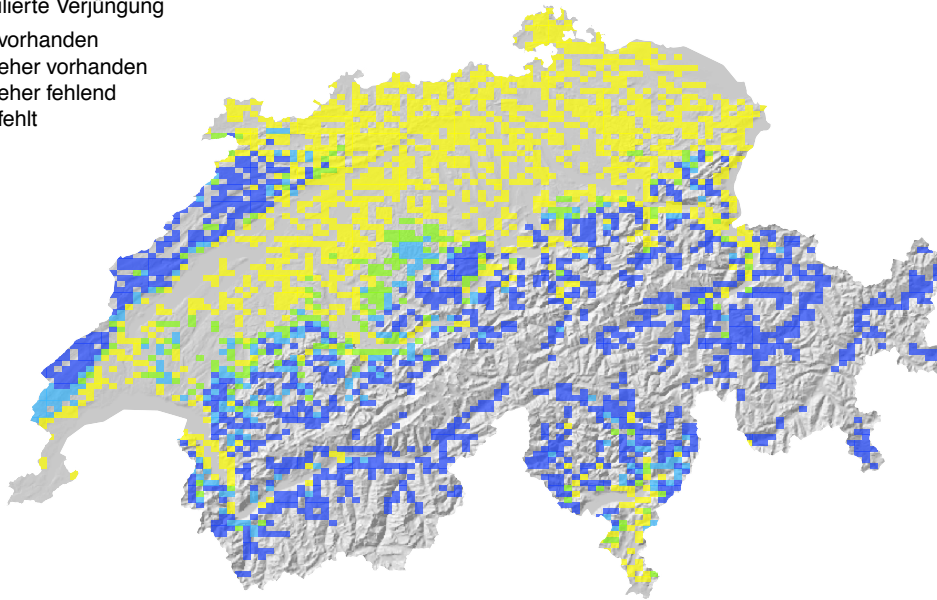


Figure A2.9: Mean simulated binary regeneration success in *Picea abies* (spruce) for A: smaller (10-40 cm) and B: larger (40-130 cm) saplings in Switzerland under 3 different RCMs around 2080 and semi-open (40% cover) canopy structure, summarized from LFI plot observations to ca. 2.0 x 2.5 km resolution for better visibility. The binary threshold indicates the cut-level to optimally split probabilities into presence and absence of regeneration per LFI plot

A: Simulated binary regeneration success (10-40 cm); open stand structure; 2080 climate

Simulierte Verjüngung

- vorhanden
- eher vorhanden
- eher fehlend
- fehlt

**B:** Simulated binary regeneration success (40-130 cm); open stand structure; 2080 climate

Simulierte Verjüngung

- vorhanden
- eher vorhanden
- eher fehlend
- fehlt

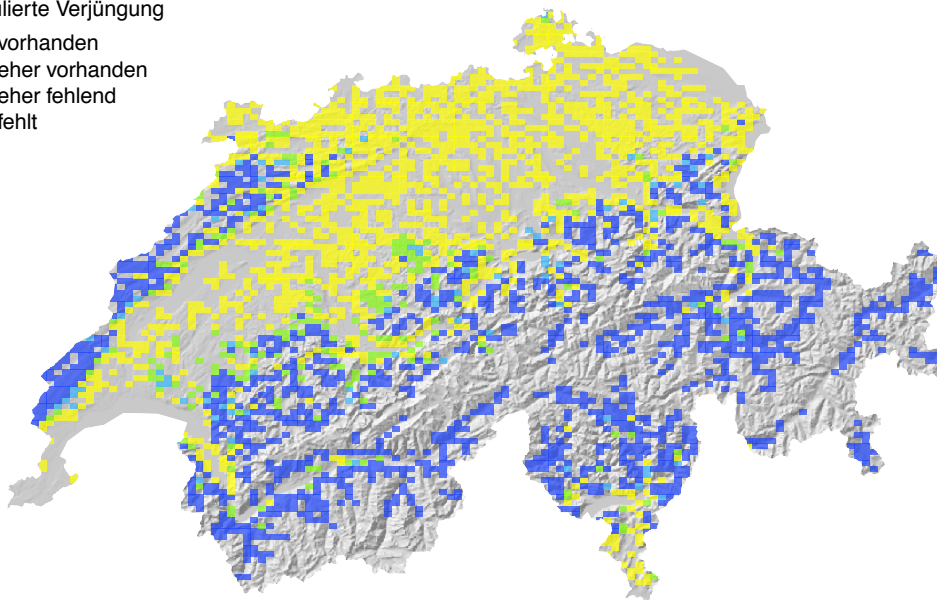
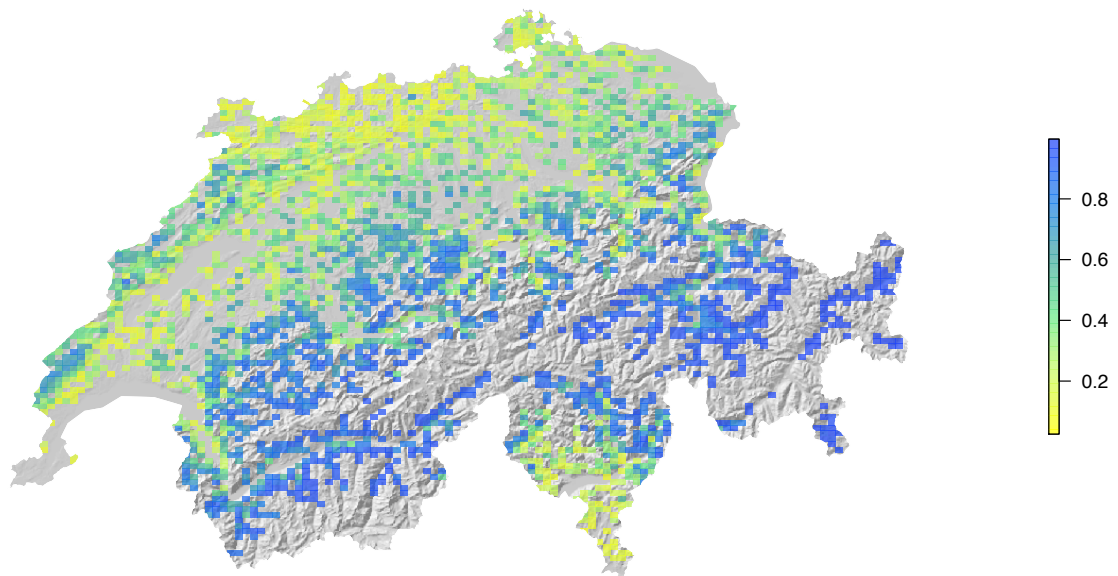


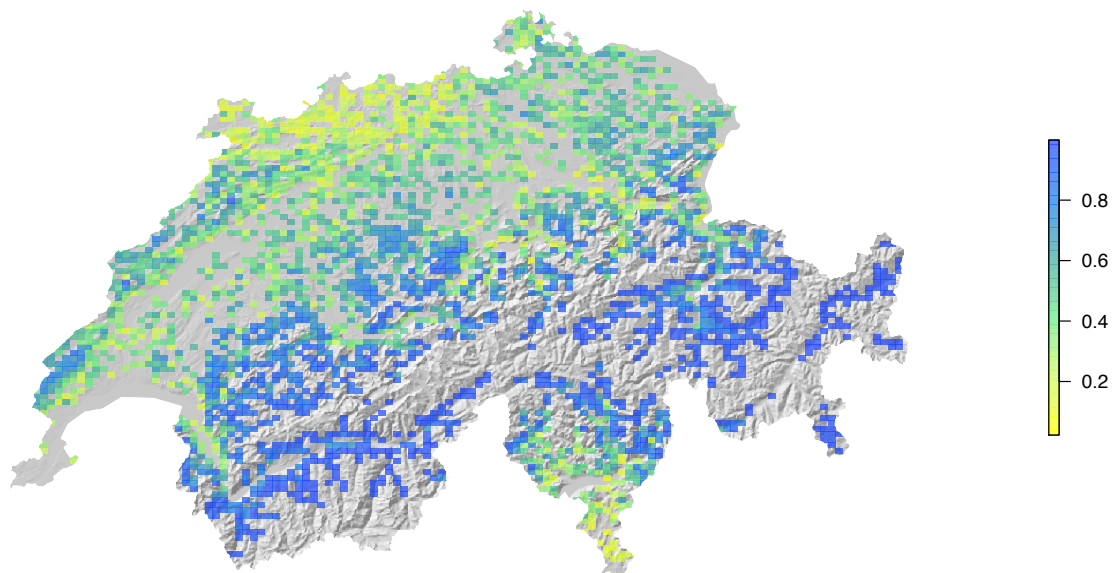
Figure A2.10: Mean simulated binary regeneration success in *Picea abies* (spruce) for A: smaller (10-40 cm) and B: larger (40-130 cm) saplings in Switzerland under 3 different RCMs around 2080 and open (20% cover) canopy structure, summarized from LFI plot observations to ca. 2.0 x 2.5 km resolution for better visibility. The binary threshold indicates the cut-level to optimally split probabilities into presence and absence of regeneration per LFI plot

A: Simulated probability of regeneration success (10-40 cm); actual stand and site conditions; current climate



Grenzwert: 0.52

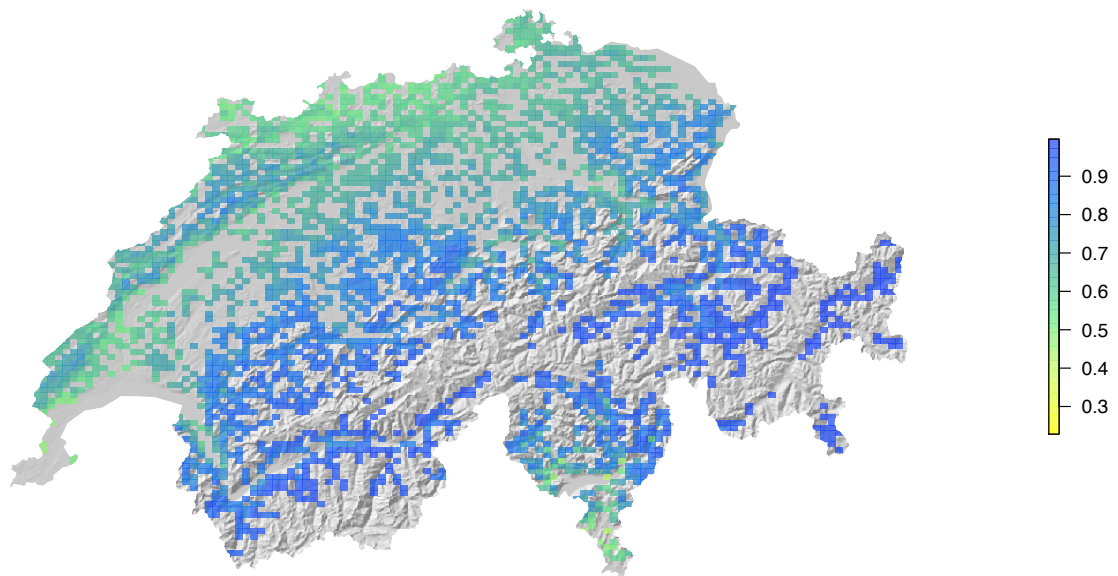
B: Simulated probability of regeneration success (40-130 cm); actual stand and site conditions; current climate



Grenzwert: 0.62

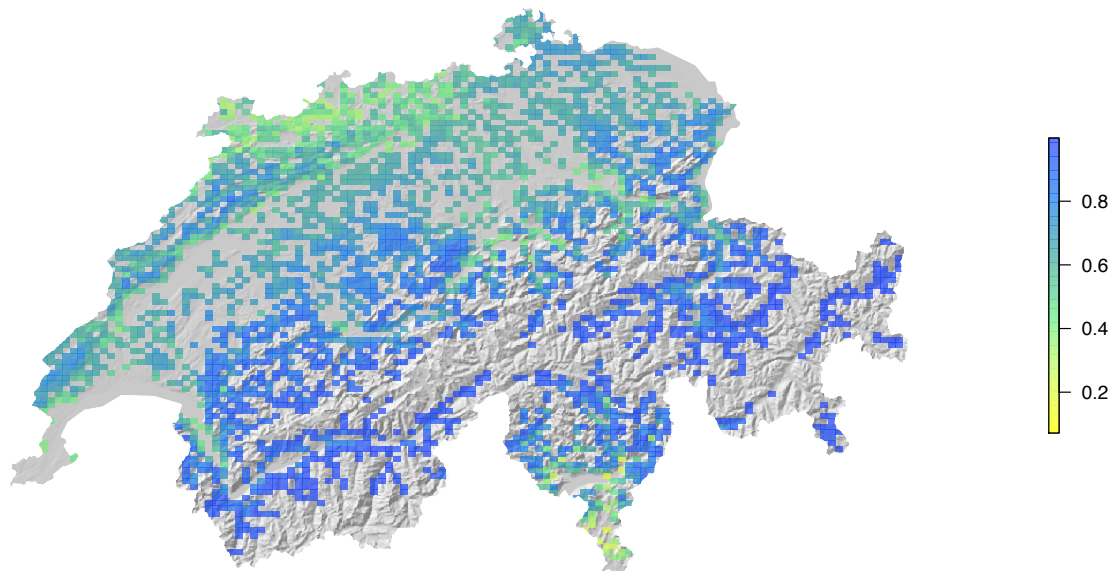
Figure A2.11: Simulated probability of regeneration success in *Picea abies* (spruce) for A: smaller (10-40 cm) and B: larger (40-130 cm) saplings in Switzerland under current climate and current canopy structure and site conditions, summarized from LFI plot observations to ca. 2.0 x 2.5 km resolution for better visibility. The binary threshold indicates the cut-level to optimally split probabilities into presence and absence of regeneration per LFI plot.

A: Simulated probability of regeneration success (10-40 cm); semi-open stand structure; current climate



Grenzwert: 0.52

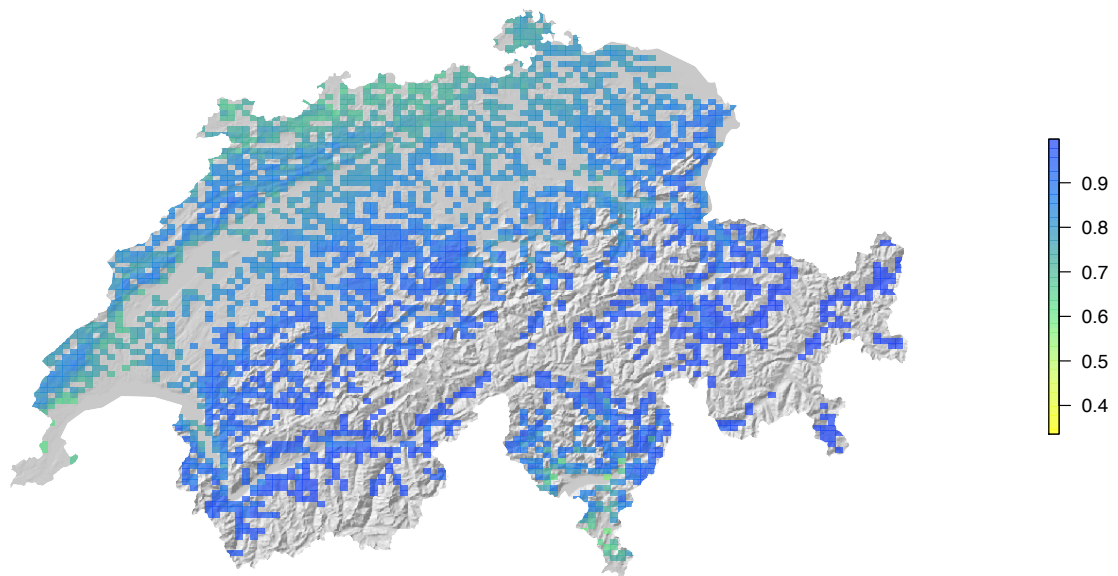
B: Simulated probability of regeneration success (40-130 cm); semi-open stand structure; current climate



Grenzwert: 0.62

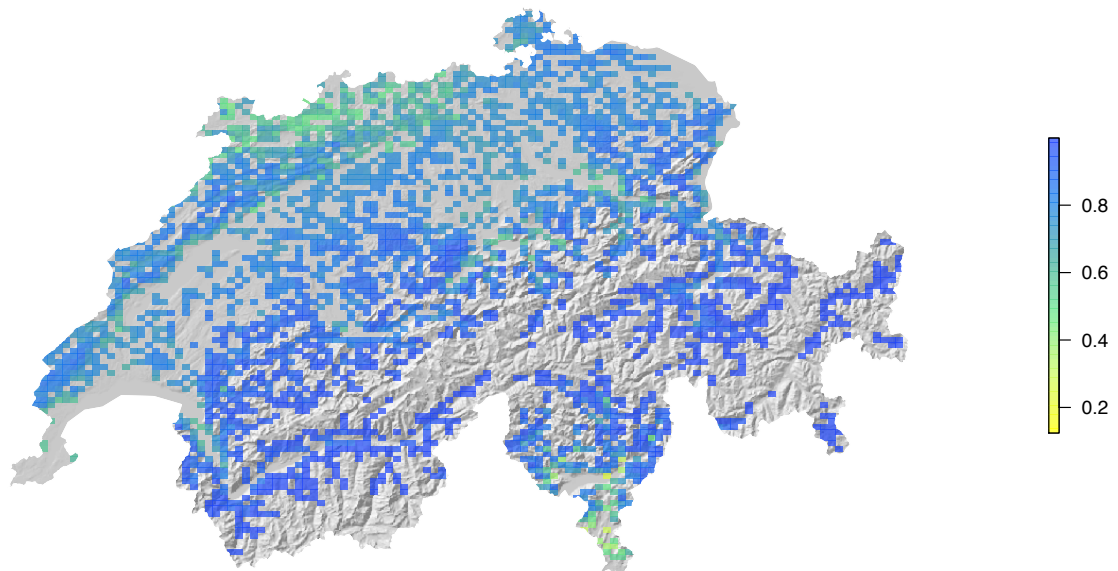
Figure A2.12: Simulated probability of regeneration success in *Picea abies* (spruce) for A: smaller (10-40 cm) and B: larger (40-130 cm) saplings in Switzerland under current climate and semi-open (40% cover) canopy structure, summarized from LFI plot observations to ca. 2.0 x 2.5 km resolution for better visibility. The binary threshold indicates the cut-level to optimally split probabilities into presence and absence of regeneration per LFI plot.

A: Simulated probability of regeneration success (10-40 cm); open stand structure; current climate



Grenzwert: 0.52

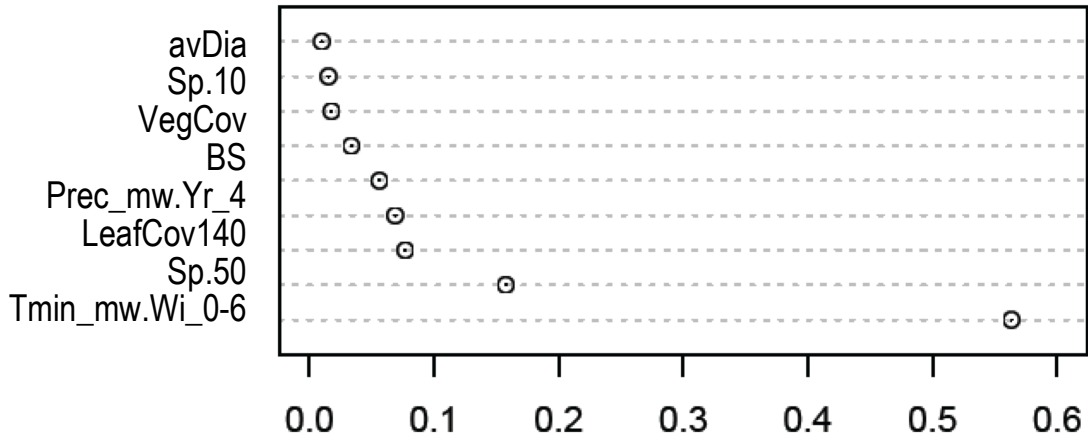
B: Simulated probability of regeneration success (40-130 cm); open stand structure; current climate



Grenzwert: 0.62

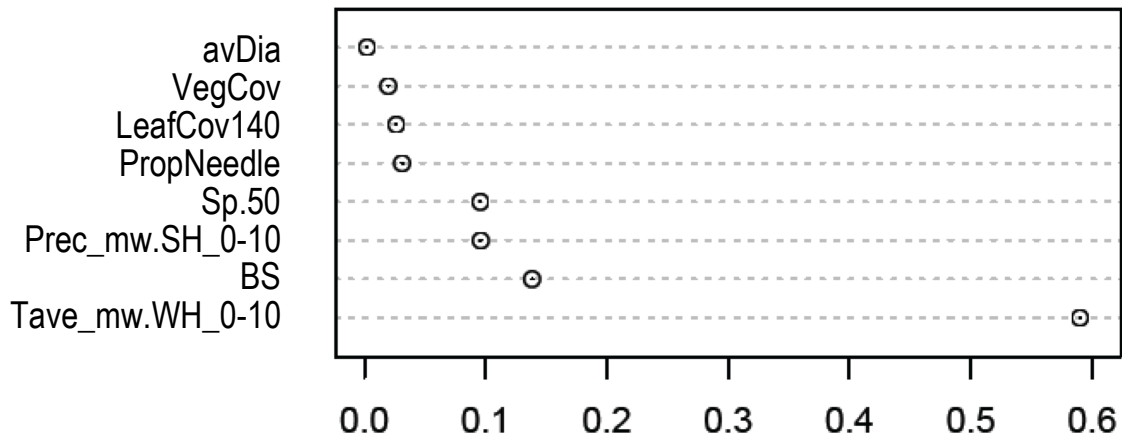
Figure A2.13: Simulated probability of regeneration success in *Picea abies* (spruce) for A: smaller (10-40 cm) and B: larger (40-130 cm) saplings in Switzerland under current climate and open (20% cover) canopy structure, summarized from LFI plot observations to ca. 2.0 x 2.5 km resolution for better visibility. The binary threshold indicates the cut-level to optimally split probabilities into presence and absence of regeneration per LFI plot.

Variable importance *Picea* (10) juveniles



R2 : 0.28 (stdCV : 0.02)

Variable importance *Picea* (10) older



R2 : 0.28 (stdCV : 0.02)

Figure A1.14: Variable importance for modelling the binary regeneration success of smaller (juveniles) and larger (older) saplings of spruce (*Picea abies*). Values on the X-axis indicate the % importance in terms of contribution to the full model.