

Past and future landscape dynamics in wooded pastures of the Jura Mountains under land-use and climate change

APPENDIX

This document provides detailed information about improvements of the model WoodPaM made for the simulations presented in the manuscript. With the exception of the sensitivity analysis at the end of the appendix, it is similarly structured to the model description in Gillet (2008). However, only refinements to this earlier model version are stated here.

METHODS

The herb submodel

Succession

In succession from fallow to understory, a lightfleck- and an edge-effect are implemented that both restrict the transformation from fallow F to understory U (flow FtoU in Gillet (2008), Equation A1). Subsequently, the cover of fallow in forest is enhanced and stand regeneration facilitated, because on fallows tree recruitment is not reduced by shading (see modifications in the tree submodel). This modification is based on our observations of the light climate and the herb layer in uneven-aged forest stands, which are characteristic in wood-pastures.

$$\text{FtoU} = (\text{TreeCover} * F) - (U * (F + 0.01 + 0.1 * (1 - \text{TreeCover}))) \quad [\text{Equation A1}]$$

The development of fallow from eutrophic pasture is made independent to dunging intensity in order to accelerate fallow succession. With the original formulation an unrealistic slow transformation of eutrophic pastures into fallows occurred in experimental simulations of abandonment, while lawns transformed into fallow much faster. Our modification assumes fallow succession to be faster under eutrophic conditions.

Fallow succession is considered to be accelerated by climate warming on both, eutrophic pastures and lawns. Thus, the altitude effect AE is added as a multiplier to the transformation flux from eutrophic pastures M to fallow F (MtoF, Gillet (2008)), while in the transformation flux of lawn to fallow (LtoF) climate warming was already considered.

Forage production

Yearly local forage production in a grid cell (LFP) is computed based on a new regression model (in comparison to Gillet 2008). The model relates empirical data on productivity from the same set of vegetation surveys from the Jura Mountains and the Alps as used in Gillet (2008) to the local pastoral value LPV and (newly) to the length of the growing season *vegdays* (Equation A2). LPV is a function of the successional state of the herb layer in a grid cell (cover of the four ecological community types: eutrophic pastureland M, oligotrophic pastureland L, fallow F and understory U). Most important, *vegdays* is not only calculated from the current year, but from the average temperature of the last 50 years, dynamically

looking back from each simulation year (see section climate submodel). By this means, we take into account that the productivity of grassland plant communities increases slowly following the general trend of temperature rise due to community adaptation, rather than spontaneously in single warm years.

$$\text{LFP} = \left(\frac{160}{1 + \exp(-2 - 0.000048 * \text{vegdays} * \text{LPV})} - \frac{160}{1 + \exp(-2)} \right) * 1000 \quad [\text{kg DM ha}^{-1} \text{ y}^{-1}] \quad [\text{Equation A2}]$$

Coefficient of determination (R^2): 0.8.12

Vegdays: Length of the vegetation period during the last 50 years [days]

LPV: Local pastoral value of the herb layer in a grid cell

The wood submodel

Shrubs

We removed the temporal delay of 5 years in shrub recruitment, because during testing of the original formulation of the model an unrealistic recruitment pattern of shrubs was simulated: Initially, low shrub cover first disappeared and after 5 years shrubs recruited numerously.

Trees

Based on the species traits available from the forest landscape model LandClim (Bugmann 1994, Schumacher 2004, Schumacher and Bugmann 2006), we implemented a total number of 13 tree species into the tree submodel of WoodPaM (see Table A1). The species pool reflects species composition of current forests in the subalpine belt of the Jura (Norway spruce *Picea abies*, beech *Fagus sylvatica*, fir *Abies alba*, maple *Acer pseudoplatanus*, Rowan berry *Sorbus aucuparia*), as well as species currently occurring at lower altitude (e.g. ash *Fraxinus excelsior* and oaks *Quercus* spec.). The latter might potentially enter the subalpine belt with projected climate warming and thus are important for consistent simulations of climate change scenarios.

We split the former life stage “tree” into two life stages in order to distinguish mature trees from young trees that do not yet produce seeds but already escaped browsing in the sapling stage. A total number of four life stages of trees (seedlings, saplings, young and adult trees) leads to a more realistic speed of recruitment of trees, because seed producing trees are less numerous. Transition rates from the sapling stage to the young-tree layer and the mature-tree layer are modified in a feasible manner considering tree growth under optimal conditions (minimum transit time in a stage) and under stress from shading (maximum transit time, see Table A1). Total tree cover is calculated from both, the cover of old and of young trees. By this means, all tree individuals taller than 5 meters are considered for habitat use of cattle, for shading of saplings and seedlings and are the determinant for the cover of understory.

We consider shading by shrubs additionally to shading by trees in the mortality of tree seedlings (flow exTh) and in seedlings' growth (flow ThToTs). Both flows are calculated as follows (Equation A3):

$$\text{exTh} = \text{Th} * \min(1, 1/\text{maThs} + \text{Blh} + (1 - \text{Lsh}) * \min(1, \text{TreeCover} + \text{Sc})) / \text{miThs} \quad [\text{Equation A3}]$$

$$\text{ThToTs} = \text{Th} / \max(\text{miThs}, \text{maThs} * \text{Blh}) * (1 - \text{Sc}) * (1 - (1 - \text{Lsh}) * \min(1, \text{TreeCover} + \text{Sc})) * \text{DDred} * (1 - \text{Blh}) * \text{sqrt}(\max(1 - \text{Drl} / \text{dst}, 0))$$

Th: number of seedlings

Lsh: tree species tolerance to shade in the seedling stage

Sc: cover of shrubs and tree saplings

Blh: browsing intensity in the herb layer (Gillet 2008)

DDred: growth reduction according to number of degree days (Bugmann 1994)

Drl: annual drought stress index (see chapter climate submodel)

maThs/miThs: maximum and minimum growth time of seedlings from the seedling to the sapling stage (see Table A1 tree species parameters).

We restrict the establishment of trees in the forest understory and on rock outcrops. In the modified establishment filter, the cover of understory is multiplied with the species specific tolerance to shade lsh (see Table A1), which favors shade tolerant species in closed forests (Equation A4). Establishment on rock is restricted in case of large rock outcrops (Equation A4), because rock face itself does not provide safe sites, only cracks in the rock face and the general bumpy terrain surface does (Béguin 2007).

The climatic restrictions of tree establishment (see chapter climate submodel and Table A1) structurally follow the LandClim forest model. Establishment fails if one of the following conditions is met: The annual drought index DrI exceeds the species specific threshold dst (see Table A1); the annual minimum winter temperature is below the species specific threshold miWT; the annual number of degree days DDS is not within the species specific interval]miDD, maDD[(Equation A4).

Resuming such dependencies of establishment of trees on the state of the herb layer and climatic conditions, rejuvenation (number of seedlings inTh) of a tree species is computed as follows (Equation A4):

$$\text{inTh} = \text{if} \quad \begin{array}{l} \text{LTmin} > \text{miWT} \\ \text{and DDS} > \text{miDD} \\ \text{and DDS} < \text{maDD} \\ \text{and Drl} < \text{dst} \end{array} \quad [\text{Equation A4}]$$

$$\text{then} \quad (\text{Rt} * (\text{Tb} + \text{TtoSum} / \text{R}) + \text{imm} * \text{im}) * (\text{U} * \text{Lsh} + \text{F} + \text{RO} * (1 - \text{RO}))$$

$$\text{else } 0$$

R: number of seedlings from adult trees inside the cell (25 m times 25 m)

TtoSum: number of trees in the neighboring cells

Rt: modifier of neighborhood seedling recruitment (Gillet 2008)

Im: flag for immigration from outside landscape

Imm: number of seedlings immigrating from outside landscape (arbitrarily set to 0.001 in order to hinder the complete extinction of tree species during simulation, see also Table A1 tree species parameters).

The parameters of tree species' sensitivity to climate used in LandClim reflect tree species behavior in central alpine climate. We let these values for most tree species unchanged, however, we adjust the behavior of spruce, beech and maple to its behavior in the oceanic climate of the Jura (see Table A1). We changed the following parameters, which Rickebusch et al. (2007) found to control tree species distributions at tree line ecotones:

Minimum number of degree days (miDD) of beech and maple: miDD(beech) and miDD(maple) are set to 514, which equals minimum number of degree days at 1600 m a.s.l., being the altitude of the tree line in the Jura. By this means, we allow beech and maple to grow up to observed altitudes (tree line).

Monthly minimum winter temperature (miWT) for establishment and seedlings' mortality (maThs) of spruce: miWT(spruce) is set to -3.9°C , which equals miWT(1600 m a.s.l.), being the altitude of the tree line (long term annual minima based on 1901-2000 observations) and seedlings' mortality is enhanced (maThs set to 12.5 instead of 25), which both mimics the limited establishment of spruce in the oceanic subalpine zone with long-lasting snow cover. Here snow fungi infect seedlings and reduce establishment success and competitive strength of spruce (Ellenberg 1996). The minimum number of degree days of spruce remained unchanged, because thick snow limits establishment (regulated by miWT and maThs) and not growth of adult trees (regulated by number of degree days).

We also adjusted the parameters of pine in order to not appear above 1000 m a.s.l., but on lower altitudes, which fits (personal) observations:

Maximum number of degree days (maDD) of pine: maDD(pine) is set to 4500 as an intermediate between maple (4491) and *Quercus robur* (4655).

Minimum number of degree days (miDD) of pine: miDD(pine) is set to 1094, which equals miDD(1000 m a.s.l.).

The growth parameters of maple were adjusted to emphasize its behavior as a gap species in beech forests:

seedlings' mortality (maThs), saplings' mortality (maTst) and young trees' mortality (maTtb) of maple has been enhanced by halving the former values (8, 40, 40) to 4, 20 and 20.

The climate submodel

The climate submodel basically computes several annual climate parameters from monthly values for temperature and precipitation, which influence herb layer dynamics, tree establishment and growth: Annual sum of degree days, minimum temperature in winter, yearly average drought stress index and apparent altitude. The latter expresses climate warming through reduced elevation, which accelerates herb layer succession and enhances its productivity (Gillet 2008). For each grid cell, these global parameters are calculated according to its topographic situation (altitude, slope, aspect).

In general, the structure of the climate submodel follows LandClim (Bugmann 1994, Schumacher 2004), which provides well elaborated formulas for tree species response to temperature and precipitation together with the necessary parameters for all relevant species. However, we substituted equations for the computation of potential evapotranspiration PET and actual evapotranspiration of trees AET with a different approach. We lack detailed data on soil depth in the Jura mountains, where soil conditions vary distinctly at the scale of meters: Rock outcrops and steep slopes carry shallow soils, while Loess deposits even enhance the depth of colluvial soils in depressions (Martignier et al. submitted). Instead of directly estimating soil depth, which is a requisite for the computation of the local water balance and the soil water storage following LandClim, we estimate AET using an equation from hydrological science (Zhang et al. 2001) and apply an empirical modifier of AET proportional to the presence of rock outcrops in a grid cell (for the estimation of rock outcrops refer to Peringer et al., in prep). For the calculation of PET, we choose the Turc-Pike formula (Pike 1964) instead of the Thornthwaite formula originally used in LandClim, because it performs better in combination with the AET calculation of Zhang et al. (2001), leading to reasonable values of drought stress (see sensitivity analysis at the end of the appendix). The climate parameters influencing vegetation dynamics are computed as follows:

Local temperature LT and LT': Due to altitude, slope and aspect, the local temperature in grid cells varies following the geomorphological conditions. First, the current monthly temperature Tvar, which is derived from the climate time series, is adjusted to the altitude A of a cell applying the month-specific elevation lapse rate ELR. Adjusted local temperature LT is calculated as follows (Equation A5):

$$LT = ([Tvar] + (Aref-A) * [ELR]/100) \quad [^{\circ}C] \quad \text{[Equation A5]}$$

Aref: altitude of the reference climate station [m a.s.l.]

ELR: month-specific elevation lapse rate of temperature [K/100m]

Second, LT is modified applying the correction factor kpMod for PET from LandClim (Schumacher 2004). This results in the local temperature LT', which reflects the temperature to depend on slope and aspect (Equation A6):

$$LT' = LT * kpMod \quad [^{\circ}C] \quad \text{[Equation A6]}$$

Bugmann (1994) derives the kpMod-correction for PET in an empirical way relating the variation of radiation with slope and aspect to measured variability in PET. Thus, kpMod is designed to vary between 1.25 and 0.875. Direct estimates of temperature dependency on slope-aspect would require a local energy-balance, because cooling effects from AET have a big influence. We base our application of kpMod to estimate local temperature on the fact that PET is coupled to temperature and both depend on the same driver (radiation).

While PET is calculated from LT (following LandClim, where kpMod is applied afterwards to correct for slope-aspect influence), the local number of degree days and minimum winter temperature are calculated from LT'. Thus, in WoodPaM local annual number of degree days and minimum winter temperature vary with microclimatic diversity induced by slope and aspect. This is a requisite to reproduce the complex of Aceri-Fagetum and spruce-rowan berry-community at the treeline, as well as fir growing at higher altitudes at warmer SW-

slopes. Without considering the topographic variability in temperature, simulated natural vegetation is only determined by altitudinal zonation, which does not allow a complex of two forest communities at the same altitude.

Minimum temperature in winter (miWT): Selection of the minimum local monthly temperature of the year (LT’).

Annual Sum of degree days (DDS):

$$DDS = \text{sum} (\max((LT' - dtt), 0) * 30.5) \quad [^{\circ}\text{C} * \text{days}] \quad [\text{Equation A7}]$$

LT’: local temperature [$^{\circ}\text{C}$]

dtt: development threshold for vegetation (5.5°C after LandClim)

30.5: average number of days per month

Growth reduction according to number of degree days (DDred): The local annual number of degree days DDS is related to the species specific interval]miDD, maDD[(see Table A1) using the parabolic equation after Botkin, cited in Bugmann (1994).

Apparent altitude (AA): The apparent altitude is a proxy for the general level of temperature climate, which drives successions in the herb layer and shrub establishment (via the altitude effect, see Gillet 2008). A decrease in AA positively influences fallow succession in the herb layer dynamics and shrub recruitment (Gillet 2008) and enhances the forage production of the herb layer expressed in kg dry matter per year (see section herb layer). We reformulated the calculation of AA in order to consider a delayed adaptation of vegetation to temperature rise. We introduced the average yearly temperature during the last 50 years *Tav50a* (dynamically looking back from each simulation year) in order to characterize the temperature level, to which plant communities are adapted. Following climate change, *Tav50a* rises far slower than mean annual temperatures do. After Equation A8, AA behaves similarly.

$$AA = A_{\text{ref}} + (T_{\text{av50a ref}} - LT_{\text{av50a}}) / ELRa * 100 \quad [\text{m a.s.l.}] \quad [\text{Equation A8}]$$

A_{ref} : altitude of the climate reference [m a.s.l.]

$T_{\text{av50a ref}}$: average temperature during the last 50 years at the climate reference [$^{\circ}\text{C}$]

LT_{av50a} : local average temperature during the last 50 years, corrected for slope-aspect effects [$^{\circ}\text{C}$]

ELRa: yearly average elevation lapse rate of temperature [0.5 K per 100 meters]

Length of the growing season (vegdays): The length of the growing season drives the productivity of the herb layer (see section herb layer). Here we also assume a slow adaptation of mountain grasslands to the productivity of lowland pastures and calculate *vegdays* from the apparent altitude as follows (Equation A9):

$$\text{Vegdays} = 320 * \exp(-0.0006 * AA) \quad [\text{days}] \quad [\text{Equation A9}]$$

AA: apparent altitude [m a.s.l.]

Drought stress response factor (dReff): The yearly drought stress response factor dReff relates annual drought index DrI to the drought tolerance of tree species dst (see Table A1) following Bugmann (1994, p. 66) (Equation A10).

$$dReff = \text{sqrt}(\text{max}(1 - (\text{DrI} / \text{dst}), 0)) \quad [\text{Equation A10}]$$

The drought stress response factor ranges between 0 and 1 and is directly applied to tree growth as a multiplier hindering transitions between life stages. Establishment of trees is hindered if drought stress index DrI exceeds the species-specific drought tolerance dst.

Annual drought index DrI: Following LandClim, DrI is the average of the monthly drought index DrIm, calculated for the (variable) vegetation period for evergreen species (development threshold dtt = 5.5°C) and for the months April to October for deciduous species (Bugmann 1994) (Equation A11).

$$\begin{aligned} \text{DrI}_{\text{evergreen}} &= \text{sum}(\text{if } [\text{LT}'] \geq \text{dtt} \text{ then } [\text{DrIm}] \text{ else } 0) && [\text{Equation A11}] \\ &\quad / \text{howmanytrue}([\text{LT}'] \geq \text{dtt}) \\ \text{DrI}_{\text{deciduous}} &= \text{sum}(\text{if } \text{element}([\text{LT}'], [4,5,6,7,8,9,10]) \geq \text{dtt} \\ &\quad \text{then } \text{element}([\text{DrIm}], [4,5,6,7,8,9,10]) \text{ else } 0) \\ &\quad / \text{howmanytrue}(\text{element}([\text{LT}'], [4,5,6,7,8,9,10]) \geq \text{dtt}) \end{aligned}$$

Following LandClim again, the monthly drought index DrIm is based on the ratio of actual transpiration of trees ETt and evaporative demand of trees Tdt (Equation A12). When actual evapotranspiration is smaller than the evaporative demand, the tree suffers drought stress.

$$\text{DrIm} = 1 - \text{ETt} / \text{Tdt} \quad [\text{Equation A12}]$$

The evaporative demand Tdt is conceptually calculated after LandClim (Equation A13):

$$\text{Td} = \text{PET} - \text{Interc} \quad [\text{mm}] \quad [\text{Equation A13}]$$

PET: potential evapotranspiration [mm]
Interc: interception [mm]

In order to approximate the hydrological situation in semi-open landscapes, which varies with tree cover and is different from closed forests, we implemented a separate calculation of interception in grasslands and in forest (Equation A14):

$$\begin{aligned} \text{Interc} &= \text{TreeCover} * \text{min}(0.3 * [\text{Pvar}], [\text{PET}]) && [\text{Equation A14}] \\ &\quad + (1 - \text{TreeCover} - \text{RO}) * \text{min}(0.15 * [\text{Pvar}], [\text{PET}]) \quad [\text{mm}] \end{aligned}$$

Pvar: monthly precipitation derived from the (stochastically varied) reference climate time series [mm]
RO: cover of rock outcrops in a grid cell

We assumed no interception on rock face, 30% interception in forest (Lyr et al. 1992) and 15% interception on grassland (Couturie and Ripley 1973, Ripley and Saugier 1978, Kelliher et al. 1993).

Potential evapotranspiration is calculated after Pike (1964) (Equation A15):

$$PET = kpMod * \max(0.4 * [LT] / ([LT] + 15) * (50 + [lga] * (0.18 + 0.62 * 0.5)), 0) \quad [\text{Equation A15}]$$

kpMod: correction factor for PET regarding slope-aspect influence (see (Schumacher 2004))

LT: first estimate of local monthly temperature [°C]

lga: solar radiation, which accounts for a latitudinal adjustment of PET values [cal/cm²/day]

While LandClim derives actual transpiration of trees ETt from a soil water balance, we calculate ETt applying an equation from hydrological science based on the aridity index AIP, which was originally developed to assess the water balance in river catchments on a yearly basis (Zhang et al. 2001). Zhang's formula considers differences in actual evapotranspiration between grassland and forest across a gradient of aridity and was validated for grassland-forest-mosaics at catchment scale. In order to estimate the actual evapotranspiration of trees ETt dynamically from the monthly climate given by temperature and precipitation, we apply the equation after Zhang et al. (2001) at a monthly basis and parameterize for forest (plant available water coefficient ω set to 2, Equation A16):

$$ET_trees = \max([Pvar] * (1 + 2 * [AIP]) / (1 + 2 * [AIP] + 1/[AIP]) * (1 - RO)^{1/2}, 0) \quad [\text{Equation A16}]$$

AIP: aridity index, calculated as follows:

$$AIP = PET / Pvar$$

Rock outcrops are applied as an arbitrary modifier to ETt subject to calibration and based on the fact that trees on shallow soils associated with rock outcrops can transpire less due to low water resources in the soil. By this means, reduced ETt leads to enhanced drought stress DrIm of such trees, which negatively impacts on establishment and growth. The exponent $\frac{1}{2}$ applied to the inverse rock cover in a grid cell (1-RO) expresses the provision of water for tree establishment and growth by cracks and soil-filled pockets in the rock face, which can be sufficient unless the cover of rock face becomes very high. Choosing $\frac{1}{2}$ is due to optimization (see sensitivity analysis at the end of the appendix).

The cattle submodel

For browsing intensity in the herb layer, additionally to fallows (tall unpalatable forbs) and rock outcrops (see Gillet 2008), we consider shrubs to protect seedlings similarly. Mostly thorny shrubs act as nursery plants and protect seedlings from browsing. Browsing intensity in the herb layer is calculated from the grazing intensity, the tree species specific resistance to browsing and the presence of protecting vegetation as follows (Equation A17):

$$Blh = GI^{bp} * BCh * (1 - F - RO) * (1 - S) \quad [\text{Equation A17}]$$

GI: local grazing intensity (Gillet 2008)

bp: resistance to browsing (see Table A1 species parameters)

BCh: cover of seedlings in the herb layer

F: cover of fallow in a grid cell

RO: cover of rock outcrops in a grid cell

S: cover of shrubs in a grid cell.

For all scenarios that shall consider current management practices (climate change scenarios starting from today), a rotational grazing system is simulated based on a division of each pasture into several paddocks. Approximating adaptive agricultural practice, the grazing duration per paddock GD_i of the herd is optimized according to the forage production of the paddock FP_i relative to all paddocks of the pasture (Equation A18):

$$GD_i = GD_{\text{year}} * (FP_i / FP_{\text{pasture}}) \quad \text{[Equation A18]}$$

GD_{year} : total grazing duration of the pasture per year (in mountain pastures around 120 days)

FP_{pasture} : sum of the forage production of all paddocks [kg DM/y]

Sensitivity analysis of drought stress calculation for trees on shallow soils

Beside forage productivity of the herb layer, drought stress on tree growth is the most important driver of simulated landscape structural changes. Future summer droughts obviously select potentially dominant tree species from the species pool dependent on the degree of climate warming and the shift in the precipitation regime.

Design

We performed a sensitivity analysis on our estimate of drought stress on trees, focusing on our method to consider soil water availability (see above), which differs from the established method in the forest landscape model LandClim (Bugmann 1994, Schumacher 2004, Schumacher and Bugmann 2006). We performed comparative simulations of vegetation development in the mountain pasture Pré aux Veaux, where rock outcrops are frequent due to ridges of limestone. Simulations run from 1950 (spin-up based on observed climate) until 2500 along the moderate climate change scenario B2. We varied the influence of rock outcrops (RO) in the drought stress estimation for trees. We use the cover of rock outcrops, which was estimated from geomorphology as an indicator for shallow soils (see above). Drought stress for trees is accordingly increased applying the following modifier (Equation A19):

$$(1-RO)^{\text{expRO}}$$

[Equation A19]

RO: Cover of rock outcrops in a grid cell

expRO: shape factor for the strength of influence of shallow soils on drought stress

The shape factor expRO for the influence of shallow soils on drought stress was set to values of 0 (no effect), 0.5 (reduced effect), 1 (linear effect) and 2 (enhanced effect). A reduced effect was based on the hypotheses, that for trees there is still water provided in cracks unless the rockface reaches a high proportion of area. An enhanced effect could be assumed considering shallow soil already dominating the soil water household when the cover of rock outcrops is little.

Results

While simulated values of drought stress hardly differ (not shown), impacts on population dynamics of tree species and landscape structure are clearly noticeable (Figure A1):

When disregarding geological and pedological conditions in drought stress calculations (expRO = 0), Spruce initially profits from climate warming and disappears, because it is outcompeted by beech in the long run.

When distinguishing between shallow and deep soils (expRO ≠ 0), dependent on the strength of the drought effect, tree growth is slowed in general and an intermediate forest breakdown results by the slow replacement of spruce by beech (see diagram for Phy4 (closed forest) in Figure A1). Most interesting, however, is the two-peak pattern in the population dynamics of spruce:

Currently (at simulation start) spruce is growing on rocky ridges, where it declines suffering drought with climate warming from 2100 on. Reduced browsing pressure due to increased forage availability after warming, however, allows spruce to establish on formerly intensively grazed and treeless deep soils. Here it can grow well and spruce recovers until it is outcompeted by immigrating beech.

Fluctuations of AIL (see Figure A1) underpin quite rapid dynamics of forest cover: As long as spruce dominates the landscape, its sensitivity to drought makes the landscape vulnerable to drought events, which act as disturbances and in turn create a heterogeneous and dynamic landscape. AIL stabilizes at a high value after beech became dominant, indicating a stable and homogeneous landscape pattern.

Conclusion

We decided to implement the reduced drought effect on shallow soils ($expRO = 0.5$) into the model in order to carefully avoid exaggeration of an effect hard to be clearly validated based on field data. We reject the null model (no effect: $expRO = 0$), because spruce suffering from drought on exposed ridges of limestone is plausible, as well as its good growth on sites with a favorable water household (deposits of loess). We think that the simulated effects at landscape level, which arise from the explicit consideration of different geological site conditions (temporary forest breakdown), are important to be considered in management decisions.

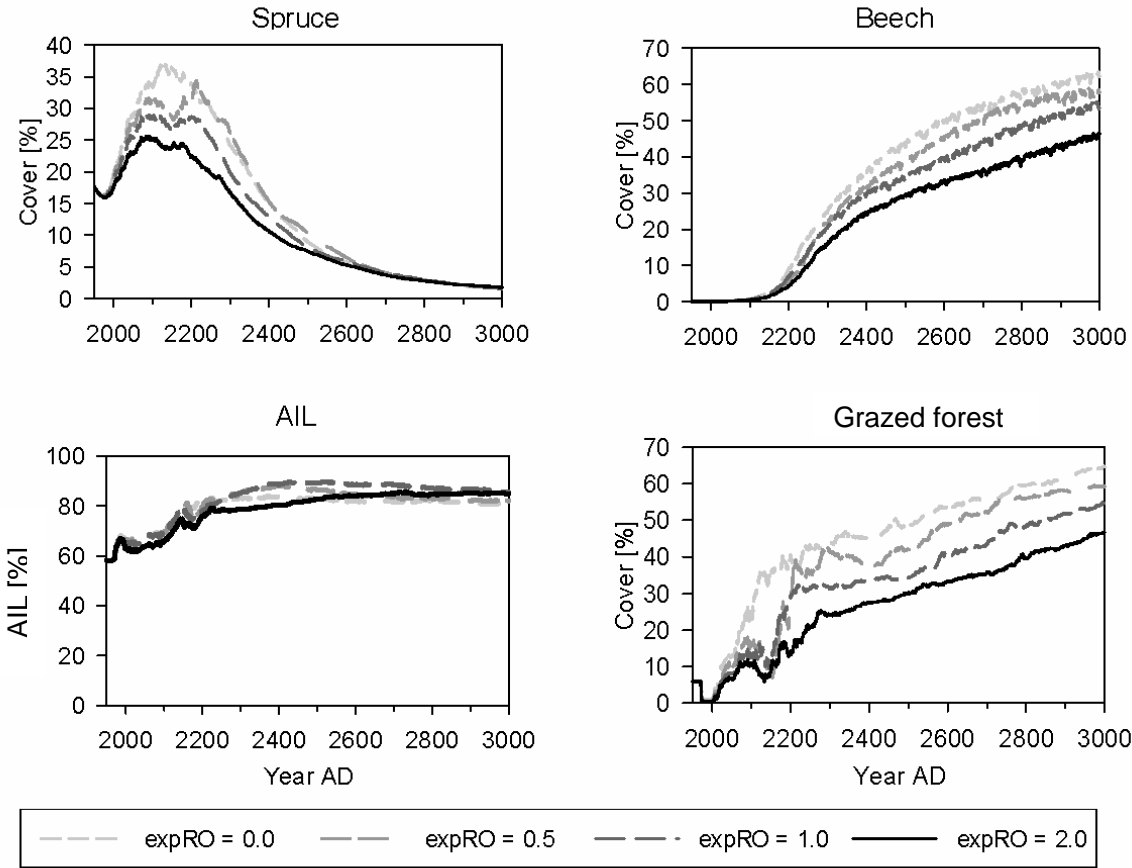


Figure A1: Population dynamics of spruce and beech and corresponding landscape structural dynamics for varying strength of the effect of shallow soils on drought stress for trees. All simulations are performed in the mountain pasture Pré aux Veaux along the moderate climate change scenario B2. The AIL is the landscape structure aggregation index (see main text) with high values indicating a homogeneous landscape.

Table A1. Tree species parameters. Parameters with an asterisk (*) are adapted to oceanic climate as described in the text.

Species name	spec	fol	bp	R	Rt	lsh	lss	miThs	maThs	miTst	maTst	miTtb	maTtb	miTt	maTt	rTh	rTs	rTt	rTb	miDD	maDD	miWT	dst	im
Abbreviation of Species name	Type of foliage. 1 for evergreen species	Resistance to browsing (increasing with value)	Modifier of neighborhood seedling recruitment	Number of seedlings from adult trees inside the cell	Seedlings' tolerance to shade (increasing with value)	Saplings' tolerance to shade (increasing with value)	Minimal transit time in the herb layer [years]	Maximal transit time in the herb layer [years]	Minimal transit time in the shrub layer [years]	Maximal transit time in the shrub layer [years]	Minimal transit time in the young tree layer [years]	Maximal transit time in the young tree layer [years]	Minimal transit time in the old tree layer [years]	Maximum age [years]	Radius of a single seedling [100 m]	Radius of a single sapling [100 m]	Radius of a single young tree [100 m]	Radius of a single old tree [100 m]	Minimal number of degree days	Maximum number of degree days	Minimum winter temperature [°C]	Index for drought tolerance (increasing with value)	Flag for immigration from outside landscape through long distance dispersal	
Picea abies	Pa	1	2	5	3	0.5	0.5	12	12.5*	8	80	10	30	100	930	0.001	0.004	0.008	0.024	385	2325	-3.9*	0.15	1
Acer pseudoplatanus.	Ap	0	1	10	4	0.6	0.7	2	4	10	20	8	20	80	550	0.001	0.005	0.012	0.036	514*	4491	-273	0.17	1
Fagus sylvatica	Fs	0	0.75	50	4	0.7	0.9	5	6	10	50	10	50	80	430	0.001	0.006	0.016	0.048	514*	4655	-4*	0.25	1
Abies alba	Aa	1	0.25	30	3	0.7	0.9	5	6	10	40	10	50	80	700	0.001	0.004	0.008	0.024	641	4491	-6	0.23	1
Pinus sylvestris	Ps	1	0.5	5	3	0.3	0.1	2	4	10	20	8	20	60	760	0.001	0.005	0.012	0.036	1094*	4500*	-273	0.37	1
Quercus petraea	Qp	0	0.75	50	4	0.4	0.3	4	6	10	30	10	40	100	860	0.001	0.006	0.016	0.048	785	4655	-5	0.25	1
Quercus robur	Qr	0	0.75	50	4	0.3	0.1	4	6	10	30	10	40	100	1060	0.001	0.006	0.016	0.048	1042	4655	-17	0.17	1
Quercus pubescens	Qh	0	0.75	50	3	0.3	0.3	5	8	10	30	15	50	90	500	0.001	0.005	0.012	0.036	1011	4655	-273	0.41	1
Carpinus betulus	Cb	0	0.5	20	4	0.6	0.7	2	4	10	40	8	50	60	220	0.001	0.004	0.012	0.036	898	4655	-9	0.25	1
Fraxinus excelsior	Fe	0	0.5	10	4	0.6	0.7	2	4	10	20	8	20	60	350	0.001	0.005	0.012	0.036	980	4491	-17	0.08	1
Tilia platyphyllos	Tp	0	0.5	20	3	0.6	0.7	2	4	10	30	8	20	60	960	0.001	0.005	0.012	0.036	1339	4491	-273	0.25	1
Acer campestre	Ac	0	0.5	10	3	0.5	0.5	2	4	10	30	8	20	50	170	0.001	0.004	0.012	0.036	1062	4491	-273	0.25	1
Sorbus aucuparia	Sa	0	1	5	4	0.4	0.3	2	6	10	20	8	20	50	110	0.001	0.004	0.012	0.036	498	4204	-273	0.33	1

Table A2: Parameters of WoodPaM, which have been newly introduced since Gillet (2008) and which are not given in Table A1. Parameters are listed in alphabetical order.

Parameter	Explanation	Unit
AIP	Aridity index	-
Aref	Altitude of the reference climate station	m a.s.l.
DDred	Growth reduction according to number of degree days (Bugmann 1994)	-
DDS	Annual number of degree days	Days
dReff	Drought stress response factor	-
DrI	Annual drought stress index (see chapter climate submodel)	-
DrIm	Monthly drought index	-
Dtt	Development threshold for vegetation	5.5°C
ELR	Month-specific elevation lapse rate of temperature	K/100m
ELRa	Yearly average elevation lapse rate of temperature	0.5 K/100 m
ETt	Actual evapotranspiration of trees	mm
Iga	Solar radiation energy, which accounts for a latitudinal adjustment of PET values	cal/cm2/day
Interc	Interception	mm
kpMod	Correction factor for PET from LandClim (Schumacher 2004)	-
LT and LT'	Local temperatures at grid cell level.	°C
LTobs	Average local temperature calculated from the observed climate time series of the years 1901-2000	
PET	Potential evapotranspiration	mm
Pvar	Monthly precipitation	mm

LITERATURE CITED

- Béguin, D. 2007. Tree regeneration and growth in wood pastures: patterns and processes. PhD Thesis. University of Neuchâtel, Neuchâtel.
- Bugmann, H. 1994. On the ecology of mountainous forests in a changing climate: a simulation study. PhD. Swiss Federal Institute of Technology, Zurich.
- Couturier, D. E. and E. A. Ripley. 1973. Rainfall Interception in Mixed Grass Prairie. *Canadian Journal of Plant Science* 53:659-663.
- Ellenberg, H. 1996. *Vegetation Mitteleuropas mit den Alpen*. 5. Auflage. Eugen Ulmer, Stuttgart.
- Gavazov, K., A. Peringer, F. Gillet, S. Siehoff, A. Buttler, and T. Spiegelberger. 2012. Dynamics of forage production in pasture-woodlands of the Swiss Jura Mountains under projected climate change scenarios. Submitted to *Ecology and Society*.
- Gillet, F. 2008. Modelling vegetation dynamics in heterogeneous pasture-woodland landscapes. *Ecological Modelling* 217:1-18.
- Kelliher, F. M., R. Leuning, and E. D. Schulze. 1993. Evaporation and Canopy Characteristics of Coniferous Forests and Grasslands. *Oecologia* 95:153-163.
- Lyr, H., H.-J. Fiedler, and W. Tranquillini. 1992. *Physiologie und Ökologie der Gehölze*. Gustav Fischer Verlag Jena.
- Martignier, L., T. Adate, and E. P. Verrecchia. Bedrock versus superficial deposits in the Swiss Jura Mountains: what is the legitimate soil parent material? *Earth Surface Processes and Landforms*, in press.
- Pike, J. G. 1964. The Estimation of Annual Run-off from Meteorological Data in a Tropical Climate. *Journal of Hydrology* 2:116-123.
- Rickebusch, S., H. Lischke, H. Bugmann, A. Guisan, and N. E. Zimmermann. 2007. Understanding the low-temperature limitations to forest growth through calibration of a forest dynamics model with tree-ring data. *Forest Ecology and Management* 246:251-263.
- Ripley, E. A. and B. Saugier. 1978. Biophysics of a Natural Grassland - Evaporation. *Journal of Applied Ecology* 15:459-479.
- Schumacher, S. 2004. The role of large-scale disturbances and climate for the dynamics of forested landscapes in the European Alps. PhD. Swiss Federal Institute of Technology, Zurich.
- Schumacher, S. and H. Bugmann. 2006. The relative importance of climatic effects, wildfires and management for future forest landscape dynamics in the Swiss Alps. *Global Change Biology* 12:1435-1450.

Zhang, L., W. R. Dawes, and G. R. Walker. 2001. Response of mean annual evapotranspiration to vegetation changes at catchment scale. *Water Resources Research* 37:701-708.