

## APPENDIX A

## Supplementary Material on LandClim Model Improvements and Parameterization

*Improvements on beetle dispersal simulations*

In the original implementation of the LandClim beetle module (Temperli et al. 2013) the simulation of the spatial distribution of beetle disturbance accounts for two distinct processes: (1) dispersal of beetles across the landscape and (2) the infestation of individual forest patches (cells in LandClim). Beetle-induced tree mortality was a separate process that only occurs in infested cells (see Temperli et al. 2013). Beetle dispersal was modelled by distributing beetle pressure ( $P_{bit}$ ) across the landscape.  $P_{bit}$  is an index (range: 0–1) that describes the local beetle population density (0 = no beetles, 1 = many beetles) and is calculated in each cell based on a) temperature-dependent spruce beetle population development, b) forest susceptibility ( $S_{cell}$ ) indicating the quality of the beetle breeding habitat by the size and basal area share of spruce trees, their drought-stress level and the amount of wind thrown spruce, and c) the beetle activity of the previous decade (Eq. 2 and 3 in Temperli et al. 2013). Because the active and wind aided yearly dispersal of *Ips typographus*, the focal bark beetle species of the original LandClim beetle module, can greatly exceed 500 m (Wermelinger 2004), Temperli et al. (2013) assumed beetles ( $P_{bit}$ ) to uniformly distribute across 10–100 km<sup>2</sup> landscapes within the 10-year model time step. That is, cell-specific  $P_{bit}$  were averaged across the landscape and this average was assigned to each cell. This assumption was appropriate for simulation landscapes with relatively uniform climate and host tree distribution as in Temperli et al. (2013), but does not hold if gradients in climate and host tree abundance limit beetle population development in parts of the simulation landscape. To overcome this deficiency we improved the LandClim beetle model by distributing  $P_{bit}$  using a classical Gaussian dispersal kernel that is commonly employed to model bark beetle dispersal (Fahse and Heurich 2011, Powell and Bentz 2014) and that describes the probability distribution  $P_D$  of the travel distance  $d$  within time  $t$ , where the diffusion coefficient  $C_D$  controls the spread of the distribution (Eq. A1):

$$P_D = \exp\left(-\frac{d^2}{4C_D t}\right) \quad \text{Eq. A1}$$

To obtain a cell-specific index of diffused beetle pressure ( $P_{bd}$ ) we summed  $P_{bit}$  values of all neighboring cells  $i$  within distance  $d(i,f) < D$  around a focal cell  $f$ , whereby we weighted  $P_{bit}$  values by  $P_D$  and adjusted the resulting sum using coefficient  $C_{bp}$  (Eq. A2).

$$P_{bd} = (P_{btl,f} + \sum_1^{i:d(i,f)<D} (P_{btl,i} \cdot P_D(d(i,f)))) \cdot C_{bp} \quad \text{Eq. A2}$$

The beetle pressure coefficient  $C_{bp}$  thus determines the scale of  $P_{bd}$  and can be used to parameterize the importance of  $P_{bd}$  in determining the spatial distribution of beetles and beetle-induced tree mortality (Eq. 4 and 7, respectively, in Temperli et al. 2013).

Infestation, the second component determining the spatial distribution of beetle disturbance, is modelled by a cell-specific infestation risk based on forest susceptibility ( $S_{cell}$ ) and beetle pressure ( $P_{bd}$ ), which in turn determines the extent (spruce biomass and area infested) and the spatial distribution of infestation (Eq. 4 and 5 of Temperli et al. 2013). In Temperli et al. (2013) wind thrown spruce biomass linearly increased the susceptibility of a forest patch to beetle infestation ( $S_{cell}$ ). In addition, wind throw was modelled to increase the susceptibility of surrounding forest patches, since beetles colonizing wind thrown trees release aggregation pheromones that attract other beetles that may colonize nearby susceptible trees (Byers 1989, 2004) and because beetles that emerge from the wind thrown trees in the year following colonization have a higher probability of killing nearby trees. Based on limited available data (Wichmann and Ravn 2001, Kautz et al. 2011), Temperli et al. (2013) implemented and parameterized this neighborhood effect of wind throw on the susceptibility of forest patches to be equally strong over a distance of 200 m, i.e. the strength of this effect did not dilute with distance from the wind thrown cell. While this approach resulted in the expected relative importance of windthrow in determining the extent and severity of beetle disturbance at the landscape-scale, the influence of wind throw on the spatial pattern of beetle disturbance was unrealistically large. If drought was of little relative importance, almost all beetle disturbed cells were located within a 200 m radius around wind thrown patches with distance to the wind throw patch being of no and stand composition and structure of little importance (Figure B5 in Appendix B of Temperli et al. 2013). Because aggregation pheromones and densities of emerging beetles dilute with increasing distance from a breeding site (e.g. wind thrown log), we would expect that with increasing distance from a wind thrown patch the simulated risk of beetle disturbance would decrease gradually and that the spatial pattern of beetle disturbance is increasingly influenced by stand composition and structure, rather than wind throw.

Since the underlying process of the neighborhood effect of wind throw is actually beetle dispersal, modelling this neighborhood effect as a modifier of forest susceptibility is inconsistent with the idea that forest susceptibility is a measure of the availability of suitable breeding habitat

for the beetles, i.e. the proportion, size and the level of drought-induced stress of standing host trees as well as the amount of wind thrown host tree material (Schmid and Frye 1976, Schmid 1981, Shore and Safranyik 1992). In the original version of the beetle model this inconsistency had to be accepted in order to account for the neighborhood effect of wind throw, because of the simplified way beetle dispersal was represented.

By modelling beetle dispersal more explicitly using an actual dispersal kernel as described above we remedied both the deficiency related to the interaction between wind and beetle disturbance, (i.e. the concentration of beetle disturbance around wind throw patches) and the deficiency of insufficient model consistency. In addition to temperature, the assessment of  $P_{bit}$  considers the beetle-killed biomass of the previous decade and forest susceptibility ( $S_{cell}$ ), whereby  $S_{cell}$  is strongly influenced by the wind thrown spruce biomass (Eq. 1 in main text). Explicitly modelling beetle dispersal, i.e. by diluting  $P_{bit}$  across the landscape using the newly introduced dispersal kernel (Eq. A2), also “disperses” the effect of increased forest susceptibility, i.e. breeding material availability, due to wind throw. This, in turn, results in the expected pattern of increased beetle disturbance risk around windthrow patches, but with this risk decreasing with increasing distance from the wind throw patch. Further, with this implementation the LandClim beetle model is more consistent in that the neighborhood effect of wind disturbance is accounted for explicitly by the underlying process of beetle dispersal.

#### *Tree species life history parameters*

Life history parameters for subalpine fir (*Abies lasiocarpa* Nutt.), Engelmann spruce (*Picea engelmannii* Parry), lodgepole pine (*Pinus contorta* Douglas), ponderosa pine (*Pinus ponderosa* Lawson) and Douglas-fir (*Pseudotsuga menziesii* Franco) were directly adopted from Schumacher et al. (2006) and parameters for aspen (*Populus tremuloides* Michx.) were derived from Burns and Honkala (1990) unless otherwise stated (Table A1). To account for the reduced dependence of clonally regenerated aspen saplings (suckers) on environmental conditions, we introduced the new species parameter  $ssTol$ . Suckers are supplied with additional resources, which increases their competitiveness over saplings from other species that regenerated from seeds (Schier et al. 1985, Swanson et al. 2010). With increasing parameter value the influence of environmental stress on the number and biomass of established saplings is reduced by modifying the assessment of species-specific plant vigor, i.e. the growth performance ( $grPer_s$ ) relative to optimal environmental conditions (Eq. 12 in Schumacher et al. 2004), as follows:

TABLE A1: Life history parameters used in LandClim for tree species of Northern Colorado.

Name	Parameter description	ABLA	PIEN	PICO	PIPO	PSME	POTR
R	Maximum growth rate (Mg/yr)	0.05	0.07	0.10	0.13	0.08	0.15
K	Maximum biomass (Mg)	3.3	9.7	11.3	14.0	11.2	9.8
maxAge	Maximum longevity (yr)	300	600	600	700	700	200
Matu	age for seed production (yr)	20	40	10	10	20	20
ED	Effective seeding distance (m)	30	30	60	40	100	240
MD	Maximum seeding distance (m)	60	180	100	150	250	800
vegP	Species is (1) or is not (0) resprouting after disturbance	0	0	0	0	0	1
spAge	Maximum age for vegetative reproduction (yr)	0	0	0	0	0	200
BioT	NE for needle leaved evergreen, D for deciduous	NE	NE	NE	NE	NE	D
folType	Foliage type	3	3	2	3	3	2
shTol	Shade tolerance (1 = very intolerant, 5 = very tolerant)	5	4	1	2	3	1
minDD	Minimum annual degree-day sum (°C)	300	400	524	1200	800	550 <sup>†</sup>
mint	Minimum establishment temperature (°C)	-99	-99	-15	-12	-15	-30
drTol <sup>‡</sup>	Drought index value at which growth stops in LandClim	0.35	0.35	0.35	0.5	0.423	0.325
brTol	Browsing tolerance (1 = very intolerant, 5 = very tolerant)	1	1	1	1	1	2
FireTol <sup>§</sup>	Tolerance to fire damage (1 = very intolerant, 5 = very tolerant)	1	2	1	5	5	1
ssTol	Stress tolerance of root suckers (range: 0–1)	0	0	0	0	0	0.7

Notes:

ABLA: *Abies lasiocarpa* Nutt., PIEN: *Picea engelmannii* Parry, PICO: *Pinus contorta* Douglas, PIPO: *Pinus ponderosa* Lawson, PSME *Pseudotsuga menziesii* Franco, POTR: *Populus tremuloides* Michx.

<sup>†</sup>Approximate annual degree-day sum historically realized at 3350 m a.s.l., the elevation limit of POTR in northern Colorado (Burns and Honkala 1990, Daly et al. 2008).

<sup>‡</sup>Drought tolerance values were originally on an ordinal scale (1 = very intolerant, 5 = very tolerant, Schumacher et al. 2006) but were later rescaled to the continuous scale of the LandClim drought index (Henne et al. 2011, Elkin et al. 2015).

<sup>§</sup>Fire tolerance rankings are based on bark allometry as in Schumacher et al. (2006).

$$\text{grPerS}_s = 1 - ((1 - \text{ssTol}) \cdot (1 - \text{grPer}_s)) \quad \text{Eq. A3}$$

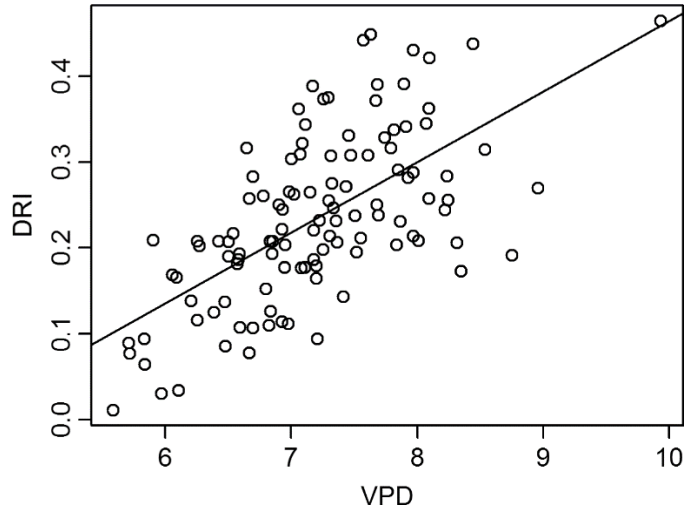
Where  $\text{grPerS}_s$  is the relative growth performance modified due to suckering.  $\text{ssTol}$  was estimated via sensitivity analysis testing the influence of  $\text{ssTol}$  on the simulated percentage of aspen regeneration in cells that were completely burned the previous decade under climatic and

edaphic conditions representative for Northern Colorado subalpine forests. This test revealed that with a  $sTol$  value of 0.7 the simulated proportion of aspen saplings closely matched empirically documented proportions of aspen saplings following stand-replacing fire in northern Colorado subalpine forests (Buma and Wessman 2012, Kulakowski et al. 2013).

### *Susceptibility assessment*

*Drought-induced susceptibility:* To assess drought-induced susceptibility ( $S_{dr}$ ) we approximated the relationship between plot-level outbreak probability and summer vapor pressure deficit (VPD) found by Hart et al. (2014a) using a logistic function and the LandClim-inherent drought-index (DRI; Bugmann and Cramer 1998, Schumacher et al. 2004). We used DRI rather than VPD as a predictor for  $S_{dr}$  for two reasons. First, all bioclimatic variables in LandClim are based on monthly temperature and precipitation data that are available globally at fine spatial resolution for historical and future (projected) time frames (e.g. Daly et al. 2008, Coulson et al. 2010). To calculate VPD, data on relative humidity or dew point temperature is necessary, which are much less prevalent especially for future climate scenarios. Second, DRI is calculated at the level of individual grid cells and accounts for cell-specific leaf area and soil water holding capacity in addition to temperature and precipitation. We therefore consider DRI a better predictor of cell-level drought-induced stress and thus susceptibility in spruce trees than available VPD estimates that at the scale of LandClim simulation landscapes (10–100 km<sup>2</sup>) only vary with elevation (Daly et al. 2008).

To relate Hart et al.'s (2014a) outbreak probabilities to DRI we first established a relationship between VPD and DRI (Figure A1). Hart et al. (2014a) used aggregated monthly air and dew point temperature data from PRISM (Daly et al. 2008) to calculate average summer VPD estimates for the spruce-fir zone of northern Colorado for years 1900–2011. We used the same aggregated air temperature and the corresponding PRISM precipitation data to calculate DRI, whereby we represented average conditions of the northern Colorado spruce-fir zone by assuming flat terrain, soil water holding capacity of 14 cm and a leaf area index of 4 m<sup>2</sup>/m<sup>2</sup>.



**FIG. A1: Relationship between the LandClim drought index (DRI) and summer vapor pressure deficit (VPD). Open circles show calculated values for years 1900–2011 for the northern Colorado spruce-fir zone and the straight line depicts the linear regression model.**

We related DRI to summer VPD using a linear regression model ( $R^2=0.378$ ):

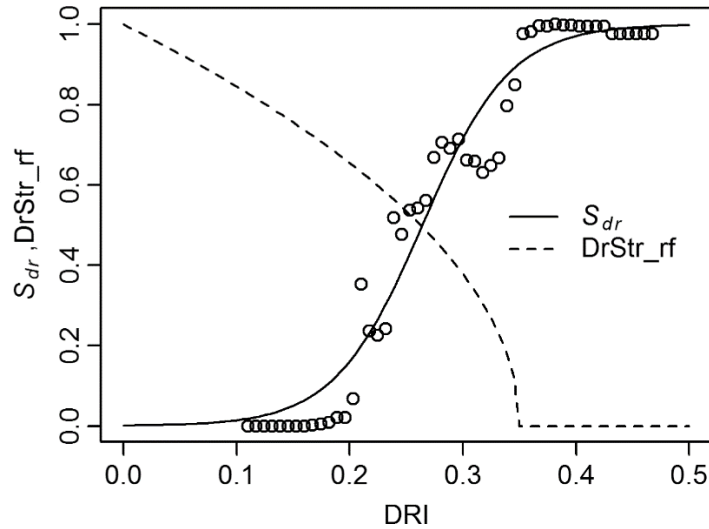
$$DRI = -0.357625 + 0.082190 \cdot VPD \quad \text{Eq. A4}$$

We derived index values for  $S_{dr}$  by scaling Hart et al.’s (2014a) outbreak probabilities (range: 0.125–0.290) between 0 and 1 assuming very low  $S_{dr}$  at the lower end of the empirically found range of outbreak probabilities and very high  $S_{dr}$  at the high end. We then substituted VPD by DRI using Eq. A4 and fitted a logistic model to the  $DRI$  and  $S_{dr}$  values (Eq. A5, Figure A2)

$$S_{dr} = \frac{1}{1+e^{-r \cdot (DRI-m)}} \quad \text{Eq. A5}$$

Where parameters  $r = 25.811525$  and  $m = 0.264013$ .  $S_{dr}$  is updated every decade. We therefore used the decadal average of DRI as input in Eq. A5.

Eq. A5 implies that drought-induced susceptibility is at 90% ( $S_{dr} = 0.9$ ) of its maximum value of 1 when drought-induced stress reduces Engelmann spruce growth to zero ( $DRI = 0.35$  and  $DrStr_{rf} = 0$ , Figure A2). In comparison to previous bark beetle simulation models that also included this relationship (Seidl et al. 2007, Temperli et al. 2013), this empirically based estimate of  $S_{dr}$  is conservative. In the previous models  $S_{dr}$  was assumed to be maximal, when simulated spruce growth was reduced to 20% of its maximum value.



**FIG. A2: Relationship between drought-induced susceptibility to beetle disturbance ( $S_{dr}$ ) and the LandClim drought index (DRI). Open circles show  $S_{dr}$  values calculated based on empirical outbreak values (Hart et al. 2014a) against DRI values for years 1900–2011 and for the northern Colorado spruce-fir zone. The solid line depicts a logistic fit to  $S_{dr}$  and DRI values and the dashed line shows the drought stress-related growth reduction factor (DrStr\_rf) for Engelmann spruce (drought tolerance = 0.35, Table A1).**

*Spruce size-induced susceptibility:* Spruce-size induced susceptibility ( $S_{dbh}$ ) was modeled based on empirical, tree-level infestation probabilities in response to spruce diameter at breast height (DBH) from a recent spruce beetle outbreak in Grand Mesa National Forest in central Colorado (Hart et al. 2014b). We assumed that these tree-level infestation probabilities (range: 0.248–1.000) can be directly translated to  $S_{dbh}$ . Hence, to obtain a continuous relationship between  $S_{dbh}$  and DBH, we fitted a logistic function to the empirical infestation probability and DBH values

$$(Eq. A6) S_{dbh} = A + \frac{(1-A)}{1+e^{-r \cdot (DBH-m)}} \quad Eq. A6$$

Where parameters  $A = 0.23$ ,  $r = 0.20488$  and  $m = 26.89512$ . To assess  $S_{dbh}$  at the cell-level the DBH of the largest spruce cohort > 10 cm DBH is used as input in Eq. A6.

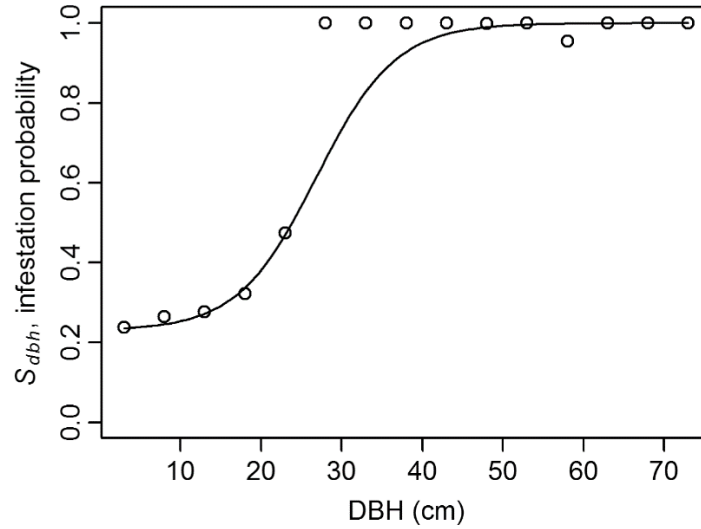


FIG. A3: Relationship between spruce size-induced susceptibility ( $S_{dbh}$ ) and spruce diameter at breast height (DBH). Open circles show empirical, tree-level infestation probability values (Hart et al. 2014b) against spruce diameter at breast height (DBH) and the line shows the logistic fit used to relate  $S_{dbh}$  to DBH.

*Spruce share-induced susceptibility:* We assessed the influence of spruce share on forest susceptibility to spruce bark beetles ( $S_s$ ) by fitting a logistic curve that approximates Schmid and Frye’s (1976) spruce share-specific hazard rating, whereby we followed Reynolds and Holsten (1996) to translate Schmid and Frye’s qualitative hazard categories (low, medium and high) to the susceptibility index values  $<0.1$ ,  $0.1-0.4$  and  $>0.4$ , respectively (Eq. A7, Figure A4).

$$S_s = \frac{1}{1+e^{-r \cdot (BAS-m)}} \quad \text{Eq. A7}$$

Where parameters  $r = 12.6776636$ ,  $m = 0.6806692$  and BAS is the basal area share (proportion) of spruce among dominant trees, i.e. the 100 largest trees per hectare or the 6 largest trees per  $25 \times 25$  m cell.



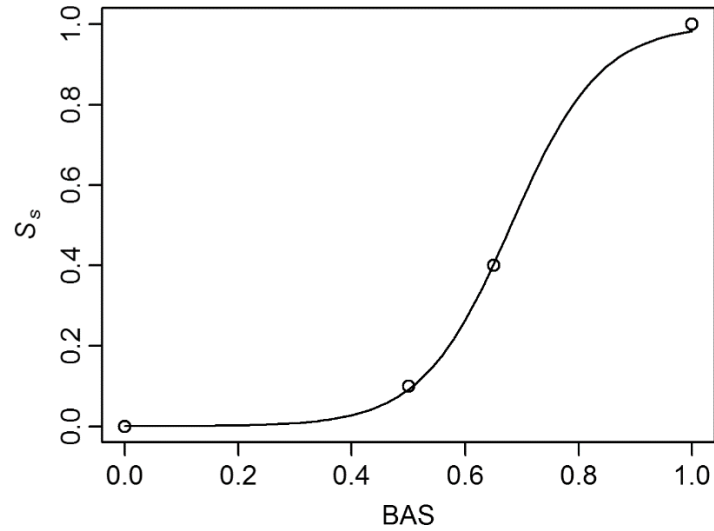


FIG. A4: Relationship between forest susceptibility due to spruce share ( $S_s$ ) and spruce basal area share (BAS). Open circles show hazard rating scores based on Schmid and Frye (1976) and Reynolds and Holsten (1996) and the line shows the logistic fit used to relate  $S_s$  to BAS.

*Wind throw-induced susceptibility:* In the absence of quantitative data on the effect of wind thrown spruce on forest susceptibility to spruce bark beetle disturbance ( $S_w$ ), we used the first order approximation Temperli et al. (2013) used.  $S_w$  was linearly related to wind thrown spruce biomass with  $S_w$  being maximal (1) when the maximum possible spruce biomass has been wind-felled, i.e. 300 Mg/ha or three large spruce trees per  $25 \times 25$  cell with a biomass of 6 Mg and a DBH of 100 cm (Eq. A8).

$$S_w = \frac{B_w}{300} \quad \text{Eq. A8}$$

Where  $B_w$  is the cell-specific biomass of wind thrown spruce trees  $>10$  cm DBH.  $B_w$  is only available to affect  $S_w$  in the time step (decade) wind disturbance occurred, since the bark on wind thrown logs desiccates within ca. two years and is no longer available for bark beetle breeding (Lindelöw and Schroeder 2008, Komonen et al. 2011).

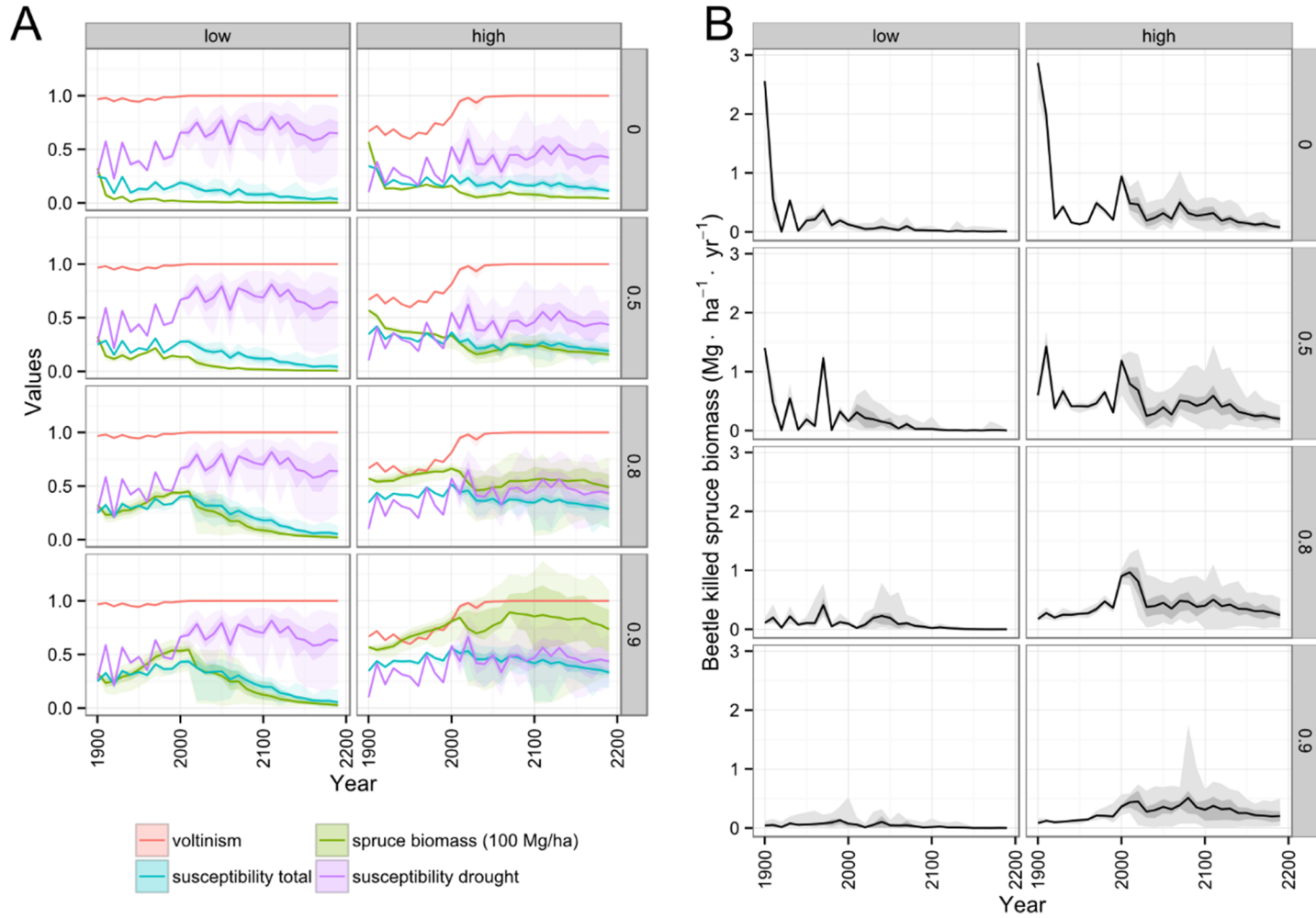
*Combination and weighting of susceptibility factors:* While combining  $S_{dr}$ ,  $S_{dbh}$ ,  $S_s$  and  $S_w$  additively to the cell-specific susceptibility index  $S_{cell}$ ,  $S_w$  was weighted ( $w_w$ ) relative to the other susceptibility factors:

$$S_{cell} = (1 - w_w) \cdot \frac{S_{dr} + S_{dbh} + S_s}{3} + w_w \cdot S_w \quad \text{Eq. A9}$$

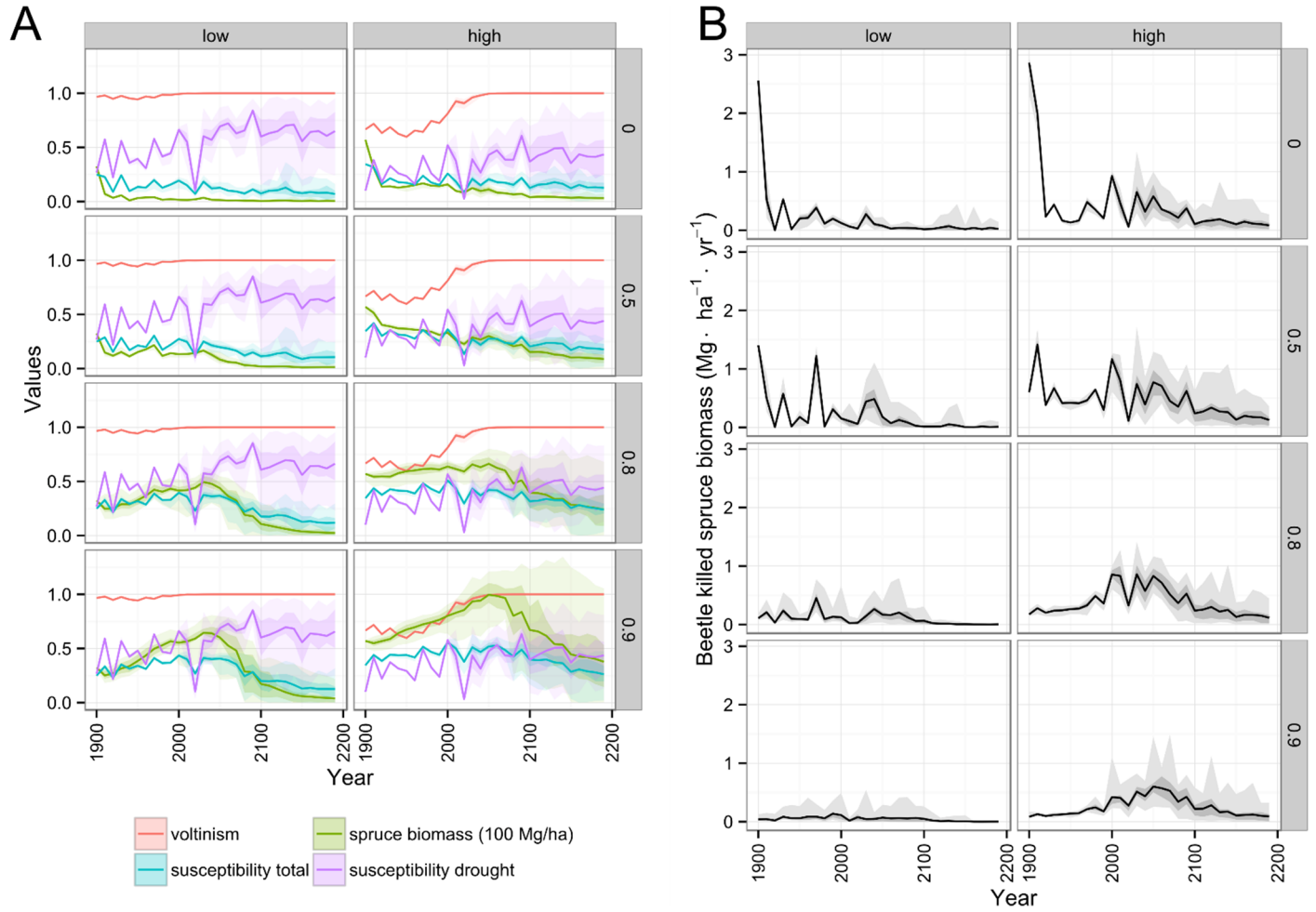
With  $w_w = 0.8$   $S_w$  was weighted four times more than  $S_{dr}$ ,  $S_{dbh}$  and  $S_s$  together. This weighting reflects the at least four times higher number of beetles that have been found to emerge from shaded wind thrown trees than from standing trees (Dyer and Taylor 1971) and the high

importance experts have attributed to wind throw as a risk factor of spruce beetle outbreak (Schmid 1981, Reynolds and Holsten 1994, Jenkins et al. 2014). To test the sensitivity of the model to  $w_w$  we ran the model with  $w_w = 0, 0.5, 0.8$  and  $0.9$  under the three climate change scenarios (Table 1) and kept all other parameters unchanged. With  $w_w = 0$  and  $0.5$  we found spruce mortality due to beetles to spike in the beginning of the simulation period (1900–1919) and to remain higher than in simulations with  $w_w$  of  $0.8$  until year 2000 (Figure A5–7). The elevated beetle-induced spruce mortality resulted in spruce biomass to drop in the beginning of the simulation period and then to remain lower than in simulations with a  $w_w$  of  $0.8$ . In contrast,  $w_w = 0.9$  resulted in lower beetle-induced spruce mortality and accordingly increased spruce biomass. Despite these differences in spruce beetle disturbance severity with varying  $w_w$ , the developments of spruce beetle disturbance under climate change scenarios (2010–2200) were similar, irrespective of  $w_w$ . Increased temperatures and drought resulted in increased beetle-induced spruce mortality in the first half of this century. By the middle of the century increasingly adverse drought conditions resulted in spruce biomass to decline, which in turn resulted in decreased spruce beetle disturbance (except for higher elevations under moderate climate change).

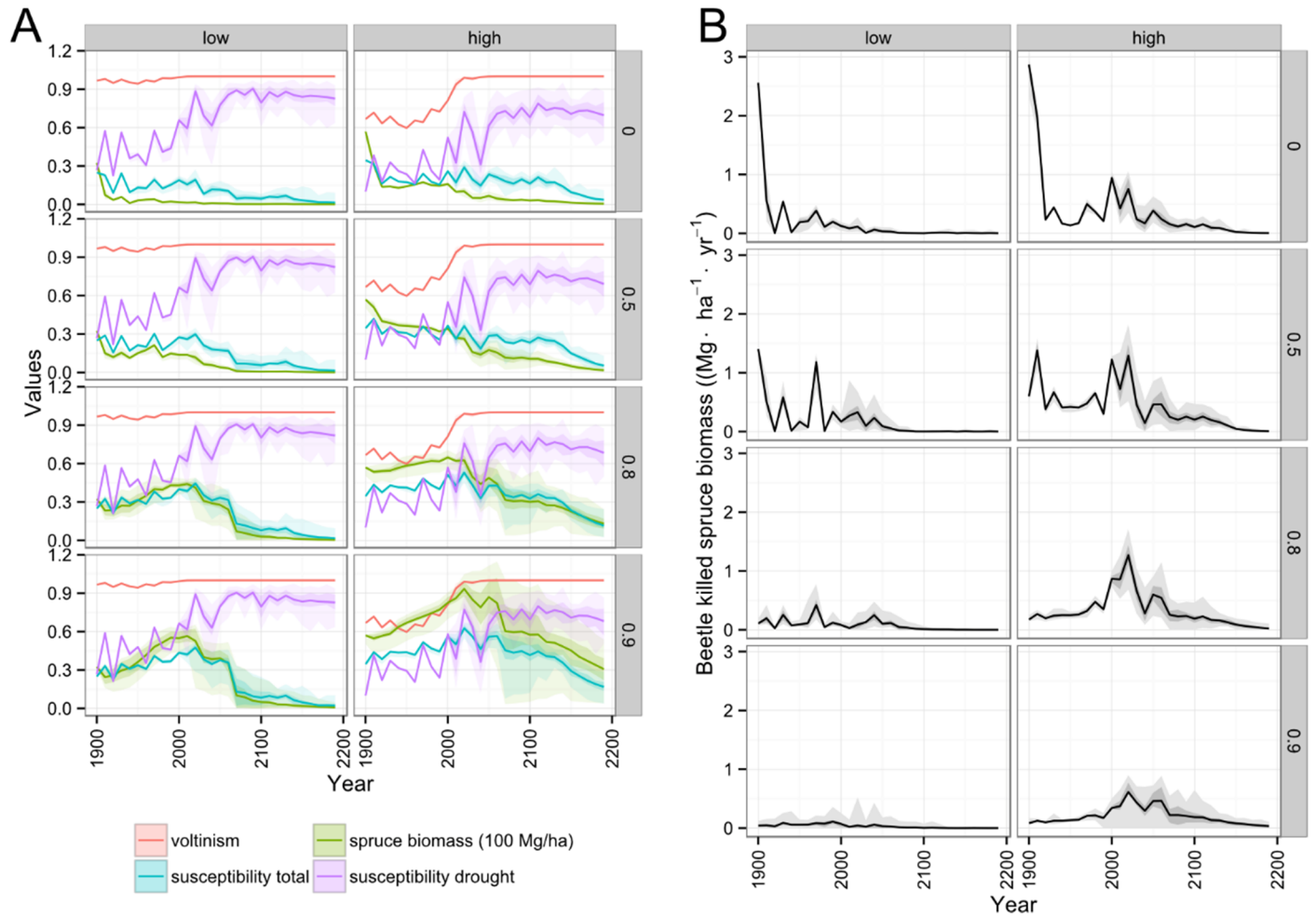
Decreasing  $w_w$  increases the importance of the abundance of large spruce trees and drought-induced susceptibility in our model and vice versa. Drought and large spruce trees affect the susceptibility to beetles of most cells in the simulated landscape whereas windthrow is a relatively rare, locally confined event. Therefore, increasing the importance of drought and large spruce abundance by decreasing  $w_w$  increases the overall susceptibility of the landscape and thus spruce beetle disturbance. Overall, this test has shown that the simulated severity of spruce beetle disturbance is indeed sensitive to how the influence of wind throw is weighted under historical climate. However, we find the dynamics in spruce biomass and spruce beetle disturbance under climate change to be unaffected by the choice of  $w_w$ . The adequate reproduction of spruce beetle rotations and climate-driven disturbance dynamics by LandClim under the historical climate with a  $w_w = 0.8$  and the literature support for a high local (within stand) importance of wind thrown logs underpins weighting wind throw four times higher than the other susceptibility factors with  $w_w = 0.8$ .



**FIG. A5: Sensitivity test of weight of wind throw for forest susceptibility under moderate +4.4°AT/-9%SP (cgcm31 A2) climate change. Development of beetle model parameters (A) and development of beetle-killed Engelmann spruce biomass (B) is shown by elevation (low:  $\leq 2800$ , high  $> 2800$  m a.s.l) and weights for windthrow in susceptibility assessments of 0, 0.5, 0.8 and 0.9 (cf. Eq. A9). See Figure 4 caption for details.**



**FIG. A6: Sensitivity test of weight of wind throw for forest susceptibility under intermediate +5.2°AT/+12%SP (ccsm3 A2) climate change. Development of beetle model parameters (A) and development of beetle-killed Engelmann spruce biomass (B) is shown by elevation (low:  $\leq 2800$ , high  $> 2800$  m a.s.l) and weights for windthrow in susceptibility assessments of 0, 0.5, 0.8 and 0.9 (cf. Eq. A9). See Figure 4 caption for details.**



**FIG. A7: Sensitivity test of weight of wind throw for forest susceptibility under extreme +7.0°CAT/-29%SP (mirroc32 A2) climate change. Development of beetle model parameters (A) and development of beetle-killed Engelmann spruce biomass (B) is shown by elevation (low: ≤2800, high >2800 m a.s.l) and weights for windthrow in susceptibility assessments of 0, 0.5, 0.8 and 0.9 (cf. Eq. A9). See Figure 4 caption for details.**

*Temperature-dependent beetle population development*

To assess temperature-dependent spruce beetle population development (phenology), we first calculate beetle voltinism, i.e. the potential number of beetle generations per year. *Dendroctonus rufipennis* is usually semivoltine, i.e. requires two years to complete one generation. However, under favorable temperatures these beetles can complete their live cycle within one year (univoltinism). While individual beetles are either semi- or univoltine, beetle populations consist of both semi- and univoltine beetles, depending on the microclimate individual beetles experienced during their larval stages. We use a spruce beetle-specific phenology model (Hansen et al. 2001) that has previously been used within the BioSIM simulation framework (Hansen et al. *unpublished manuscript*, Bentz et al. 2010) and evaluate the yearly probability of the

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occurrence of univoltine spruce beetle generations ( $P_u$ ) based on temperature and then calculate population level voltinism ( $V$ ) as follows:

$$V = 0.5 + 0.5 \cdot P_u \quad \text{Eq. A10}$$

Hansen et al.'s (2001) model uses time series of daily minimum and maximum temperatures to predict the  $P_u$  in a given year. In LandClim all climate-dependent processes are simulated based on monthly mean temperatures. In order to comply with this data resolution and to maintain model simplicity and tractability we approximated Hansen et al.'s (2001) original phenology model with a sigmoidal logistic function relating  $P_u$  to annual degree day sums  $>5.5^\circ\text{C}$  (aDD):

$$P_U = \frac{1}{1+e^{-r(aDD-m)}} \quad \text{Eq. A11}$$

Where parameters  $r = 0.01021744$  and  $m = 848.65213059$ . These parameters were estimated by fitting Eq. A11 to data points of annual degree day sums calculated from monthly mean temperatures using the method implemented in LandClim (Bugmann 1994, Schumacher et al. 2004) and yearly probability of univoltinism estimated based on daily minimum and maximum temperatures from 7 climate stations in Colorado using Hansen et al.'s (2001) original phenology model. Climate station data were selected to contain at least two 10-year periods of continuous temperature record (missing values of individual days were filled in with temperature records of the same week). These climate data represent a large part of subalpine Colorado, are located between 2658 and 3459 m a.s.l. and span the full range of temperatures conducive to 0 to 100% probability of univoltinism (Figure A8, Table A2). We used aDD as a predictor of  $P_u$  as this variable has previously been used to model spruce beetle phenology (Werner and Holsten 1984).

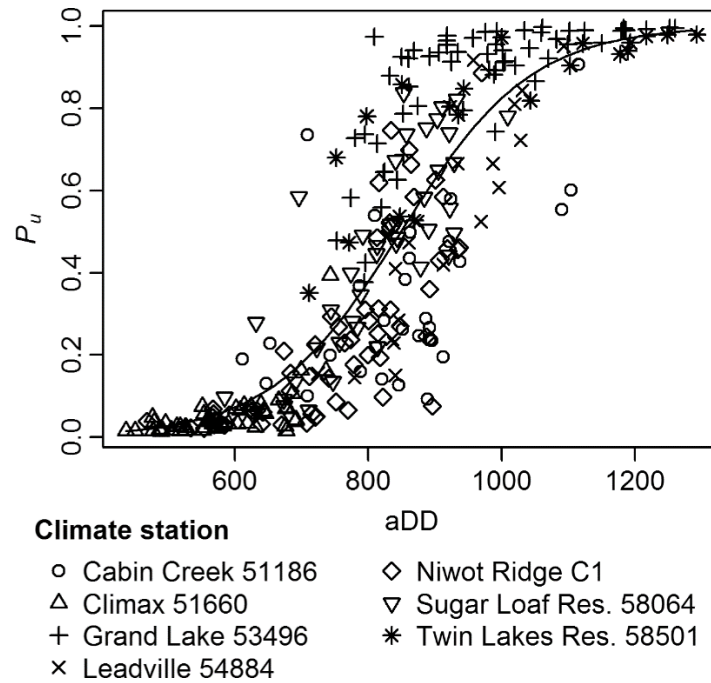


FIG. A8: Yearly probability of univoltinism ( $P_u$ ) calculated using Hansen et al.'s (2001) spruce beetle phenology model against annual degree day sums from seven climate stations in Colorado. Point symbols refer to different climate stations (identified by station name and number). The curve shows a logistic fit through the data points and represents the approximated model that was implemented in LandClim.

Table A2: Climate stations (names and elevation) and the data range used to approximate Hansen et al.'s (2001) spruce beetle phenology model.

Station name and ID	Elevation (m a.s.l.)	Data range used (years)
Cabin Creek 51186	3054	1968–1977, 1982–2001
Climax 51660	3459	1953–1972, 1977–2006
Grand Lake 53496	2658	1949–2008
Leadville 54884	3030	1949–1968
Niwot Ridge C1	3018	1953–2012
Sugar Loaf Reservoir 58064	2969	1957–1966, 1975–2004
Twin Lakes Reservoir 58501	2804	1968–1977, 1997–2006

By using aDD, we only implicitly accounted for the potential of cold spells inhibiting beetle population growth (Miller and Werner 1987). As winter temperatures are projected to increase even more than summer temperatures under all climate change scenarios that we considered (Table 1), we expect that the importance of cold-induced mortality in limiting spruce beetle population development will decrease with climate change (Bentz et al. 2010).

*Soil input*

The LandClim-inherent water balance model used to estimate drought (i.e. the cell-specific drought index DRI) requires spatially explicit input on available soil water content (Bugmann and Cramer 1998, Schumacher et al. 2004). The perimeter of our case study landscape intersected two polygons of the relatively coarse-scale STATSGO soil data base (Schwarz and Alexander 1995) and thus only provided reference values (the finer-grained SSURGO data base did not cover the National Forest Area in Colorado and thus our case study landscape). The layer on the available water content (AWC) in the top 150 cm of the soil indicated values of 9.3 and 10.6 cm. On the flat terrain of the valley bottom ca. 300 m southwest of the study area STATSGO indicated an AWC value of 27.4 cm. Given these reference values and the fact that STATSGO does not account for variation in AWC with fine-scale topography, we assumed that AWC may be as low as 6 cm at highest elevations and at ridge tops and as high as 20 cm at lowest elevations of the drainage that our case study area encompasses.

Following Henne et al. (2013) we used the compound topographic index (CTI) and elevation to interpolate between the minimum (6 cm) and maximum (20 cm) AWC values. CTI quantifies catenary landscape position (ridges, slopes and trenches) and is correlated to soil depth and other variables that determine AWC (Moore et al. 1993, Gessler et al. 2000). We used the Spatial Analyst tools in ESRI ArcGIS 10 to calculate CTI for each LandClim grid-cell. We then divided the CTI values by elevation to correct for elevation and called this new index CTIE. Irrespective of catenary landscape position, CTIE values are higher at lower elevations and account for increased soil deposition at lower elevations. The interpolated, cell-specific AWC was then calculated as follows:

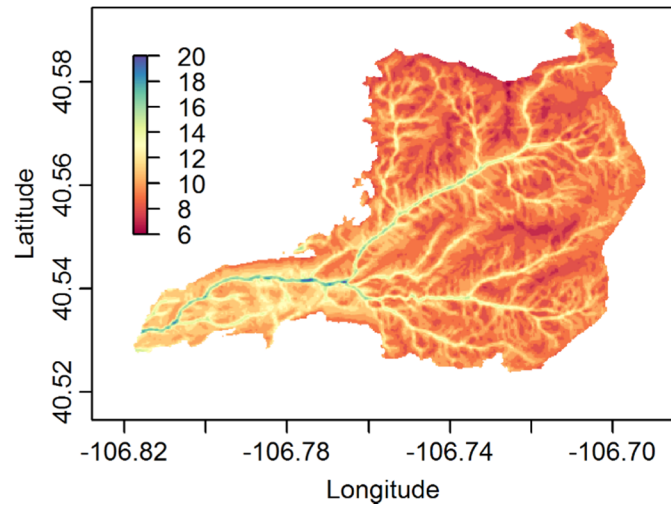
$$AWC_i = AWC_{min} + b \cdot (CTIE_i - CTIE_{min}) \quad \text{Eq. A12a}$$

with

$$b = \frac{AWC_{max} - AWC_{min}}{CTIE_{max} - CTIE_{min}} \quad \text{Eq. A12b}$$

Where  $i$  indicates a specific cell,  $AWC_{min} = 6$  cm,  $AWC_{max} = 20$  cm and  $CTIE_{min}$  and  $CTIE_{max}$  are the lowest and highest cell-specific CTIE values in the case study landscape. Using this interpolation procedure the distribution of AWC reflects the topography of the case study landscape (Figure A9).





**FIG. A9: Mapped available water content (AWC) in cm used as LandClim input.**

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