**Paleo Iberia Landscape Fire Succession Model (PalIber LFSM)**

**Documentation**

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There are three main modules in the model:

* Resources
* Succession
* Disturbance

**Resources**

Resources are those available to vegetation to grow and in the model here are dictated by water and light availability (soil nutrients etc are ignored). Water is a function of climate and soil. Light is a function of aspect, slope and vegetation (i.e. shade from competing vegetation).

Resources are treated as boundary conditions in the model in the model and are provided by the user in the form of weather streams and topography (currently a drop-down to generate random topography but could be input DEM data in future). **Weather streams** are monthly temperature and precipitation for each month in each year of the simulation. Monthly temperature and precipitation are assumed to spatially uniform across the modelled environment. Monthly values are used so that variation in seasonality can be investigated (e.g. same total rainfall but concentrated in shorter time spans).

Table 1. Environmental Constants used in the model

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| *Parameter* | *Units* | *Description* | *Value* | *Source* | *Procedures* |
| kDTT | °C | development threshold | 5.5 | Table 3.16 of Bugmann 1994 | setup  calc-uDD |
| elr | °C m-1 | environmental lapse rate | 0.00649 | https://en.wikipedia.org/wiki/Lapse\_rate#Environmental\_lapse\_rate | setup  calc-temp |
| Heat index (hi) | °C | Sum of monthly indexes given by (t/5)1.514 used in calculation of PET (Eq 1) |  | Thornthwaite 1948, p89 | calc-PET |
|  |  |  |  |  |  |

*Patch Temperature [calc-temp procedure]*

The landscape-wide temperature (set by a user-provided weather stream) is modified for each patch according to the elevation of the patch and the environmental lapse rate.

Ptemp = ltemp – (elevation \* elr)

*Potential Evapotranspiration (PET) [calc-PET procedure]*

PETm is monthly Potential Evapotranspiration given by:

see Thornthwaite (1948) p89

Where

t is mean monthly temperature

alpha = (0.000000675 \* hi ^ 3) - (0.0000771 \* hi ^ 2) + (0.01792 \* hi) + 0.49239

PET is calculated for each month using the above and then can be modified for the slope and aspect of individual patches (see Bugmann 1994, Eq 3.73 and 3.74) via kSlAsp and SlAsp parameters but currently this is implemented spatially uniformly across the landscape.

*Drought Index (DI) [calc-DI procedure]*

Annual Drought Index is calculated as a function of monthly Evapotranspiration and monthly water demand (greater value indicates greater drought stress):

Bugmann & Cramer (1998) Eq 18

Em = monthly evapotranspiration from soil

Dm = monthly water demand

Where

Bugmann & Cramer (1998) Eq 10

Sm = monthly supply of water from soil, given by:

Henne et al. (2011) Appendix 1 (Supp Mat)

soilMm = monthly soil moisture

soilMmax = soil moisture capacity

And

Bugmann & Cramer (1998) Eq 9

Ps,m = monthly precipitation surplus given by:

Bugmann & Cramer (1998) Eq 2

And

Bugmann & Cramer (1998) Eq 11

Pi,m = monthly intercepted precipitation (as of 04Dec14 Pi,m = 0 as it will depend on veg type and phenological status, if this is added in future see Bugmann and Cramer 1998 Eq 15 and p.253 )

SoilMmax is specified by the user:

see Henne et al. 2013 Eq. 1

where AWC is the available water capacity (cm × cm-1), and D is soil depth (cm).

Currently, soil conditions are assumed to be spatially uniform across the landscape. Future versions of the model should aim to represent spatial variation in soil conditions.

*Degree Days [calc-uDD procedure]*

Calculation of degree days in year and cell:

Eq 3.72 from Bugmann 1994

where:

uDD is annual sum of degree-days

DD is annual sum of degree-days for the given year and cell

T is the temperature for the given month, year and cell

kDTT is development threshold temperature (specified in Table 3.16 of Bugmann 1994 as 5.5)

kDays is mean number of days per month (specified in Table 3.16 of Bugmann 1994 as 30.5)

gCorr is empirical correction formula (which Bugmann calculated by comparing two different approaches to estimating uDD - ignore or use this? see Table 3.9 in Bugmann for values by month)

*Overall Patch Resources [calc-resources procedure]*

The relative level of soil moisture and degree-day resources available are calculated using:

*patch-resources = DDres + Wres / 2*

Where

Wres = (eq 3.26 Bugmann 1994) [note this accounts for insufficient water when DI > DrTol]

And

*DDres =* (eq. 9 in Fyllas et al. 2007) [note: this follows Bugmann and Solomon (2000) in that it is an asymptotic function (not parabolic as used previously by Bugmann 1994) that does not reduce growth at upper thermal limits and therefore also does not need a maximum growing degree days parameter].

If either Wres or DDres <= 0, *patch-resources* = 0

**Succession**

In the model succession is modelled by combining the state-and-transition approach presented by Millington et al. (2009) with gap dynamics type approaches such as LANDCLIM (Bugmann 1994, Fyllas et al. 2007, Henne et al. 2013).

The primary assumption is that the plant functional type (PFT) for which overall patch resources are greatest will grow fastest and therefore in time out-compete other PFTs. However, before a PFT can become dominant it must first establish itself, dependent on:

* Seed availability or resprouting material (currently model assumes seeds are available for all PFTs uniformly across the landscape and so this requirement is not represented; spatially-explicit representation of see dispersal should be included in later versions)
* Barriers preventing establishment is seed is available

Barriers preventing establishment are represented in the model using ‘flags’ that indicate when conditions in a cell (patch) are unsuitable for establishment [see calc-resources procedure]. Currently the barriers represented are:

* Drought: via cell DI and PFT DrTol parameter (see table x).
* Minimum Winter Temperature: via cell minimum monthly temperature (minT) and PFT minWT parameter (see Table 2).
* Minimum Degree Day requirement: via cell degree days (DD) and PFT minDD parameter (see Table 2)
* Shade Tolerance: depending on other vegetation in the cell and PFT ShTol parameter (see Table 2)

Rules for establishment of PFTs are as follows:

* Drought: DI > DrTol (Fyllas et al. 2007 eq 11 uses this, LADCLIM [Bugmann, Henne] does not)
* Winter Temperature: minT > minWT (see Bugmann 1994 eq 3.1)
* Degree Days: DD > minDD (e.g. see Bugmann 1994 eq 3.5)
* Shade: ShTolT > other PFT ShTol (Schumacher et al. 2004), except when no other vegetation present in which case ShTol <= 3

The rationale behind the rules for shade tolerance are that PFTs can only establish if they are more shade tolerant than other PFTs in the cell Schumacher et al (2004) or if no vegetation is present PFTs must be relatively shade intolerant.

Another barrier to establishment that has been used previously (e.g. Bugmann 1994), and which could be implemented in a later version of this model is browsing by ungulates (goats etc).

Transitions between dominant land covers are modelled using the approach in Millington et al. (2009) *[update-transitions, update-Tin-lc, update-vegAge procedures]* with direction of change (dD) towards the PFT with greatest *patch-resources* and which has no barriers to establishment and time to transition (dT, years) given by:

*10 + patch-resourcesdlc \* (maturitydD \* (1 + (1 - patch-resourcesdD)))*

Where *patch-resourcesdlc* is the *patch-resources* of the PFT being replaced, *maturitydD* is ‘age to maturity parameter’ (Maturity, table x) for the replacing PFT and *patch-resourcesdlc* is the *patch-resources* of the replacing PFT.

Table 2. Vegetation Parameter specified by the user [pft-mtx]

|  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| *id* | *minDD* | *minWT* | *Tree* | *BioT* | *Maturity* | *MaxAge* | *Resprout* | *ShTol* | *BrTol* | *DrTol* | *FireTol* |
| 0 | 1554 | 2 | 0 | 2 | 10 | 100 | 1 | 3 | 5 | 5 | 1 |
| 1 | 2303 | 2 | 1 | 1 | 20 | 275 | 0 | 1 | 3 | 6 | 3 |
| 2 | 1773 | -99 | 1 | 2 | 20 | 600 | 1 | 6 | 1 | 5 | 1 |
| 3 | 1237 | -1 | 1 | 0 | 10 | 1510 | 0 | 4 | 1 | 4 | 1 |

Id: -1 = bare, 0 = shrubs (*Erica arborea*), 1 = pine (*Pinus halepensis*), 2 = oak (*Quercus ilex*), 3 = decid (*Castanea sativa*) Values above are for the species shown in brackets, taken from Henne et al. (2013, supplementary material) and Bugmann (1994, Table 3.11) and Henne et al. (2011, Table 2) [Maturity for C. sativa not confirmed]

minDD: minimum Degree Days needed by the PFT

minWT: minimum monthly (Winter) temperature PFT will tolerate

Tree: can this PFT take tree form (1), shrub only (0) or both (2)

BioT: needle-leaved evergreen (1), broad-leaved evergreen (2), or deciduous (0)

Maturity: age from which seed production begins (yr)

MaxAge: maximum age a cohort can live (yr)

Resprout: can this PFT reproduce from lignotubers? (1 = yes, 0 = no)

ShTol: shade tolerance (1 = very intolerant, 6 = very tolerant)

BrTol: browsing tolerance (1 = very tolerant, 5 = very intolerant) [NB: reverse ranking]

DrTol: drought tolerance (1 = very intolerant, 6 = very tolerant)

FireTol: sensitivity to fire damage of trees that have reached the canopy

**Disturbance**

This is the currently most incomplete aspect of the current version of the model. The primary disturbance currently represented in the model is fire *[fire-simulate and associated procedures]*. The current implementation uses a cellular-automata approach similar to Millington et al (2009), albeit simplified (i.e. no influence of slope or wind on spread). Ignition frequency and location is also not currently well represented.

Responses to fire by different PFTs (e.g. seed survival, resprouting vegetation) are also not currently represented but could be by exploiting the *FireTol* parameter (Table 2). Similarly, responses of PFTs to browsing is also not represented but could be using the *BrTol* parameter (Table 2).

**References**

Bugmann, H. K. M. (1994). *On the ecology of mountainous forests in a changing climate: a simulation study* (Doctoral dissertation, Swiss Federal Institute of Technology Zürich).

Bugmann, H. K., & Solomon, A. M. (2000). Explaining forest composition and biomass across multiple biogeographical regions. *Ecological Applications*, 10(1), 95-114.

Bugmann, H., & Cramer, W. (1998). Improving the behaviour of forest gap models along drought gradients. *Forest Ecology and Management*, 103(2), 247-263.

Fyllas, N. M., Phillips, O. L., Kunin, W. E., Matsinos, Y. G., & Troumbis, A. I. (2007). Development and parameterization of a general forest gap dynamics simulator for the North-eastern Mediterranean Basin (GREek FOrest Species). *Ecological Modelling*, 204(3), 439-456.

Henne, P. D., Elkin, C. M., Reineking, B., Bugmann, H., & Tinner, W. (2011). Did soil development limit spruce (Picea abies) expansion in the Central Alps during the Holocene? Testing a palaeobotanical hypothesis with a dynamic landscape model. *Journal of Biogeography*, 38(5), 933-949.

Henne, P. D., Elkin, C., Colombaroli, D., Samartin, S., Bugmann, H., Heiri, O., & Tinner, W. (2013). Impacts of changing climate and land use on vegetation dynamics in a Mediterranean ecosystem: insights from paleoecology and dynamic modeling. *Landscape Ecology*, 28(5), 819-833.

Millington, J. D., Wainwright, J., Perry, G. L., Romero-Calcerrada, R., & Malamud, B. D. (2009). Modelling Mediterranean landscape succession-disturbance dynamics: a landscape fire-succession model. *Environmental Modelling & Software*, 24(10), 1196-1208.

Schumacher, S., Bugmann, H., & Mladenoff, D. J. (2004). Improving the formulation of tree growth and succession in a spatially explicit landscape model. *Ecological Modelling*, 180(1), 175-194.

Thornthwaite, C. W. (1948). An approach toward a rational classification of climate. *Geographical Review*, 55-94.