Supplementary information to: Modelling soil and landscape evolution– the effect of rainfall and land use change on soil and landscape patterns

W. Marijn van der Meij1,2, Arnaud J. A. M. Temme3,4, Jakob Wallinga1, Michael Sommer2,5

1Soil Geography and Landscape Group, Wageningen University and Research, P.O. Box 47, 6700 AA, Wageningen, The Netherlands

2Research Area Landscape Functioning, Working Group Landscape Pedology, Leibniz-Centre for Agricultural Landscape Research ZALF, Eberswalder Straße 84, 15374 Müncheberg, Germany

3Department of geography, Kansas State University, 920 N17th Street, Manhattan, KS 66506, USA

4Institute of Arctic and Alpine Research, University of Colorado, Campus Box 450, Boulder, CO, 80309-0450, USA

5Institute of Environmental Science & Geography, University of Potsdam, Karl-Liebknecht-Straße 24-25, 14476 Potsdam, Germany

*Correspondence to*: W. Marijn van der Meij (marijn.vandermeij@wur.nl)

This supplementary information provides the equations and parameters used to develop and run HydroLorica. We provide the equations for adjusted or newly introduced processes and we refer to earlier work for processes that haven’t been modified from earlier versions. We conclude with Table S1 which provides all parameters we used in our simulations, including references.

We first provide the model equations. The model parameters can vary in space and time, depending on parameter and process. We indicate this in the parameters by adding a subscript of *xy* to indicate variation in space, subscript *l* to indicate a specific soil layer, subscript *z* to indicate a certain depth and subscript *t* to indicate variation in time.

# Hydrologic processes

The hydrological module partitions rainfall (*Pt*) into three components: evapotranspiration (*ETxy,t*), infiltration (*Ixy,t*) and surface flow (*Ronnxy,t* & *ROffxy,t*). Evapotranspiration is calculated from longitude, temperature and slope position, and is corrected for vegetation type using a vegetation correction factor *cveg*(Allen et al., 1998). The complete hydrological module is described in detail in Appendix A of van der Meij et al. (2018)

# Determination of vegetation type

Distinction between grassland and forest vegetation in the natural phase of soil formation depends on local water availability. We adjusted the Budyko curve (Budyko and Miller, 1974) to determine local water stress, which is a determinant of vegetation type (Thompson et al., 2010). Instead of the traditional ratio between annual precipitation and potential evapotranspiration, we used the sum of annual infiltration *Ixy,t* and actual evapotranspiration *ETaxy,t* to calculate water stress *WSxy,t* at location *xy* in year *t* (Eq. S1). In landscapes without overland flow, infiltration plus actual evapotranspiration equals precipitation. However, in landscapes with overland flow, redistribution of water, captured by spatially varying infiltration rates, can change local water availability. Vegetation type at location *xy* depends on the value of *WSxy,t*, with wetter places having forest and drier places having grassland (Eq. S2).

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|  | S1 |
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# (Bio-)geomorphic processes

Creep is simulated as diffusive process. The total amount of creep *creepxy,t* [kg] at location *xy* and year *t* is calculated by multiplying the potential creep *creeppot,t* [kg m-2] with the sine and cosine of the maximum slope *Λmax* to all its neighboring cells and cell size *dx2* [m2] (Gabet et al., 2003) (Eq. S3). *creeppot,t* depends on vegetation type (Gabet et al., 2003; Wilkinson et al., 2009). The fraction of *creepxy,t* that is transported to neighboring cell *i* (*creepxy,t→i* [m]) is calculated by dividing slope gradient *Λi* towards neighbour *i* to the power of factor *p*, by the sum of slope gradients to the power of factor *p* to all lower neighbours *J* (Eq. S4). *creepxy,t→i*is distributed over all soil layers *L*, proportionally to the fraction of the integral of the depth decay function over the upper and lower depths (*zupp,xy,l,t* and *zlow,xy,l,t* [m]) of layer *l* divided by the integral of that depth decay function over the entire soil depth *sdxy,t* [m] (Eq. S5). The shape of the depth decay function is controlled by depth decay parameter *ddCR* [m-1] and average layer depth *zxy,l,t.* The creep leaving layer *l* is distributed over neighboring layers at location *i* proportional to the size of the vertical boundary between the layers.

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|  | S3 |
|  | S4 |
|  | S5 |

Tree throw affects soil and landscape depending on the dimensions of the root clump and the transport distance. The depth *d* and width *w* dimensions of the root clump *dimwd,a* [m] are scaled with tree age *a* [years] and have maximum dimensions *dimwd,max* [m] (Eq. S6). Soil material is collected from cells and layers that are covered by dimensions *dimwd,a*, proportionally to the overlap of the root clump with cell dimensions. The soil material is homogenized and deposited at cell *i* that is located at distance *TD* [m] in the direction of the fall. Transport distance *TD* is calculated using root clump width *dimw* and root clump depth *dimd* and slope *Λi* in the falling direction (Eq. S7).

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|  | S6 |
|  | S7 |

Water erosion and deposition are calculated using the same approach as the original *Lorica* model, with the difference that we use the annual sum of daily overland flow as driver of erosion, in contrast to one annual calculation of water flow. We refer to Temme and Vanwalleghem (2016) for a detailed description of this process.

Tillage consists of two parts: homogenization and erosion. Homogenization occurs completely over all layers that fall in the predetermined plough depth *pd* [m]. Tillage erosion is simulated as diffusive process (Govers et al., 1994), using the equations of the landscape evolution model LAPSUS (Baartman et al., 2012). LAPSUS uses units in meters to calculate transport from one location to another. This is why we calculate local tillage transport in meters too. We use the ratio between local tillage [m] and the layer thicknesses at the eroding location [m] to determine the fraction of soil material that is transported from a certain layer. When this fraction is higher than one, the entire layer is transported and a new fraction is calculated for the underlying layer and remainder of the local tillage. Local tillage rate *tillxy→i* [m] is calculated based on potential tillage rate *tillpot* [-], slope in transport direction *Λi*, plough depth *pd* [m] and a factor that distributes the tillage over all lower lying neighbors J, proportional to their slope to the power of factor *p* (Eq. S8).

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# (Bio-)pedogenic processes

We simulated three (bio-)pedogenic processes that change texture and organic matter properties in loess landscapes. These are clay translocation, bioturbation and soil organic matter uptake and breakdown.

We adapted a new way of simulating clay translocation, using the advection equation of Jagercikova et al. (2017). The diffusive part of clay translocation as described by Jagercikova et al. (2017) is separately modeled by bioturbation. The clay advection *advxyz,t* [m] at a given location *xy* with depth *z* [m] in year *t* is a function of annual infiltration *Ixy,t* [m] at that location and potential advection *adv0* [m]. We reduced the advection with infiltration asymptotically to limit translocation at high infiltration rates, when the amount of dispersible clay becomes a limiting factor. The parameters were chosen so that an infiltration of 500 mm resulted in an advection of 0.5\*potential advection *adv0*. The advection decreased exponentially with depth following depth decay rate *ddCT,xy,t* [m-1] (Eq. S10), which is scaled with local infiltration from potential depth decay rate *ddCT* [m-1] (Eq. S9). The local advection *advxyz,t* was multiplied with bulk density [kg m-3], clay fraction [-] and the dimensions of the cell [m-3] to get the amount of clay to be eluviated [kg].

Not all clay in the soil can be translocated. Part of it is not available to the percolating water, because it is bonded to other minerals and organic matter. We used the equations of Brubaker et al. (1992) to estimate the part of the clay that is water-dispersible *fclay,xyz,wd*[-], i.e. that is available for translocation by water (S12). We estimated the required *CECxyz* with a pedotransfer function from Ellis and Foth (1996), using the local fractions of clay *fclay,xyz* and organic matter *fOM,xyz* [-] (Eq. S11). This approach is similar to the one used in soil profile evolution model SoilGen2 (Finke, 2012).

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|  | S9 |
|  | S10 |
|  | S11 |
|  | S12 |

We used the same approach to calculate bioturbation and the soil organic matter uptake and decomposition as the original Lorica model. We refer to Temme and Vanwalleghem (2016) for a detailed description of these processes.

Table S: Overview of new and adjusted model parameters in this study. In the last column, T&V2016 refers to Temme and Vanwalleghem (2016), Cal. means the parameters are calibrated, Est. means the parameters are estimated.

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| Type | Process | Parameters | Symbol | Spec | Rate | Unit | Ref |
| Hydrologic processes | Evapo-transpiration | Vegetation correction | *Cveg* | Grass | 0.75 | - | (Allen et al., 1998) |
|  | Forest | 0.85 | - |
|  | Cereals | 0.45 | - |
| (Bio-)geomorphic processes | Water erosion and sedimentation | Multiple flow factor | *p* |  | 4 | - | T&V2016 |
| Exponent of overland flow | *m* |  | 1.67 | - |
| Exponent of slope | *n* |  | 1.3 | - |
| Erodibility | *K* |  | 0.0003 | - |
| Erosion threshold | *TCmin* |  | 0.1 |  |
| Creep | Potential creep rate | *creeppot* | Grass | 4.3 | kg m-2 a-1 | (Gabet et al., 2003; Wilkinson et al., 2009) |
|  |  | Forest | 5.3 | kg m-2 a-1 |
|  |  | Cereal | 4.3 | kg m-2 a-1 |
|  | Depth decay rate | *ddCR* |  | 2 | m-1 | T&V2016 |
| Tree throw | Max root clump width | *dimw,max* |  | 4 | m | Est. |
|  | Max root clump thickness | *dimd,max* |  | 0.7 | m | Est. |
|  | Tree age |  | Maximum | 300 | a | (Rozas, 2003) |
|  |  |  | Fully grown | 150 | a |
|  | Fall frequency |  |  | 0.00002 | Trees m-2 a-1 | Est. |
| Tillage | Plough depth | *pd* |  | 0.2 | m | (van der Meij et al., 2019) |
|  | Potential tillage | *tillpot* |  | 1 | - | Est. |
| (Bio-)pedogenic processes | Clay translocation | Potential advection | *Adv0* |  | 0.0025 | m a-1 | Est. |
| Potential depth decay rate | *ddCT* |  | 3.5 | m-1 | Est. |
| Bioturbation | Potential bioturbation rate | *BTpot* | Grass | 4.3 | kg m-2 a-1 | (Gabet et al., 2003; Wilkinson et al., 2009) |
|  |  |  | Forest | 5.3 | kg m-2 a-1 |
|  |  |  | Cereal | 4.3 | kg m-2 a-1 |
|  | Depth decay rate | *ddBT* |  | 2 | m-1 | T&V2016 |
| SOM cycle | Potential input | *SOMpot,in* | Grass | 0.67 | kg m-2 a-1 | Cal. (Guo and Gifford, 2002; Liu et al., 2011) |
|  |  |  | Forest | 0.62 | kg m-2 a-1 |
|  |  |  | Cereal | 0.42 | kg m-2 a-1 |
|  | Depth decay rate | *ddCC,in* |  | 2 | m-1 |
|  | Fractionation factor | *fhum* |  | 0.8 | - | T&V2016 |
|  | Decomposition rate | *SOMdec,y* | Young OM | 5 | % a-1 | Cal. (Guo and Gifford, 2002; Liu et al., 2011) |
|  |  | *SOMdec,o* | Old OM | 1 | % a-1 |
|  | Depth decay rate | *DdCC,dec* |  | 1 | m-1 |

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