Modeling pedogenesis at multimillennium timescales

Achievements and challenges

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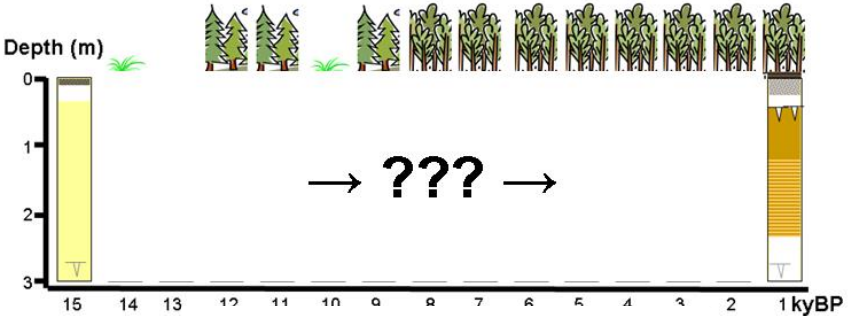
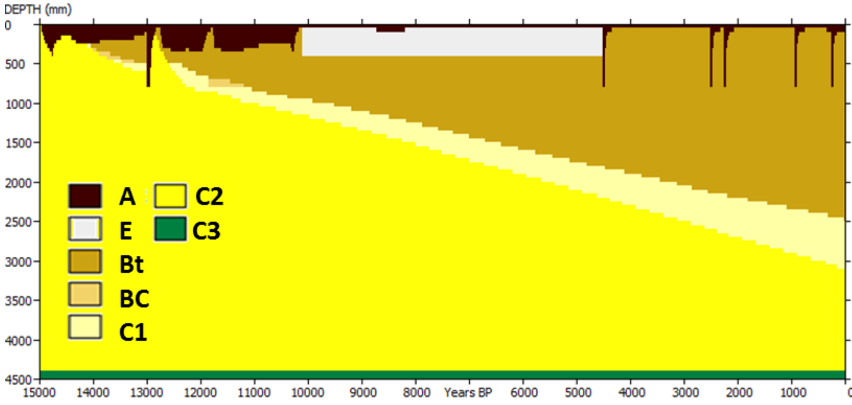
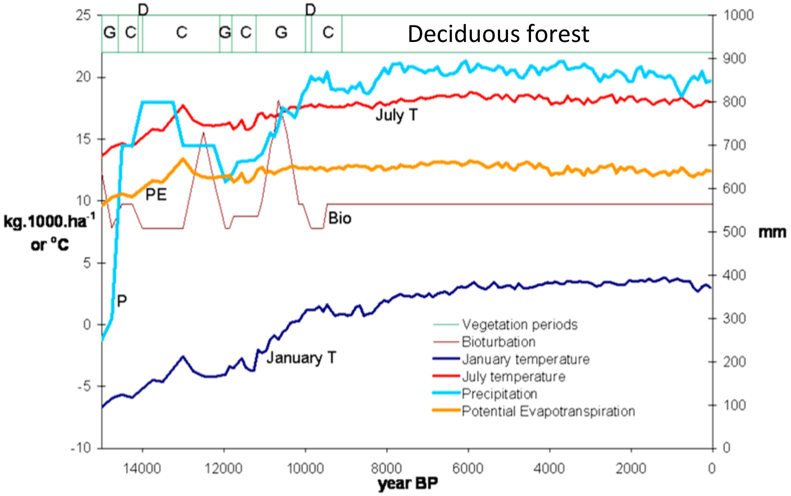




Introduction

Vadose zone modeling	Pedogenesis modeling	"Misery"
Sat/Unsat Water flow		BC's
Solute flow		BC's
Chemistry, exchange reactions		complexity
Heat flow	Heat flow	BC's
Weathering	Weathering (chem, phys)	complexity
C-cycle	C-cycle	BC's
	Soil formation processes: Clay migration, bioturbation, podzolisation, …	Process Coverage
(multi-) annual + (sub-)second	(multi-)millennium + sub-second	Runtime



SoilGen2 Flow of water, solutes, heat

Based on LEACHM(2003) model

- Water flow: Richards' equation

$$\frac{\partial h}{\partial t} C(\theta) = \frac{\partial}{\partial z}\left[K(\theta)\frac{\partial H}{\partial z}\right] - U(z,t)$$

- Solute flow: CDE

$$\frac{\partial c_L}{\partial t}(\theta + \rho K_d + \varepsilon K_H) = \frac{\partial}{\partial z}\left[\theta D(\theta,q)\frac{\partial c_L}{\partial z} - q c_L\right] \pm \Phi$$

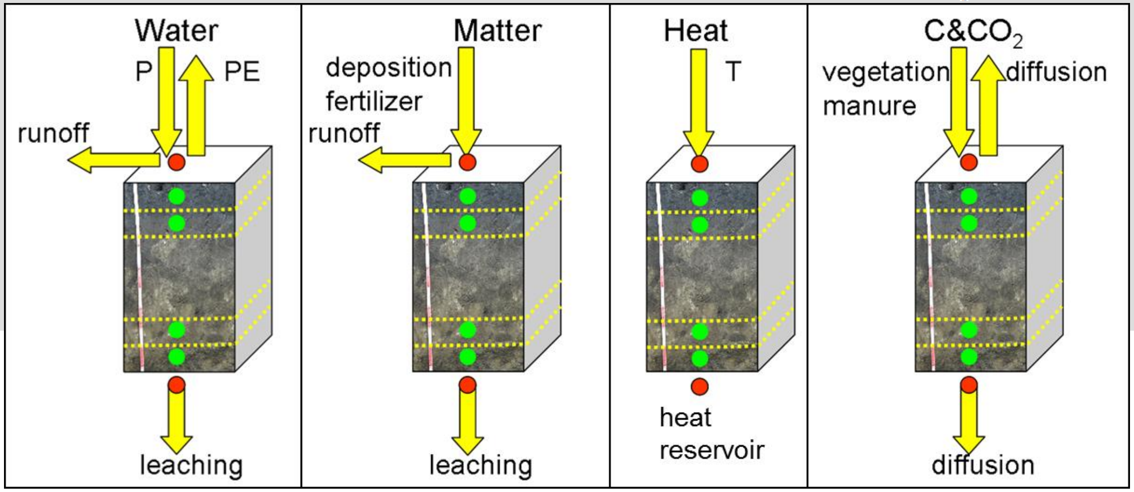
- Heat flow eq.

$$\frac{\partial T}{\partial z} = \frac{\partial}{\partial z}\left(\frac{K_t(\theta)}{\beta}\,\frac{\partial T}{\partial z}\right)$$

Added

- Diffusive gas transport (CO_2)

$$\varepsilon \cdot \frac{\partial c}{\partial t} = D(T)_{gs} \cdot \frac{\partial^2}{\partial z^2} + P(z,t)$$

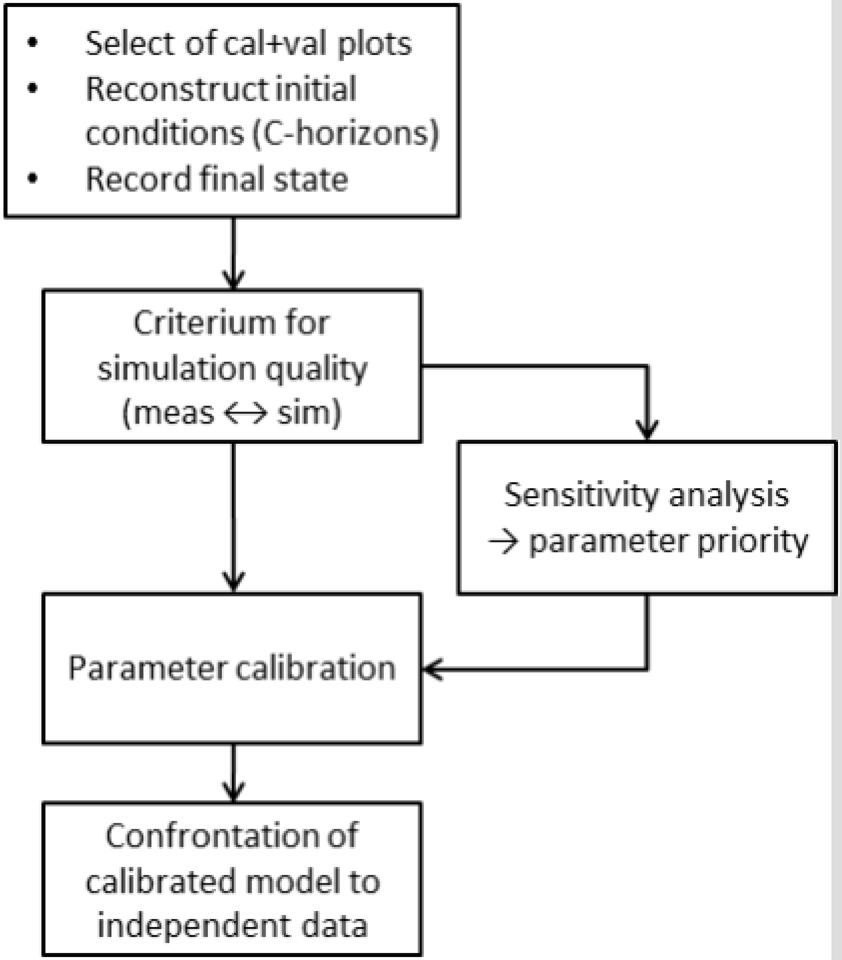


Examples

SoilGen2 = enhanced transport model

Environmental factor		Processes covered	Time scale (year)
CLimate	Temperature	Flow of water solutes heat *Temperature effects on chemistry, C-turnover, water flow*	 $10^{-8} – 10^{-4}$ $10^{-8} – 10^{-4}$ 10^{-4}
	Precipitation: water		
	Precipitation: solutes		
	Evaporation		
Organisms	Vegetation	Soil-Plant cycles of C, Ca, Mg, K, Na, Al	10^{-3}
	Fauna	Bioturbation	10^{0}
	Human influence	Effects of Fertilization and Plowing	10^{0}/pulse
Relief	Slope	Runoff	$10^{-8} – 10^{-4}$
	Erosion / Sedimentation	Effects of Removal or Addition of top layers	10^{0}/pulse
	Local variants of T, P, E	Effects of slope exposition of Heat/water/solute flow	
Parent material	Texture	Physical weathering, Clay migration	10^{3} - 10^{1}
	Mineralogy	Cation exchange, Weathering primary minerals, Chemical Dissolution/Precipitation, Chemical equilibriums	10^{3} - 10^{1}
	Species of Ca, Al, Mg, K, Na, …		
Time	Change of boundary conditions	Effects of changing climate, vegetation and soil management	

Calibrations and tests



- Select of cal+val plots
- Reconstruct initial conditions (C-horizons)
- Record final state

Criterium for simulation quality (meas ↔ sim)

Sensitivity analysis → parameter priority

Parameter calibration

Confrontation of calibrated model to independent data

Notes:

- Calibration involved only process parameters, not time series or initial conditions
- Confrontation to final state after 1000 year (OC%), x000 year (decalcification), 15000 year (clay%)
- Long runtime (≈1 CPU-week/run) > minimal number of calibration runs

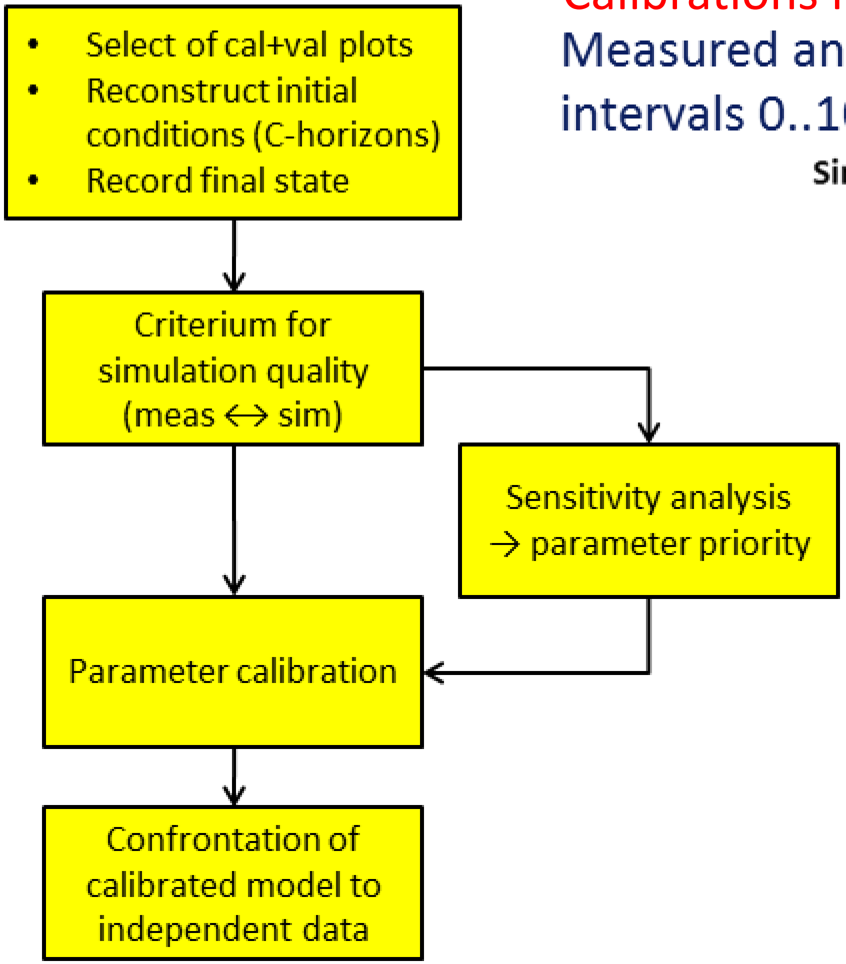
Calibration methods:

a. SA followed by iterative dissection-type calibration per sensitive parameter (OC%)

b. Generic calibration by comparison to data-based metamodel (decalcification)

c. Fit relation model quality – parameter values and find function minimum (clay%)

Calibrations and tests: OC%



- Select of cal+val plots
- Reconstruct initial conditions (C-horizons)
- Record final state

Criterium for simulation quality (meas ↔ sim)

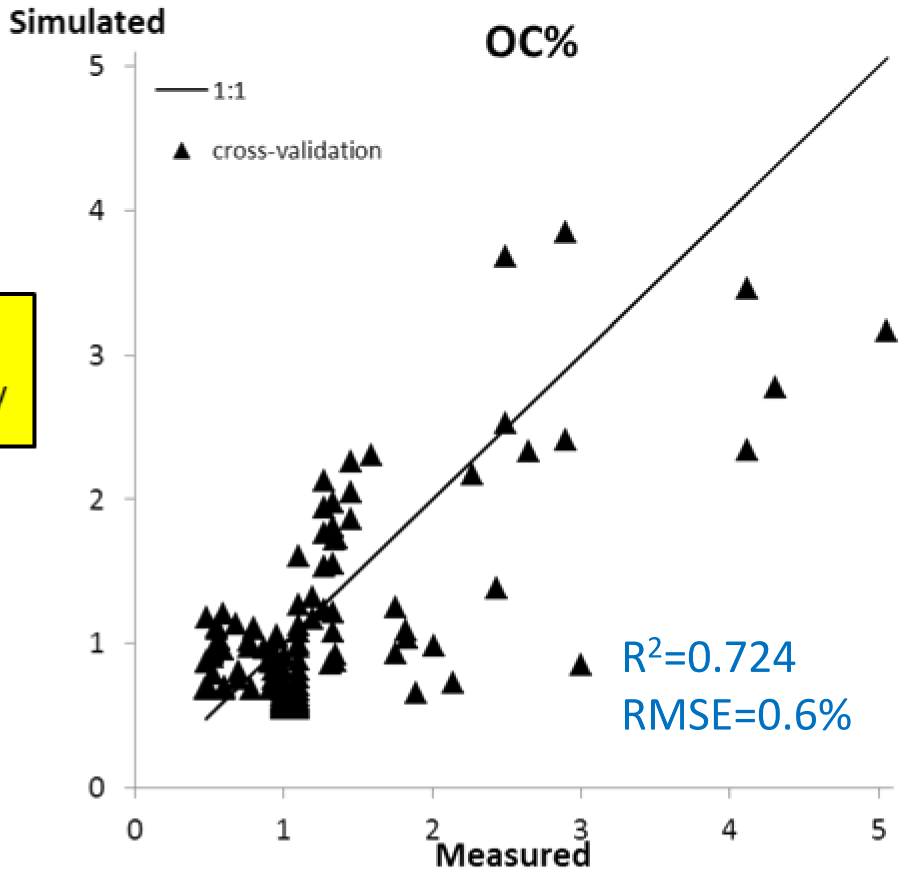
Sensitivity analysis → parameter priority

Parameter calibration

Confrontation of calibrated model to independent data

Calibrations refer to last 1000 years

Measured and simulated OC% over 5 cm depth intervals 0..100 cm in 6 locations (Belgium and China)



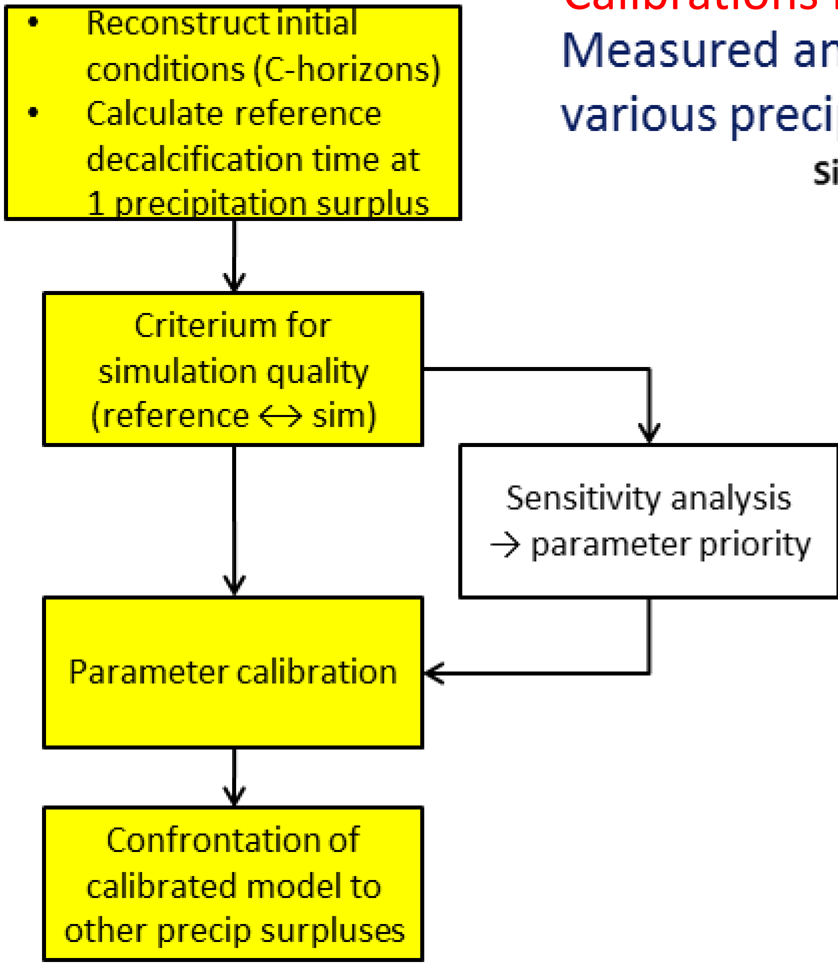
Top layer simulations of OC a little too low. Ectorganic OC not shown

Yu, Finke, Guo, Wu. 2013. Geoscientific Model Development.

Calibrations and tests: Decalcification

Calibrations refer to x000 years

Measured and simulated time-to-decalcification for various precipitation surpluses



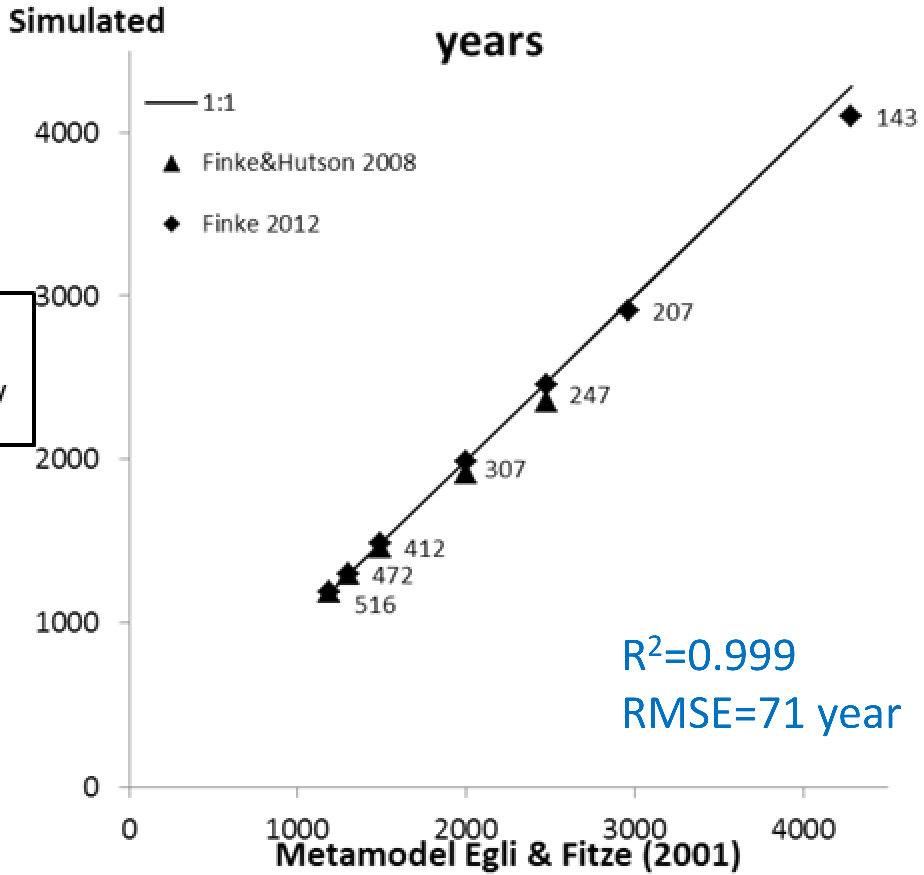
- Reconstruct initial conditions (C-horizons)
- Calculate reference decalcification time at 1 precipitation surplus

Criterium for simulation quality (reference ↔ sim)

Sensitivity analysis → parameter priority

Parameter calibration

Confrontation of calibrated model to other precip surpluses



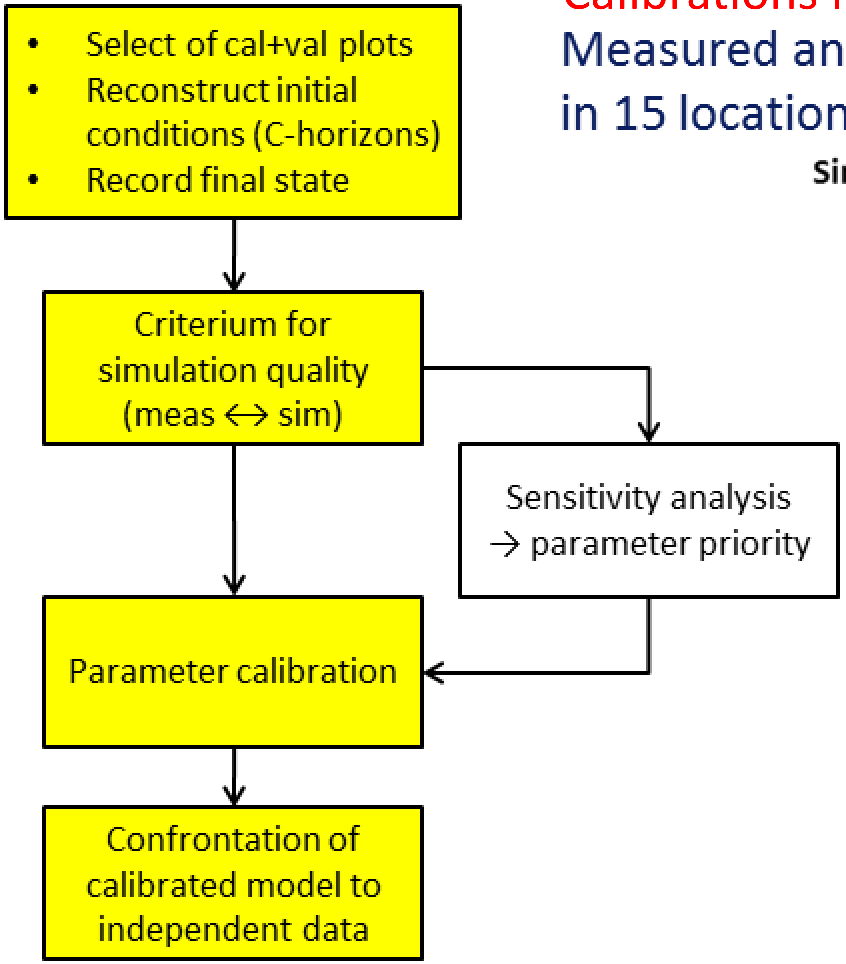
R^2=0.999

RMSE=71 year

OK, but time series of precipitation surplus is highly uncertain!

Finke & Hutson, 2008. Geoderma + Finke, 2012. Quaternary International

Calibrations and tests: Clay%



- Select of cal+val plots
- Reconstruct initial conditions (C-horizons)
- Record final state

Criterium for simulation quality (meas ↔ sim)

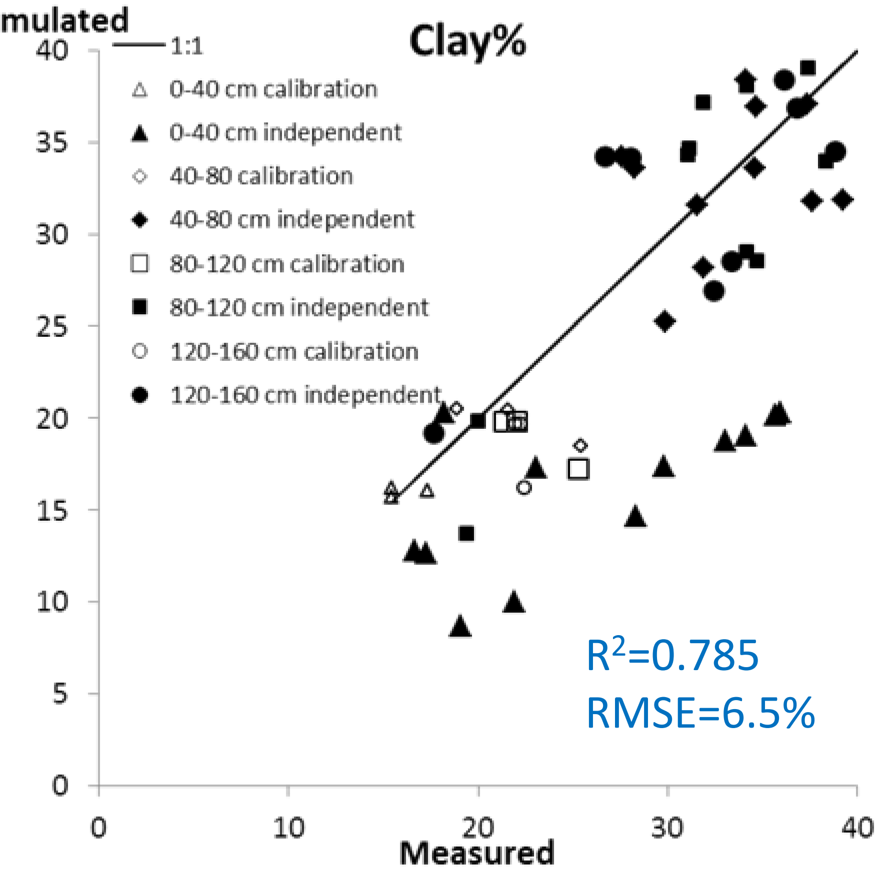
Sensitivity analysis → parameter priority

Parameter calibration

Confrontation of calibrated model to independent data

Calibrations refer to last 15000 years

Measured and simulated clay% over 4 depth intervals in 15 locations (Belgium and Norway)



Too high clay eluviation in topsoil layer 0-40

Finke, 2012. Quaternary International + Sauer et al., 2012. Quaternary International

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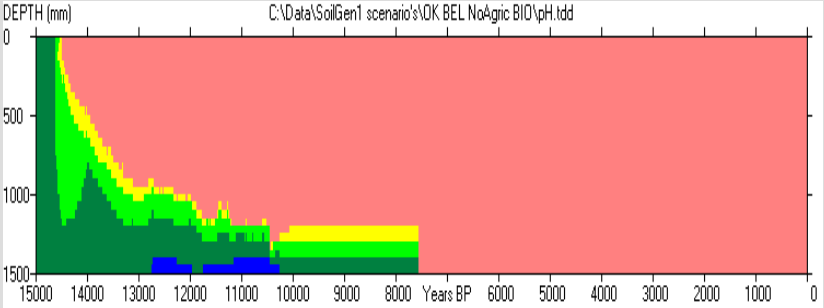
Cases: Climosequence + Toposequence

Effect climate evolution on soil pH

Model = sensitive to effect climate

Belgium



4.0000 - 5.0000 🟥
5.0000 - 6.0000 🟨
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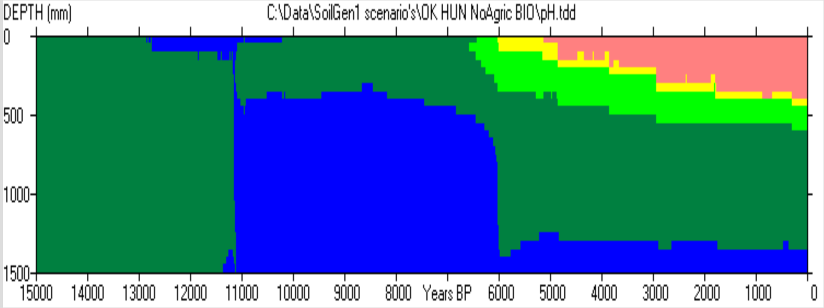
7.0000 - 8.0000 🟩
8.0000 - 8.2600 🟦

Hungary

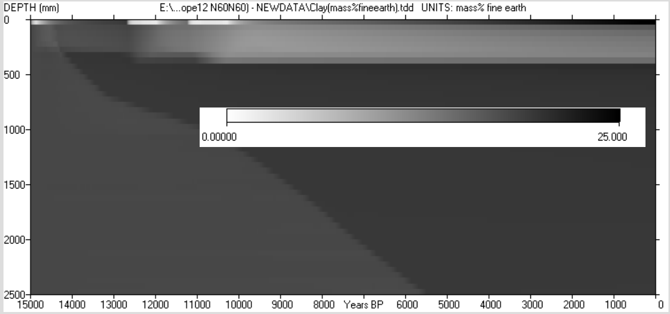


Finke & Hutson, 2008. Geoderma

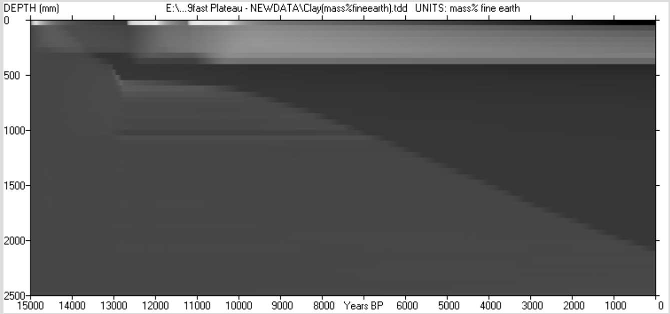
Effect slope exposition on clay leaching, Belgium

Model = sensitive to effect topographic position

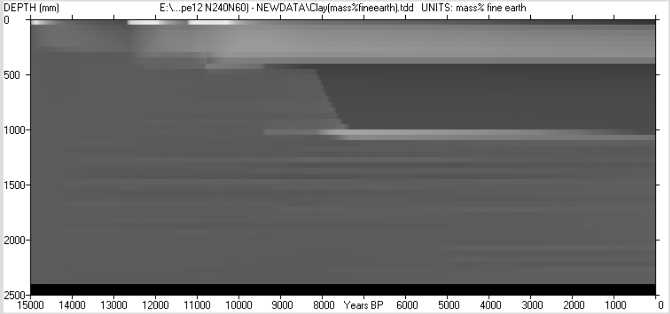
South exposed: more rain + higher PE



Plateau



North exposed: Less rain + lower PE



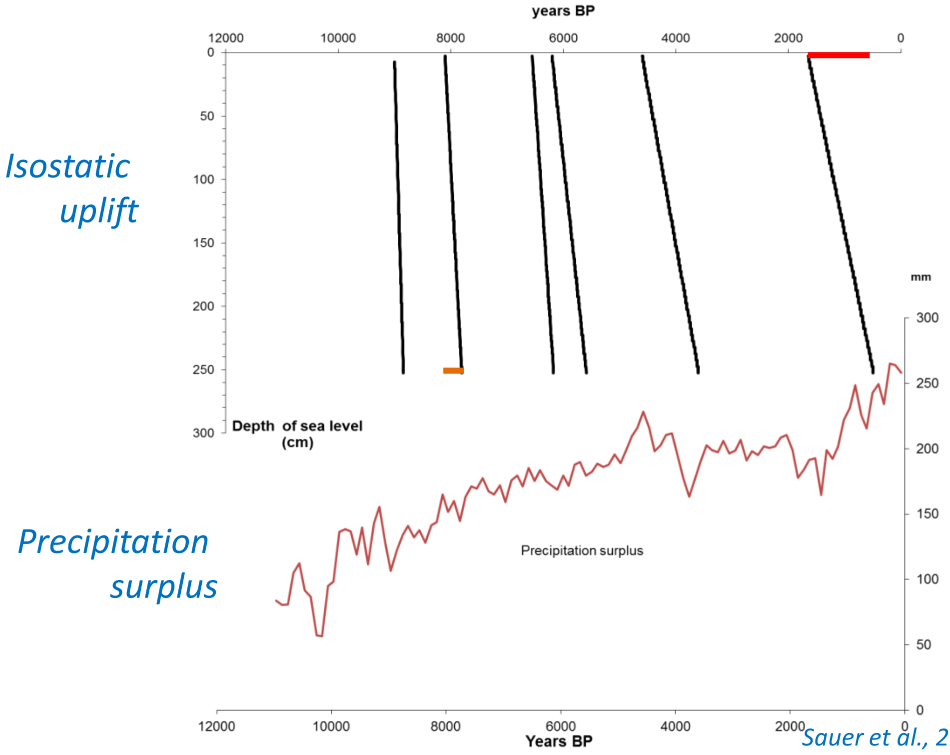
Finke, 2012. Quaternary International

Case: Chronosequence

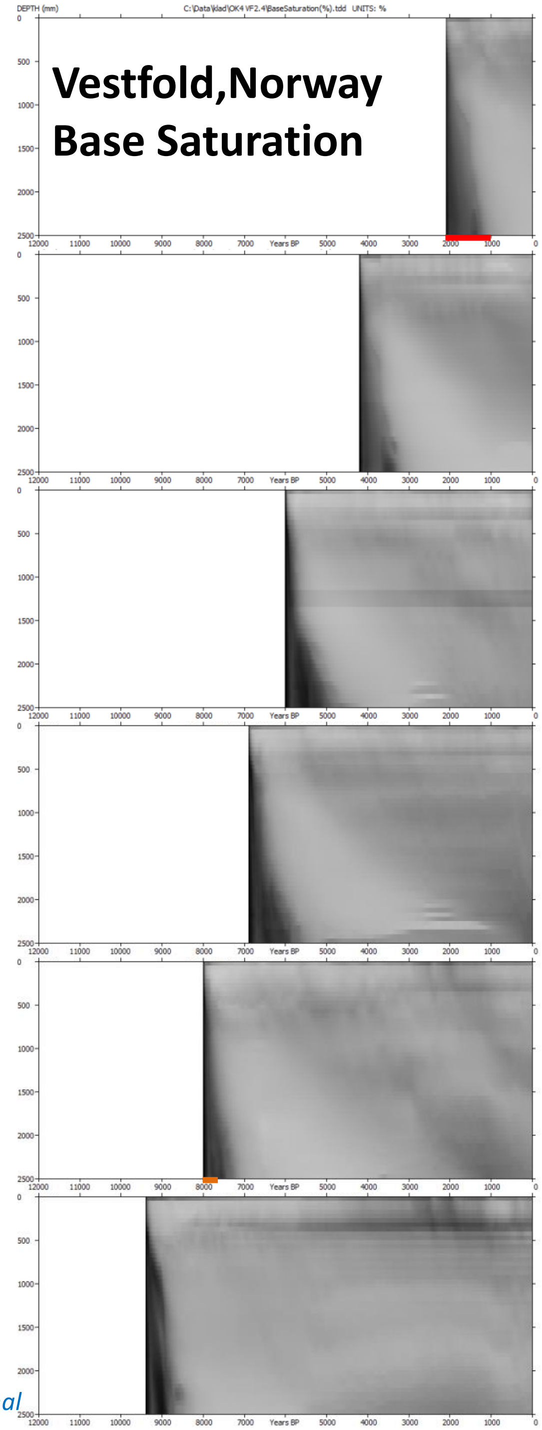
Effect soil age on non-linear development of soil properties in 12 - 1.9 kBP chronosequence

- Slower recent uplift rates related to slower leaching of “marine legacy” basic cations”
- Countering effect of higher recent precipitation surplus (P-PE)

Model = sensitive to “non-linear” soil development



Sauer et al., 2012. Quaternary International



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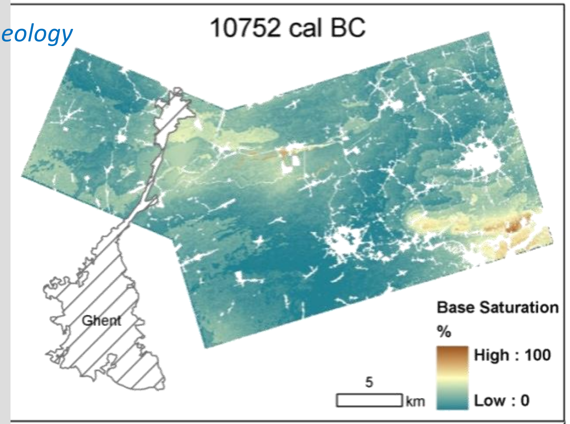
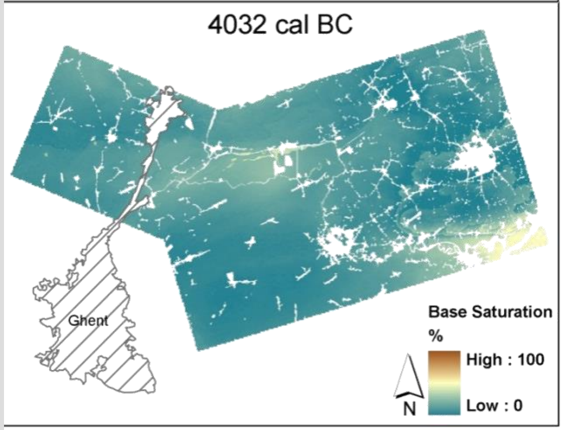
Case: Soilscape reconstruction

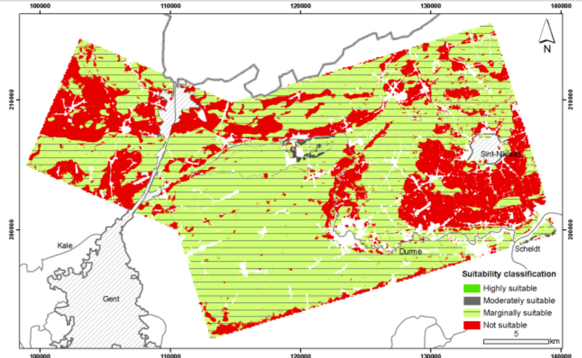
Archaeological land evaluation, Belgium *Zwertvaegher et al. 2010. Geoarchaeology*

1. Modeling terrain evolution *Vermeer et al. In review*
2. Modeling 3D hydrology *Zwertvaegher et al. 2013. Geoarchaeology*
   - Calibration and quality testing
   - Application
3. Modeling 1D soil evolution *Zwertvaegher et al. In review*
   - Multiple locations
   - Take erosion and deposition from terrain model
   - Take water fluxes (or water tables) from hydrological model
   - DSM for interpolation of soil characteristics to full extent
4. Land evaluation of past land uses in past landscapes

Model = applicable in soilscape reconstruction



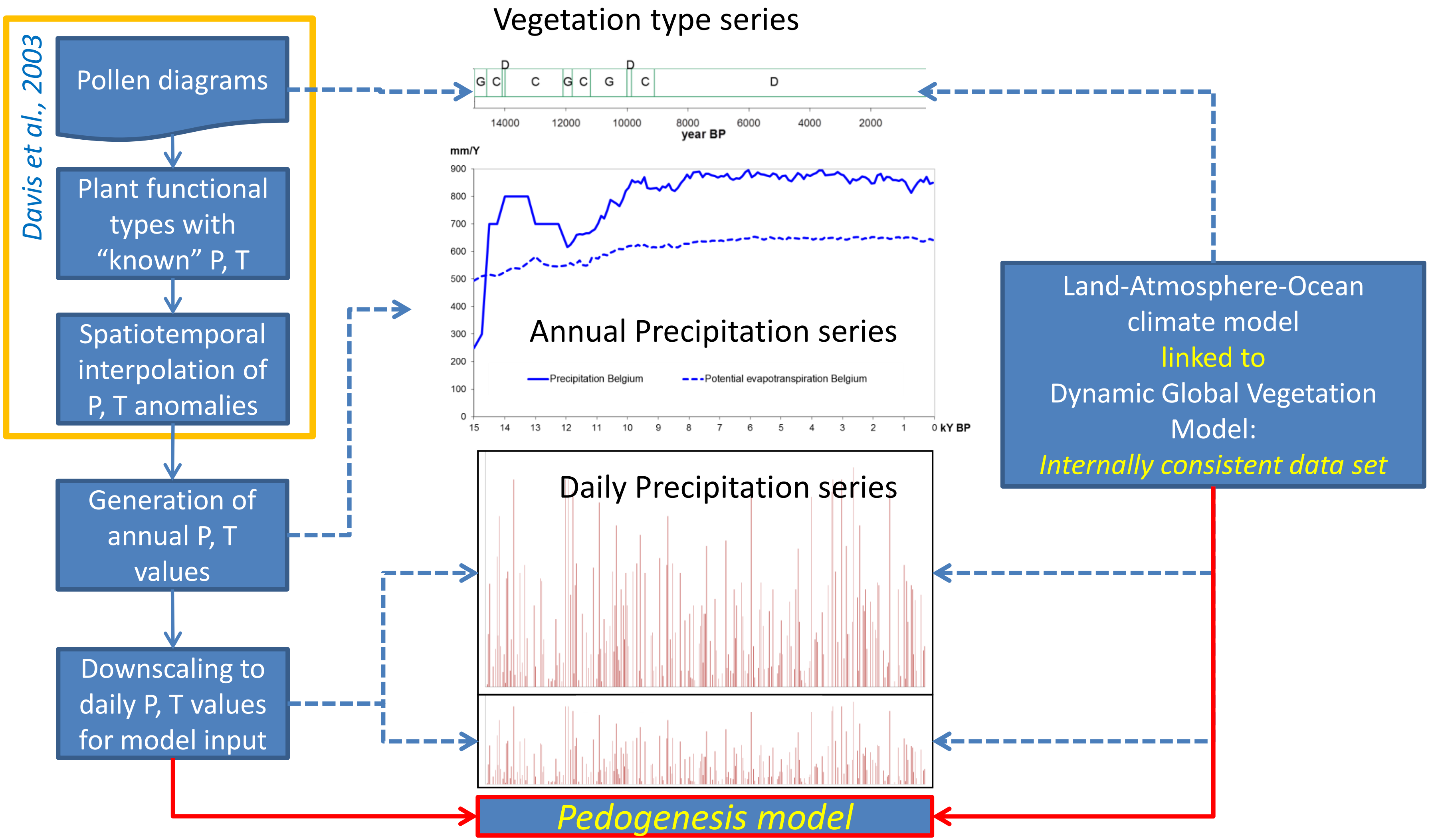




Zwertvaegher, 2012. PhD-thesis

Challenge 1: Multimillennium boundary conditions

Reconstructed boundary conditions are a major source of uncertainty on model results. Consistency?



Davis et al., 2003

Pollen diagrams

Plant functional types with "known" P, T

Spatiotemporal interpolation of P, T anomalies

Generation of annual P, T values

Downscaling to daily P, T values for model input

Vegetation type series

Annual Precipitation series

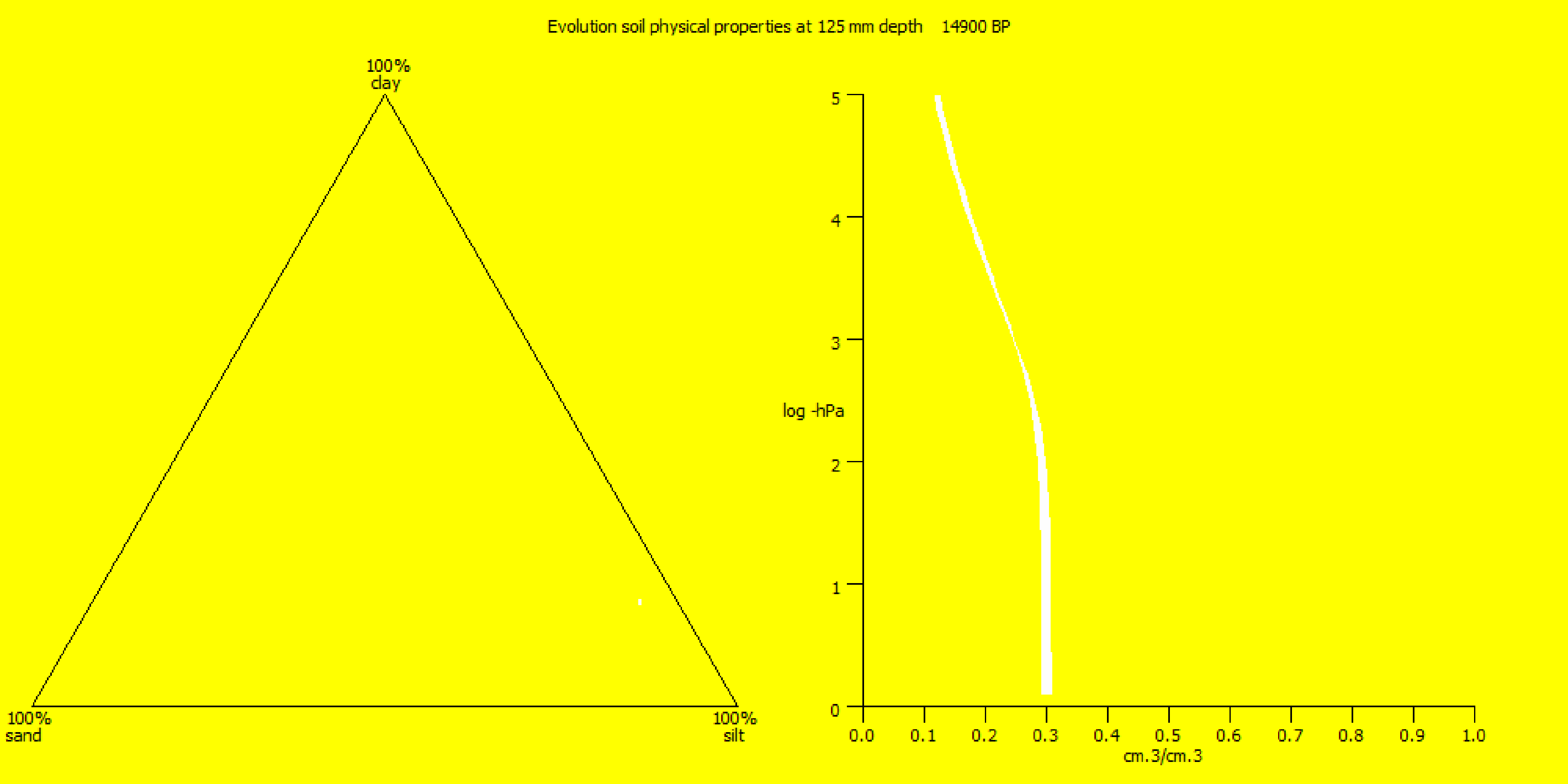
Daily Precipitation series

Land-Atmosphere-Ocean climate model
linked to
Dynamic Global Vegetation Model:
Internally consistent data set

Pedogenesis model

Challenge 2: Panta rhei and hydrological parameters

Pedogenesis= ΔOC, decalcification, weathering, clay migration → Δρ, Δtexture, Δh-θ-K, Δstructure. PTFs?



Challenge 3: Calibration and performance testing

Runtime issues, final state calibration. Efficient calibration methods and smart evaluation proxies?

Issues:

1. Long runtime = no brute force methods. *What else?*

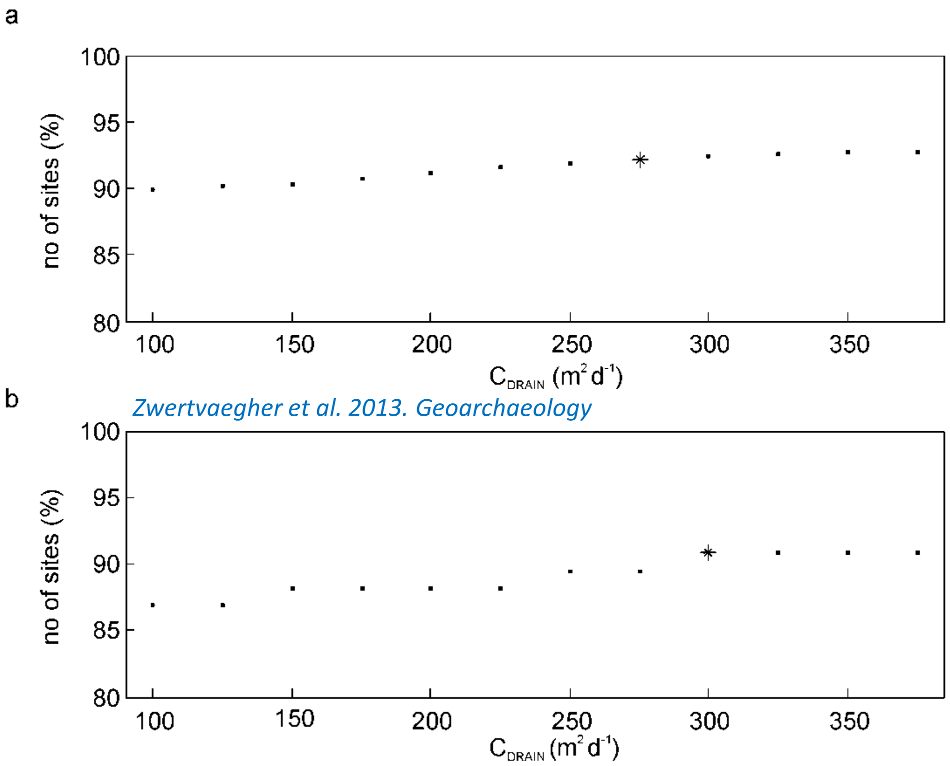
2. Confronting simulations to data and proxies (*not just final state calibration*).
Ex: Calibration of MODFLOW phreatic water tables over period 12.7 kBP - present

- Calibration using the mapped drainage class (1953), but also by:

(a) Maximizing the number of dated and dry archaeological sites (“dry feet proxy”)

(b) Maximizing the number of sites where the bottom of the Podzol-Bh is above the water table at least 1500 years (“time-integrated proxy”)

ALT: chronosequence calibration.



Zwertvaegher et al. 2013. Geoarchaeology

Challenge 4: Soil redistribution

Importance

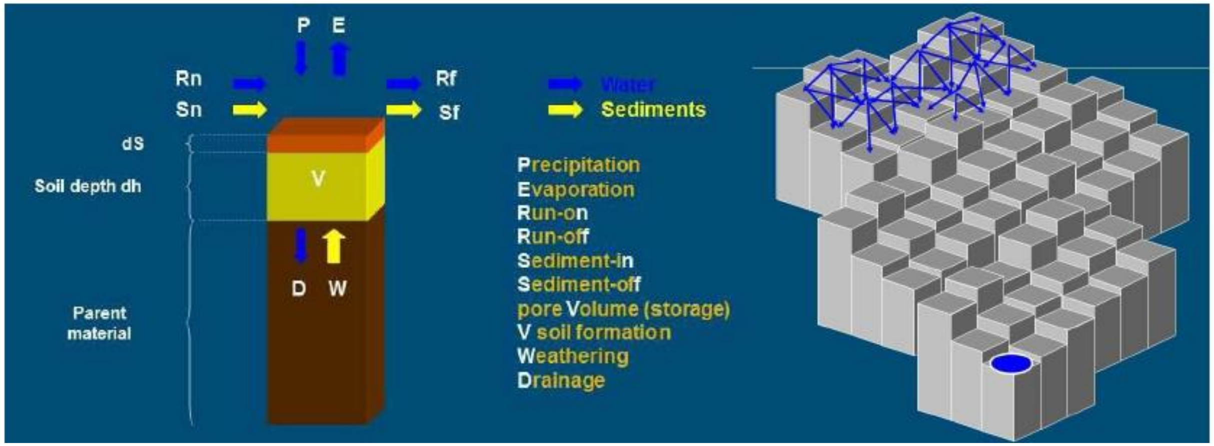
- C-sequestration in erosion/deposition landscapes
- Understanding feedback mechanisms between soil development / erosion

Approaches

1. Linked soil-landscape-vegetation models (e.g. Zwertvaegher et al. in review)
2. Integrated soil-landscape-vegetation models (e.g. Schoorl et al. 2012)

Challenges

1. Computational effort
2. Reconstruction of boundary conditions in human-affected landscapes
3. Quantification interactions soil-water-vegetation-mass redistribution



Conclusions

Pedogenetic modeling is feasible

Work needed on

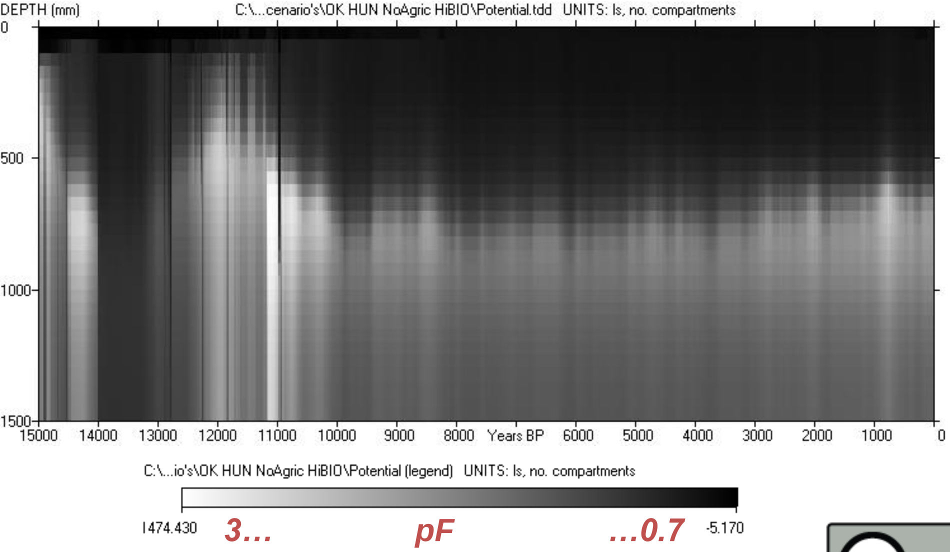
1. Process coverage (e.g. Podzolisation)
2. Generating “mutually consistent” BC (e.g. by Climate-Vegetation models)
3. Quantification effect changing soil structure on hydro props (e.g. ripening)
4. Efficient calibration and smart proxies along the timeline
5. Soil-landscape interactions

Thank you

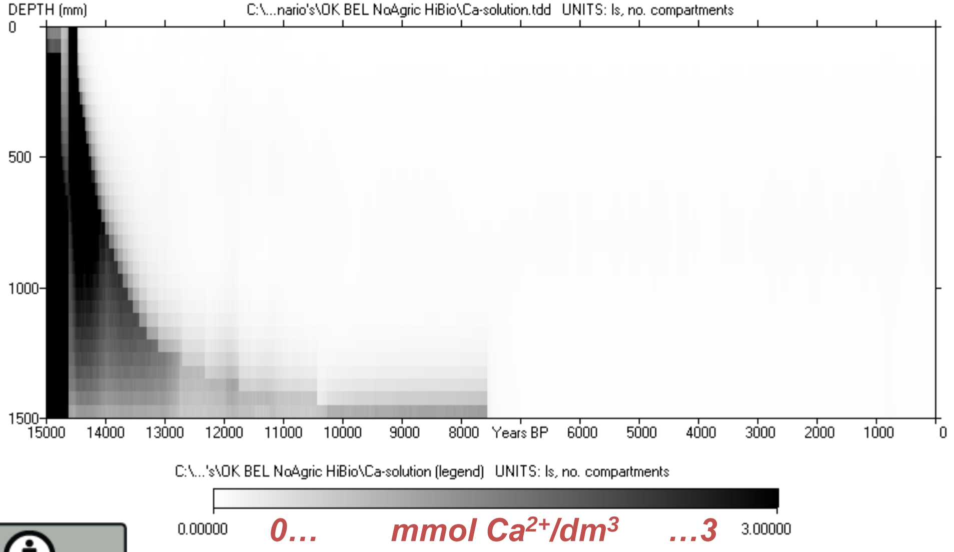
PS:

Water flow drives pedogenesis

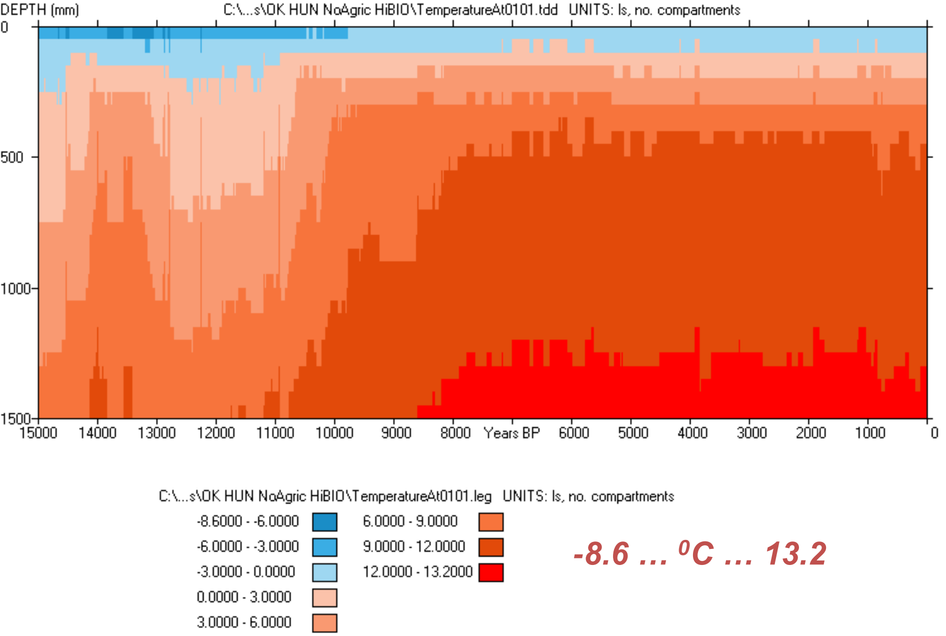
- Water flow → pF 31-12-yyyy



Solute flow → Ca^{2+} 31-12-yyyy



- Heat flow → Temperature 31-12-yyyy



Gas flow → pCO_2 31-12-yyyy