# ISMC2021

## ISMC2021-1 abstracts

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# Belowground processes in Terrestrial Biosphere Models, the forgotten half

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Drought stress is an important threat for plants in tropical forests, especially in the context of human-induced increase of drought frequency and severity observed in regions like the Amazon basin. Terrestrial Biosphere Models are key tools to predict the future of tropical ecosystems as they allow estimating the resilience of ecosystems by simulating various future scenarios. Previous vegetation model runs have suggested a complete dieback of the Amazon or a rapid transition towards Savannah-like ecosystems because of increasing drought frequency while others have forecasted an overall greenup due to fertilization. A part of the discrepancy between those predictions stems from the representation of below-ground processes that substantially differ between models. How sensitive those models are to soil parameters and below-ground processes has been only sporadically addressed to this date, while answering this question is critical to make reliable predictions.

In this study, we compared the sensitivities of three state-of-the-art Terrestrial Biosphere Models, namely ORCHIDEE (big-leaf), ED2 (cohort-based), and LPJ-GUESS (individually-based) to the variability in soil properties over the Amazon. These three models are representative of the existing range of vegetation models but differ in their representation of the rooting system, the soil hydraulic properties and the plant below-ground functioning. We ran multiple model simulations with different soil maps and compared how the growth primary productivity, evapotranspiration and drought stress simulated by each model varied with soil properties. Those soil maps were derived from Soilgrids by retaining the most frequent soil class for each simulated pixel, or the one with the lowest or the highest clay content. The analysis revealed that all three models were weakly sensitive to soil texture, making clear that Terrestrial Biosphere Models require a better representation of below-ground processes in order to accurately simulate drought stress and water competition.

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# Retrieving Soil Physical Properties via Assimilating SMAP Brightness Temperature Observations in the Community Land Model

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Basic soil physical properties (i.e., soil texture and organic matter) and associated soil hydraulic properties (i.e., soil water retention curve and hydraulic conductivity) play an essential role in land surface models (LSMs) for estimating soil moisture. With the physical link between soil properties, LSMs and Radiative Transfer Models (RTMs), the soil physical properties can be retrieved, using a LSM coupled with a microwave L-band emission observation model in a data assimilation framework. To this purpose, this paper couples an enhanced physically-based discrete scattering-emission model with the Community Land Model 4.5 (CLM), to retreive soil physical properties using the Local Ensemble Transform Kalman Filter (LETKF) algorithm, assimilating Soil Moisture Active and Passive (SMAP) Level-1C (L1C) brightness temperature at H and V polarization ( and ) separately, assisted with in situ measurements at the Maqu site on the eastern Tibetan Plateau. Results show the improved estimate of soil properties at the topmost layer via assimilating SMAP ( H, V), as well as at profile using the retrieved top-layer soil properties and a prior depth ratio. The use of and shows varied sensitivities to retrievals of different soil compositions (i.e., sand, clay, silt) and soil moisture estimates. However, analyses show that the retrieved soil properties with fine accuracy are not sensitive factors affecting soil moisture estimates. Instead, uncertainties of CLM model structures shall be considered, such as the fixed PTFs (pedotransfer functions), the hydraulic function describing soil water retention curve and the water stress function determining root water update.

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# The Role of Vadose Zone Physics in the Soil Hydrothermal and Ecohydrological Response of a Tibetan Meadow Ecosystem to Freeze-Thaw Cycles

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The vadose zone is a zone sensitive to environmental changes and exerts a crucial control in ecosystem functioning and even more so in cold regions considering the rapid change in the seasonally frozen ground under climate warming. While the way in representing the underlying physical process of the vadose zone differs among models, the effect of such differences on soil hydrothermal regimes, and then ecosystem functioning and its ecohydrological response to freeze–thaw cycles are seldom reported. Here, the detailed vadose zone process modeling framework STEMMUS (Simultaneous Transfer of Energy, Mass and Momentum in Unsaturated Soil) was coupled with the ecohydrological model Tethys–Chloris (T&C) to investigate the role of influential physical processes during freeze-thaw cycles. The physical representation is increased from using T&C coupling without STEMMUS enabling the simultaneous mass and energy transfer in the soil system (liquid, vapor, ice) – and with explicit consideration of the impact of soil ice content on energy and water transfer properties – to using T&C coupling with it. We tested model performance with the aid of a comprehensive observation dataset collected at a typical meadow ecosystem on the Tibetan Plateau. Results indicated that explicitly considering the frozen soil process and vapor flow significantly improved the soil moisture/temperature profile simulations and facilitated our understanding of the water transfer processes within the soil-plant-atmosphere continuum. We further demonstrated the linkage between the vadose zone physics-induced difference in soil hydrothermal regimes and the ecosystem water/carbon cycles. This research highlights the important role of vadose zone physics for ecosystem functioning in cold regions and can support the development and application of future Earth system models.

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# Are Earth system models able to reproduce the soil heterotrophic respiration fluxes?

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Earth system models (ESMs) are numerical representations of the Earth system aiming at representing the climate dynamic including feedbacks between climate and carbon cycle. $CO_2$ flux due to soil respiration including heterotrophic respiration coming from the soil organic matter (SOM) microbial decomposition and autotrophic respiration coming from the roots respiration is one of the most important flux between the surface and the atmosphere. Thus, even small changes in this flux may impact drastically the climate dynamic. It is therefore essential that ESMs reliably reproduce soil respiration. Until recently, such an evaluation at global scale of the ESMs was not straightforward because of the absence of observation-derived product to evaluate heterotrophic respiration fluxes from ESMs at global scale. Recently, several gridded products were published opening a new research avenue on climate-carbon feedbacks. In this study, we used simulations from 13 ESMs performed within the sixth coupled model intercomparison project (CMIP6) and we evaluate their capacities to reproduce the heterotrophic respiration flux using three gridded observation-based products. We first evaluate the total heterotrophic respiration flux for each model as well as the spatial patterns. We observed that most of the models are able to reproduce the total heterotrophic respiration flux but the spatial analysis underlined that this was partially due to some bias compensation between regions overestimating the flux and regions underestimating the flux. To better identify the causes of the identified bias in predicting the total heterotrophic respiration flux, we analysed the residues of ESMs using linear mixed effect models and we observed that lithology and climate were the most important drivers of the ESMs residues. Our results suggest that the response of SOM microbial decomposition to soil moisture and temperature must be improved in the next ESMs generation and that the effect of lithology should be better taken into account.

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# The role of soil hydro-physical properties in the atmospheric water cycle

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Soil hydro-physical properties are necessary components in regional climate simulation; yet, the parameter inaccuracies introduce uncertainty in the representation of surface water and energy fluxes leading to differences in land-atmosphere interactions, and precipitation. This study examines the uncertainties in the North American atmospheric water cycle that result from the use of different soil datasets. Two soil datasets are considered: STATSGO from the United States Department of Agriculture and GSDE from Beijing Normal University. Each dataset's dominant soil category allocations differ significantly at the model's resolution. Large regional discrepancies are found in the assignments of soil category, such that, for instance, in the Midwestern US (hereafter, Midwest), there is a systematic reduction in soil grain size allowing the impacts of the differing assignments to project onto regional scales.

The two simulations are conducted from June 1–August 31, 2016–2018 using the Weather Research and Forecasting Model coupled with the Community Land Model version 4. In the Midwest, where soil grain size decreases from STATSGO to GSDE, the GSDE simulation experiences reduced mean latent heat flux (–15 W $m^{-2}$), and increased sensible heat flux (+15 W $m^{-2}$). The boundary layer thermodynamic structure responds to these changes resulting in differences in mean CAPE and CIN. In the GSDE simulation, there is more energy available for convection (CAPE: +200 J $kg^{-1}$) in the Midwest, but it is more difficult to access that energy (CIN: +75 J $kg^{-1}$). Differences arise in dynamic quantities, as well: the vertically-integrated moisture fluxes suggest a reduction in continental cyclonic rotation co-located with the decrease in latent heat flux and, the vertically-integrated moisture flux convergence is also affected. This combination of thermodynamic and dynamic responses culminate in a reduction of precipitation in the Midwest, which can be related to changes in the placement of soil hydro-physical properties.

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# Historical soil maps with a reference to redoximorphic features as basis for ecohydrological modelling.

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Historical soil maps with a reference to profile redoximorphic features have obvious utility for ecohydrological modelling. That is particularly pertinent in areas with shallow water tables where catchments have both dry and moist parts, latter due to moisture source from either upper or low boundary. However, there is no convenient method for converting maps to hydrological model state variables. Here we propose that the steady state continuity equation in kinematic wave form can be parameterized using expert knowledge of the typical water table depth (WTD) for soils with different hydromorphy degrees based on redoximorphic features. To test the approach, six hillslope-based computational units (catenas) were obtained, for use in simulations, by automated of the Samovetc and Izberdey catchments in the Tambov region (Russia) using lumpR software. Five of the six catenas began at poorly drained flat upslope positions with soils with various degrees of saturation by shallow groundwater and one began at a well-drained upslope position. We guided parameterization of the kinematic wave model by critical range of the WTD known to correspond to each soil group on historical soil map of hydromorphy degree. Application of expert knowledge in this manner alone yielded a broad range of possible WTD values (e.g. 1.5-5 m for a semi-hydromorphic soil) for each soil entity, but linking a catena by the fundamental physical constraint of flow continuity enabled narrowing of the range to 0.2-1 m thereby reducing it by ca. 80%. We further tested the shallow water table approximation in the WASA-SED ecohydrological model based on catenary approach to simulate soil moisture profiles referring explicitly to soil groups of different hydromorphy degree and distinguish stagnic and gleyic regimes of waterlogging. The results show that the approach could substantially improve crop and water management precision.

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# Agricultural hillslope soil heterogeneity challenges: first experimental results from SUPREHILL critical zone observatory

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SUPREHILL is a new (2020) and first Croatian critical zone observatory (CZO), focused on local scale agricultural e.g., vineyard hillslope processes. The experimental setup includes an extensive sensor-based network accompanied by weighing lysimeters and instruments for surface and subsurface hydrology measurement. The field measurements are supported by novel laboratory and numerical quantification methods for the determination of water flow and solute transport. This combined approach will allow the research team to accurately determine soil water balance components (soil water flow, preferential flow/transport pathways, surface runoff, evapotranspiration), the temporal origin of water in hillslope hydrology (isotopes), transport of agrochemicals, and to calibrate and validate numerical modeling procedures for describing and predicting soil water flow and solute transport. First results from sensors indicate increased soil moisture on the hilltop, which is supported by precipitation data from rain gauges and weighing lysimeters. The presence of a compacted soil horizon and compacted inter-row parts (due to trafficking) of the vineyard seems to be highly relevant in regulating water dynamics. Wick lysimeters confirm the sensor soil moisture data, while showing a significant difference in its repetitions which suggests a possibility of a preferential flow imposed by local scale soil heterogeneity. Measured values of surface and subsurface runoff suggest a crucial role of these processes in the hillslope hydrology, while slope and structure dynamics additionally influence soil hydraulic properties. We are confident that the CZO will give us new insights in the landscape heterogeneity and substantially increase our understanding regarding preferential flow and nonlinear solute transport, with results directly applicable in agricultural (sloped agricultural soil management) and environmental (soil and water) systems. Challenges remain in characterizing local scale soil heterogeneity, dynamic properties quantification and scaling issues for which we will rely on combining CZO focused measurements and numerical modeling after substantial data is collected.

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# Visualization and quantification of NDVI dynamics in semiarid grasslands through recurrence tools.

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Grassland dynamics are constantly changing at a variety of spatial and temporal scales. Remote-sensing techniques are used to detect, identify, and monitor ecosystem changes at multi-temporal scales. Particularly, Normalized Difference Vegetation Index (NDVI)-based time series are important to obtain numerical observations related to vegetation dynamics.

It is within this context that Recurrence Plots (RPs), Cross Recurrence Plots (CRPs) and Recurrence Quantification Analysis (RQA) offer new insight into the analysis of non-linear processes. Altogether, recurrence techniques could describe the whole dynamics of the system, explore its temporal behaviour, and quantify its structure through complexity measures. The goal of this study is to compute recurrence techniques to visualize and quantify the temporal dynamics of the semiarid grassland-climate system.

In this work, we chose a semiarid grassland area in the centre of Spain, characterized by a Mediterranean climate. Multispectral images were composed for 8-days and they were acquired from MODIS TERRA (MOD09Q1.006) product from 2002 to 2018. Then, NDVI time-series was generated from four pixels with a spatial resolution of 250 x 250 $m^2$. Temperature and precipitation time-series were obtained from a nearby meteorological station and transformed into an 8-day time step.

Our results demonstrated that RPs showed the seasonality of the NDVI time-series. Furthermore, abrupt changes in NDVI time series were detected at specific times, implying that an atypical event occurred during that time. Temperature-NDVI CRPs showed a periodical pattern between them, on the other hand, precipitation-NDVI CRPs showed more erratic behaviour. We also found that a maximum lag between the two time-series could be detected through recurrence techniques. Overall, our findings suggest that temperature and precipitation present a dynamic complexity that is revealed in NDVI response. Therefore, RPs and CRPs are an alternative and complementary method to analyse and quantify non-stationary process, such as vegetation dynamics.

## Reference

Almeida-Ñauñay, A. F., Benito, R. M., Quemada, M., Losada, J. C., & Tarquis, A. M. Complexity of the Vegetation-Climate System Through Data Analysis. In International Conference on Complex Networks and Their Applications. Springer, Cham., 609-619, 2020

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# Spatial rangeland variability: using summary statistics and multifractal analysis to classify and monitor rangelands.

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Rangelands ecosystem comprises more than a third of the global land surface, sustaining key ecosystem services and livelihoods. Unfortunately, they suffer from severe degradation on a global scale. Tailored-monitoring of rangeland will allow us to improve their management and maintain their social-ecological systems.

MODIS data are commonly used to calculate Normalized Differenced Vegetation Index (NDVI) and NDVI anomaly (NDVIa) to monitor rangelands. In this study, we compare summary statistics and multifractal analysis to see if using complexity based tools improves our ability to differentiate land uses and types using remote sensing.

We collected time series using satellite data of MODIS (MOD09Q1.006) from 2000 to 2019. An area from southeastern Spain (Murcia province) of 6.25 $Km^2$ was selected. This area comprised 132 pixels with a spatial resolution of 250 x 250 $m^2$ and a temporal resolution of 8 days. This area includes irrigated and rainfed crops, shrubs and forested patches.

Multifractal detrended fluctuation analysis (MF-DFA) focuses on measuring variations of the moments of the absolute difference of their values at different scales. This allows us to use different multifractal exponent such as generalized Hurst exponent (H(q)), and its range (ΔH) to characterize the area. Here, we have selected H(1), H(2) and ΔH, to reflect variance, persistence and multifractality, respectively. Then, we compare them to the average, standard deviation and kurtosis of our NDVI and NDVIa series.

Our results indicate that MF-DFA, allow us to see more clearly the differences among the pixels than the summary statistics. Particularly H(1) and H(2) of NDVI reflects more precisely the vegetation profile and land uses of the selected area. On the other hand, NDVIa allows us to highlight those pixels where several uses occur, or some feature such as roads interact with NDVI. MF-DFA appears as a promising tool to classify and monitor rangelands.

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# Parametrizating Soil Surface Fluxes in the JULES Land Surface Model

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The parametrization of land-atmosphere interactions in numerical weather prediction and climate models is a topic of active and growing interest, especially in connection with extreme events such as heat waves and droughts. Semiarid regions are sensitive to drought and are currently expanding, but they are often poorly represented in numerical models. On forecasting timescales, comparisons of simulated land surface temperature against retrievals from satellites often show significant cold biases around noon, whilst, on climate timescales, land surface models often fail to represent droughts realistically. Inadequate treatment of the land surface, and particularly of soil properties and soil moisture, is likely to contribute to such errors.

Efforts to develop improved parametrizations of soil processes in the JULES land surface model for application in weather prediction and climate simulations are underway. Whilst processes at the soil surface are a central part of this, to obtain acceptable performance it is also important to consider the surface flux budget as a whole, including the treatment of the plant canopy. Here, we shall describe the current status of developments aimed at improving the representation of evapotranspiration and ground heat fluxes in the model, noting the major issues encountered. The importance of accurately representing the impact of soil moisture on thermal properties will be stressed. Results from initial studies will be presented and we shall offer a perspective on future developments.

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# Soil organic matter dominates the magnitude of porosity and bulk density in temperate soils, with important implications for land surface models

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Soil porosity controls the flow of mass and energy through soil, and thus plays a fundamental role in regulating hydrological and biochemical cycling at the land surface. Global land surface and earth system models commonly derive porosity from soil texture using pedotransfer functions. This does not allow for response to change in environment or management, or potentially important climate feedbacks. Furthermore, the approach does not fully represent the baseline spatial variation in this important soil property. Here we show that porosity, and bulk density (BD), depend on SOM in temperate soils, using two comprehensive national data sets, covering the full range of soil organic matter (SOM) (n=1385 & n=2570). Our novel use of analytical models with machine learning (ML) algorithms opens up new physical insight into controls on porosity and BD, while generalized additive mixed models (GAMMs) provide further insights and opportunities for prediction. Our models allow us to consider influence of management on soil compaction and recent observations that soil porosity responds to climate change. The dependence of soil porosity on SOM, more so than texture, indicates the need for a paradigm shift in the conceptualization and modelling of these soil physical properties. Broad habitat was also an important control, and explained some of the variance in the relationship between SOM and porosity. This highlights that changes in soil porosity may occur due to land use or climate change, and will create feedbacks to hydrological and biogeochemical cycling which should be represented in Global land surface models. This will also be important for other pedotransfer functions, e.g. the use of BD to determine carbon stock from concentration. In addition, we found opportunities for improved representation of the spatial pattern of porosity, even in the absence of measured data on SOM, based on climate and earth observation data.

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# Improving the global modeling of soils in JULES and the Unified Model: Updating from UM/HWSD to SoilGrids soil properties and from the Brooks & Corey to the van Genuchten soil-hydraulics model

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We have updated the soil properties used in JULES (Joint UK Land Environment Simulator), which is the land-surface component of the UM (Unified Model, the UK Met Office's climate model). JULES models the interaction of the land surface with the atmosphere, and simulates the energy, water, and carbon fluxes. JULES allows either: (i) the Brooks & Corey (BC) model for estimating soil hydraulic properties, or (ii) the van Genuchten (VG) model but using hydraulic parameters translated from the BC model. One advantage of the VG model over the BC model is the smoother dependence of water retention upon matric potential for nearly saturated soils. Herein, we report on our work towards fully implementing the VG model in JULES and in the UM, through the implementation and evaluation of several VG pedotransfer functions (PTFs) for estimating the soil hydraulic parameters used in the hydraulic functions.

We have tested three VG PTFs in global offline JULES runs (driven with WFDEI data over 1979-2012): the combination of Tóth et al. PTFs 17 & 20, the Weynants et al. PTF, and the Zhang & Schaap ROSETTA3 H1 PTF (modified for sandy soils). We also modernized the soil basic properties that are conventionally used for JULES and the UM, from the UM version of the Harmonized World Soil Database (HWSD) to the SoilGrids database.

Evaluation of JULES simulations shows (i) that the modified version of the Zhang & Schaap ROSETTA3 H1 PTF is the best VG option, and (ii) that it compares favorably with the BC control model (which uses the Cosby et al. PTF and the UM/HWSD soils), in terms of the surface energy balance and the mitigation of near-surface temperature biases over mid-latitude continental regions. This modified version of the Zhang & Schaap ROSETTA3 H1 PTF with SoilGrids soils is also currently being used in coupled land-atmosphere UM runs.

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# Improving soil moisture predictions from a land surface model by optimisation of pedotransfer functions.

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Accurate soil moisture predictions from land surface models are important in hydrological, ecological and agricultural applications. Despite increasing availability of wide area soil moisture measurements, few studies have combined soil moisture predictions from models with in-situ observations beyond the point scale. This work uses the LAVENDAR data assimilation framework to markedly improve soil moisture estimates from the JULES land surface model using field scale Cosmic Ray Neutron sensor observations from the UKCEH COSMOS-UK network. Rather than directly updating modelled soil moisture estimates towards measured values, we optimize constants in the underlying pedotransfer functions (PTF) which relate soil texture to soil hydraulics parameters. In this way we generate a single set of newly calibrated PTFs based on field scale observations from a number of UK sites with different soil types. We demonstrate that calibrating PTFs in this way can improve the performance of JULES. Further, we suggest that calibrating PTFs for the soils on which they are to be used and at the scales at which land surface models are applied (rather than on small-scale soil samples) will ultimately improve the performance of land surface models, potentially leading to improvements in flood, drought and climate projections.

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# Clays are not created equal – effects of clay mineral type on soil hydraulic and mechanical properties

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Clay minerals dominate the soil colloidal fraction and often carry the largest specific surface area – a property that controls various soil hydraulic and mechanical properties (SHMPs; e.g. water retention, permeability, and internal friction). Differences in microscale structure among clay mineral types in tropical and temperate regions affect the specific surface area and result in higher permeability and internal friction angle values for tropical soils with inactive kaolinite clay minerals. Presently, the soil clay size fraction used to parameterize SHMPs with pedotransfer functions (PTFs) ignores clay mineral type, leading to inconsistent parameter representation. In this study, we present new PTFs informed by clay minerals, enabling enhanced estimation of friction angle and saturated hydraulic conductivity. To capture higher conductivity and lower air entry values in tropical soils, we developed a hierarchical packing model and validated this new PTF approach using literature data from various tropical regions. We leveraged recent global maps of clay minerals to demonstrate that a strong climatic and spatial segregation of active and inactive clays enable spatially resolved consideration of clay mineral type in SHMP estimation. We applied these clay-informed PTFs to improve SHMP representation regionally with implications for a wide range of hydrological and geomechanical Earth surface processes.

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# Quantifying the effect of post-wildfire soil water repellency on runoff

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Several factors are believed to contribute to post-wildfire flooding and debris flows. One contributing factor—the occurrence of post-wildfire soil water repellency—lacks a quantitative mechanism to incorporate the effects in physically-based runoff models. For this study, a physically-based model was developed linking the contact angle (degree of water repellency) to sorptivity. The model was verified in laboratory experiments using a silica sand proxy. The effects of water repellency on infiltration were illustrated. Further, the effect of water repellency on runoff was simulated using the AGWA-KINEROS2 watershed model with data from rainfall following the 2009 Station fire in the San Gabriel Mountains of southern California, USA. Results show water repellency has a quantifiable effect on runoff production, an effect enhanced by the dry soil moisture conditions common after wildfires.

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# A Pore Scale Characterisation of Plant Mucilage - Integrating Imaging, NMR, and Polymer Modelling

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Plant roots secrete polymeric gels during root growth known as mucilage, which aid in root growth, nutrient acquisition, and water retention. Mucilage plays an important role in augmenting many soil physical and biogeochemical processes local to the root zone. However, most studies infer the effects of mucilage by reporting changes in the bulk soil. This investigation quantifies the isolated physical behaviour of plant mucilage in a highly simplified soil-analogous environment. We placed drops of hydrated mucilage between two flat surfaces to form liquid bridges and monitored their evolution under drying conditions considering different mucilage mass fractions. We used this information to develop a multi-phase model that characterises the mucilage-water interactions based on a polymeric description of the mucilage volume fraction. Unlike pure water liquid bridges that rupture, the hydrated mucilage liquid bridges collapsed under drying, but maintain connection between the surfaces. NMR imaging shows loss of water from the liquid bridge, particularly from the regions furthest from the surface contacts. Model of drying liquid bridges quantifies mucilage accumulation near the corners of the boundary where the adherence to surfaces is likely to occur. The modelled accumulation times overlapped with monitored bridge collapse for the different mass fractions. Consistency with the model and measurement results highlight the model's ability to predict a transition when the hydrated mucilage mixture no longer behaves like a liquid. Results suggest that diffusion type models are not adequate for describing pore scale mucilage transport processes, indicating that mucilage's zone of influence is local to the root, and the transition out of this zone is spatially sharp.

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# Modelling the effects of fertiliser solubility and soil buffer power on phosphorus uptake by spring wheat using an image-based approach

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Phosphorus (P) is critical for plant growth and can limit crop yields, but rock phosphate (the primary source of agricultural P) is a finite resource which is predicted to run out within 50-250 years. However, since P is important for short-term yield gains, it is often over-applied, causing run-off and water pollution. It is crucial to apply the right fertilisers at the most efficient rate, time, and place to protect our food security and environment for the future.

Optimal application requires an understanding of the processes affecting P availability to plants. Fertilisers range from soluble in water (e.g TSP) to only slightly soluble (e.g. struvite). However, experiments testing the efficacy of fertilisers with different solubilities have reached variable results. Standard soil testing methods sample at fixed time points, while the dissolution, diffusion, sorption and uptake of P are dynamic processes, so to make predictions we must understand those dynamics.

We used image-based modelling to investigate the predicted effects of dissolution rate and soil buffer power on P uptake by spring wheat root systems taken from X-ray CT images. We added a P source to represent a fertiliser granule and modelled the predicted P uptake based on 1 day, 1 week, and 14 week dissolution of the same amount of P for two realistic soil buffer powers.

We demonstrated that rapid dissolution increased short-term root uptake, but dissolution over 1 week did not differ from dissolution over 1 day. We also found that root system architecture has a large effect on the efficiency of a P fertiliser pellet, highlighting the importance of application location. These results provide a starting point for predictive modelling of the efficacy of different P fertilisers in different soils, and our image-based approach gives the ability to add different root architectures for different species or varieties.

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# A Model and Image Based Investigation of *X. fastidiosa* Within Host Dynamics

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Photosynthesis relies on the transport of water and sugars from roots to leaves facilitated by two key tissues: xylem and phloem. Blockages in the xylem/phloem, either by structures formed by the pathogen itself or those formed by the plant as a defence mechanism, disrupt the soil-plant-atmosphere continuum and cause many vascular plant disease symptoms. *Xylella fastidiosa* (*X. fastidiosa*) is a bacterium that colonises internal plant vascular networks causing pathogenic effects on several commercially important crops, including those associated with the olive quick decline syndrome causing devastating olive decline in Apulia, Southern Italy. Despite a growing research effort since the recent detection of *X. fastidiosa* in Europe, the exact processes leading to *X. fastidiosa* disease symptoms are not fully understood due to difficulties in observing internal plant structures.

Our goal is to utilise models to elucidate fundamental processes that lead to olive quick decline syndrome. We are developing a mathematical model describing within-host biofilm development that predicts water-stresses that ultimately inhibit plant functionality. Our approach is centred on the assumption that the biofilm structure is determined by the arrangement of extracellular polysaccharide (EPS) molecules, and as such, our model contains a polymer-physical description of *X. fastidiosa* biofilm formation dynamics. We used our model, requiring minimal empirical assumptions, to replicate biofilm aggregation observed by microfluidics. We have also produced X-ray Computed Tomography (XCT) images of vascular networks in both resistant and susceptible olive cultivars. We are using these images to test whether susceptibility is correlated with morphological differences that might influence fluid flow through the plant. This work improves the understanding of possible cultivar resistance mechanisms to aid informed breeding and orchard management, and model simulations will provide insights for understanding xylem blockages and their relation to observed symptom severity.

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# A Wind Tunnel Simulation of Windproof Effectiveness of Simulated Shrubs with Different Spatial Configurations

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A better understanding of the distribution of the airflow field and wind velocity around the simulated shrubs is essential to provide optimized design and maximize the efficiency of the windbreak forests. In this study, a profiling set of Pitot Tube was used to measure the airflow field and wind velocity of simulated shrubs by wind tunnel simulation. The effects of form configurations and row spaces of simulated shrubs on windproof effectiveness were in-depth studied. We come to the following results: The weakening strength to wind velocities of hemisphere-shaped and broom-shaped shrubs at 26.25 cm was mainly concentrated below 2 cm near the root and 6-14 cm in the middle-upper part, while the spindle-shaped shrubs were at 0.2-14 cm above the canopy, which meant the windproof effect of spindle-shaped shrubs was was better than that of hemisphere-shaped and broom-shaped. With the improvement of row spaces, the weakening height to wind velocities of the hemisphere-shaped shrubs at 35 cm was only concentrated below 2 cm near the root exclude for the 6-14 cm at 26.25 cm, which presented the hemisphere-shaped shrubs were not suitable for the layout of wide row space. Further, the form configurations of simulated shrubs had a stronger influence on wind velocity than row spaces. Moreover, the designed windbreaks with *Nitraria tangutorum*, which more effectively reduced the wind velocity among the windbreaks compared to behind the windbreaks. In the wind control system, the hemisphere-shaped windbreaks should be applied as near-surface barriers, and the windbreaks of broom-shaped and spindle-shaped can be used as shelterbelts above the near-surface. These analytical findings offer theoretical guidelines on how to arrange the windbreak forests for preventing wind erosion in the most convenient and efficient ways.

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# Modelling coating cohesion effect on soil mechanical stability and permeability of the biopore - matrix interface pore region

**Luis Alfredo Pires Barbosa** and Horst H. Gerke

Biopore surface is often characterized by finer particles and increased concentration of polysaccharides from root and earthworm exudates, presenting physico-chemical properties different from those of the soil matrix. Such exudates controls not only the wettability or sorption properties but also the adhesive forces of the surrounding soil particles. Thus, increased mechanical stability may be expected on biopore-matrix interface affecting preferential flow and transport processes, as well.

However, it is still unknown (i) to what extent the particle cohesion in the coated region is able to increase the resilience of the biopore to an external loading and (ii) how it affects the permeability of the biopore-matrix pore region.

We created a discrete element model (DEM) model of a hollow cylindrical soil sample with a coated biopore in the center (i.e., 1 cm height, 1 cm outer and 0.6 cm inner diameter). The spherical particles in the model presented diameter of 0.13 mm for the coated material and 0.22 mm for the soil matrix. The cohesion among particles in the soil matrix was set to a constant value of 10.9 MPa while the cohesion among particles in the coated region varied between 10.9 and 50.9 MPa. The sample was subjected to axial compression and the force and cracks recorded. The permeability in the radial direction from the biopore to soil matrix was calculated using ImageJ and a 3D stokes solver (FDMMS).

The increment in the coating cohesion increased the overall soil stiffness in terms of the Young's modulus. Before axial compression, the calculated hydraulic permeability for the interface coating and matrix was 182 $\mu m^2$. After compression, although the lower coating cohesion resulted in a larger number of cracks, permeability increased with coating cohesion. This suggests that with increasing soil stiffness, the cracks decrease in number but increase in length (i.e. improved connectivity).

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# Same soil - different climate: crop model inter-comparison with lysimeter data of translocated monoliths

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Crop model comparisons have mostly been carried out to test predictive ability under previous climate conditions and for soils of the same location. However, the ability of individual agricultural models to predict the effects of changes in climatic conditions on soil-ecosystems beyond the range of site-specific variability is unknown. The objective of this study was to test the predictive ability of agroecosystem models using weighable lysimeter data for the same soil under changing climatic conditions and to compare simulated plant growth and soil-ecosystem response to climate change between these models. To achieve this, data from the TERENO-SOILCan lysimeters-network for a soil-ecosystem at the original site (Dedelow) and data from the lysimeters with Dedelow soil monoliths transferred to Bad Lauchstädt and Selhausen were analysed. The transfer of the soils took place to a drier and warmer location (Bad Lauchstädt) and to a warmer and wetter location (Selhausen) compared to the original location of the soils in Dedelow with the same crop rotation. After model calibration for data from the original Dedelow site, crop growth and soil water balances of transferred Dedelow soil monoliths were predicted using the site-specific boundary conditions and compared with the observations at Selhausen and Bad Lauchstädt. The overall simulation output of the models was separated into a plant-related part, ecosystem-productivity (grain yield, biomass, LAI) and an environmental part, ecosystem-fluxes (evapotranspiration, net-drainage, soil moisture). The results showed that when the soil was transferred to a drier region, the agronomic part of the crop models predicted well, and when the soil was moved to wetter regions, the environmental flow part of the models seemed to predict better. The results suggest that accounting for climate change scenarios, more consideration of soil properties and testing model performance for conditions outside the calibrated range and site-specific variability will help improve the models.

**crop-soil modelling initiative**: Jannis Groh (1,2), Efstathios Diamantopoulos (3), Xiaohong Duan (4), Frank Ewert (1), Florian Heinlein (4), Michael Herbst (2), Maja Holbak (3), Bahareh Kamali (1), Kurt-Christian Kersebaum (1,5), Matthias Kuhnert (6), Claas Nendel (1), Eckart Priesack (3), Jörg Steidl (1), Michael Sommer (1), Thomas Pütz (2), Jan Vanderborght (2), Harry Vereecken (2), Evelyn Wallor (1), Tobias K.D. Weber (7), Martin Wegehenkel (1), Lutz Weihermüller (2), Horst H. Gerke (1) - (1) Leibniz Centre for Agricultural Landscape Research (ZALF), Müncheberg, Germany (2) Forschungszentrum Jülich GmbH, Agrosphere, Institute of Bio- and Geoscience IBG-3, Jülich, Germany (3) Department of Plant and Environmental Science, University of Copenhagen, Copenhagen, Denmark (4) Helmholtz Zentrum München□German Research Center for Environmental Health, Neuherberg, Germany (5) The Czech Academy of Sciences, Global Change Research Institute, Brno, Czech Republic (6) Institute of Biological and Environmental Science, University of Aberdeen, Aberdeen, United Kingdom (7) Institute of Soil Science and Land Evaluation, University of Hohenheim, Stuttgart, Germany

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# J-DISTAS: predict field readiness to ensure efficiency of field operations and avoid soil compaction.

**Marine Lacoste**[1], Hocine Bourennane[1], Mathieu Lamandé[2,3], Clément Dupré[4], Annie Duparque[4], Damian Martin[4], Guillaume Brisset[5], Rémy Duval[5], Pierre Descazaux[6], Myriam El Adas[7], and Pascale Métais[7]

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Sustainable crop production implies high efficiency of field operations and protection of the soil as a natural resource. Soil physical fertility is threatened by compaction, especially deep soil horizons for which remediation is more critical. Increased soil compaction, linked to the increase of agricultural equipment weight, causes yield losses on spring and summer crops. To avoid soil compaction and ensure field operations efficiency, including satisfactory crop production in a cost-effective way, field readiness prediction is necessary. Field readiness is defined by the combination of soil workability (soil suitability for cultural operations) and soil trafficability (soil capacity to support machinery during traffic without soil physical degradation).

Available tools focused on one part of the problem, e.g. soil compaction risk in deep soil horizon, or possibility of efficient field operation ; each has usually been built for a specific pedoclimatic context, which questions its application in a broader context. Available tools also frequently need to be upgraded to better consider compaction risk according to machinery evolution.

The J-DISTAS project (2019-2022) aims at evaluating and improving these tools, and structuring them to create a prototype of interoperable tools to predict field readiness. The resulting tool will be based on the combination of two mechanistic models (Terranimo for soil compaction and the CHN crop model for soil water content), pedotransfer functions to estimate soil water potential and soil workability, and a decisional tool of field readiness build from expert knowledge. Its ability to predict field readiness and its sensibility to input data will be evaluated.

The developed inter-operable tools could be used as a decision support tool that includes field readiness in strategic decisions, conception of cropping systems in the context of global changes, or optimization of mechanical cost for equipment in agricultural machinery, and will help to soil physical quality protection.

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# Evaluating the interaction of biofilms, organic matter and soil structures at the pore scale

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Key functions of soils, such as permeability or habitat for microorganisms, are determined by structures at the microaggregate scale. The evolution of elemental distributions and dynamic processes can often not be assessed experimentally. So mechanistic models operating at the pore scale are needed.
We consider the complex coupling of biological, chemical, and physical processes in a hybrid discrete-continuum modeling approach. It integrates dynamic wetting (liquid) and non-wetting (gas) phases including biofilms, diffusive processes for solutes, mobile bacteria transforming into immobile biomass, and ions which are prescribed by means of partial differential equations. Furthermore the growth of biofilms as, e.g., mucilage exuded by roots, or the distribution of particulate organic matter in the system, is incorporated in a cellular automaton framework (CAM) presented in [1, 2]. It also allows for structural changes of the porous medium itself (see, e.g. [3]). As the evolving computational domain leads to discrete discontinuities, we apply the local discontinuous Galerkin (LDG) method for the transport part. Mathematical upscaling techniques incorporate the information from the pore to the macroscale [1,4].
The model is applied for two research questions: We model the incorporation and turnover of particulate OM influencing soil aggregation, including 'gluing' hotspots, and show scenarios varying of OM input, turnover, or particle size distribution.
Second, we quantify the effective diffusivity on 3D geometries from CT scans of a loamy and a sandy soil. Conventional models cannot account for natural pore geometries and varying phase properties. Upscaling allows also to quantify how root exudates (mucilage) can significantly alter the macroscopic soil hydraulic properties.

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# Responses of bacterial communities to spatial distribution and biogeochemical migration in Panzhihua mining tailing

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Heteropogon contortus were the domiant plants in Panzhihua mining tailing due to the characteristic of drought-enduring and toxicity resistance. The aim of this work was to determine the effects of the successive planting of Heteropogon contortus on soil characteristics, including heavy metals contents and biogeochemical migration. Spatial distribution of heavy metal and enzyme activity in surface soils and rhizosphere soil as well as responses of bacterial community were systematically researched. In the meanwhile, High-throughput 16s RNA sequencing results indicated that the abundance and diversity of bacterial communities from different altitude locations were quite diverse in soil samples. The contents of some heavy metals and enzyme activity markedly affected on the structures of bacterial communities surface soils and rhizosphere soil. The most abundant bacterial communities were Actinobacteria (29.74 %), Proteobacteria (28.06 %), Chloroflexi (13.73%) in phylum level in the original soil samples. The abundance of Proteobacteria (19.87 %, 27.57 %, 29.35 %) and Patescibacteria (1.56 %, 1.83 %, 2.66 %) of non-rhizosphere soil was gradually increased along with the increasing latitude, which is just the opposite rule to the abundance of Acidobacteria (17.19 %, 14.58 %, 11.77 %) and Gemmatimonadetes (4.61 %, 3.17 %, 2.86 %). Results in this study emphasized the heavy metal contaminations in soils and rhizosphere soil, providing valuable information on how heavy metal contamination influences soil bacterial communities across a chronosequence spanning 50 years.

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# Modeling water and nutrient uptake by crops: simulate uptake to predict growth or simulate growth to predict uptake?

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We developed root scale models that simulate water and nutrient uptake by crops. Water flow in the soil and root systems was linked in order to describe root water uptake as a function of root properties and distributions, soil and leaf water potentials. One of the underlying motivations is to predict the crop water stress level and its impact on transpiration and growth. The mechanistic description of water fluxes resulted in models that were sensitive to hydraulic properties of the root system, including root density, and root distribution with depth. These sensitivities improved predictions of crop water uptake and water stress in different soils and for different water treatments. Crucial was the correct representation of the root system and its response to different 'treatments'. Thus, in order to predict the impact of water stress on growth, the growth response to the water stress must be predicted. So far, these response functions and especially the distribution of carbon within the plant to the different plant organs are empirical functions. A coupled carbon and water flow model within the plant is a way forward to more mechanistic descriptions of these responses. A similar storyline can be developed for nutrient uptake. Mechanistic nutrient uptake models do not consider nutrient transport within the root system but focus on transport towards the root surface. Multi-scale flow and transport simulations demonstrated that small scale transport towards growing root tips and root system scale water and nutrient distributions controlled nutrient uptake. These simulations predicted the observed interaction between water and phosphate uptake of an upland rice crop. However, here again, simulated uptake depended on the root development in response to nutrient and water stress. Mechanistic descriptions of root growth response to nutrients require a further understanding of plant physiological processes that cause these responses.

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# Using natural abundances of stable water isotopes to constrain vertically distributed root water uptake of forest trees

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The water balance in forest soils is strongly affected by vertical distribution of root water uptake. Our objective is to constrain the parametrization of root water uptake in the field by using the naturally occurring, seasonal variability in stable isotope signatures in precipitation to trace water fluxes through the soil and into the trees.

The 1D soil hydrologic model LWFBrook90.jl contains the necessary processes to accurately reproduce hydrometric observations of volumetric soil moisture content and soil matric potential at forest sites in Switzerland. Root water uptake is described with a gradient-driven model using vertically varying root density and moisture-dependent rhizosphere resistivities. The hydrologic model will be extended with transport and fractionation processes to enable the modeling of isotopic signatures in soil and tree water.

We present a planned field sampling campaign over two subsequent vegetation seasons at 10 long-term monitoring forest sites. Soil water is sampled with lysimeters at four soil depths, and tree water is sampled from the xylem with increment corers. Both types of samples are taken bi-weekly. First results from an ongoing multi-year soil water sampling campaign show that the signal can be traced along the soil profile and are presented to illustrate the approach.

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# Spatiotemporal assessment of phosphorus release from a fertiliser granule and its diffusion into bulk soil: a combined experimental and modelling study

**Chiara Petroselli**, Katherine A. Williams, Arpan Ghosh, Daniel McKay Fletcher, Siul A. Ruiz, Tiago Gerheim Sousa Dias, Callum P. Scotson, and Tiina Roose
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Phosphorus (P) is a limiting nutrient for crops and it is therefore highly managed in human activities such as agriculture. Not only the global phosphate rock reserves are going to be exhausted in a century, but P can also be lost from fields with the runoff ending up contaminating water bodies and causing eutrophication.

This study is aimed at investigating P release from a fertiliser granule at high spatial and temporal resolution to optimise fertilisation timing, match crop requirements and reduce runoff. Experimental data consist of time-resolved P concentration in the soil solution at three different depths and total P concentration profile determined via total soil digestion. We observed a rapid, single-pulse release of P from the fertiliser granule shortly after soil wetting (<2h). The pulse reaches the furthest probe (3 cm) within the same timeframe, then P concentration in the soil solution gradually decreases over the following 150 hours due to adsorption.

As the experimental data did not match the model-predicted P diffusion behaviour, a new modelling approach was used to reproduce the data. The model accounts for P diffusion and adsorption onto soil particles, resulting in the temporal evolution of P concentrations both in the soil solution and adsorbed onto soil particles. As the final total P concentration in soil reflects the initial P concentration profile in the soil solution, the model shows that adsorption onto soil particles happens faster than diffusion. Additionally, the model gives an estimate of diffusion, adsorption and desorption rates, as well as the maximum distance that P can travel from the source.

Combining high-resolution experiments with modelling provided a new insight into P release and diffusion from a fertiliser granule. The results can inform optimal fertilisation timings to improve crop yields while reducing P application rates and undesirable side effects such as eutrophication.

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# A computational history and outlook of nitrogen use efficiency and precipitation-optimal fertilisation timings in agriculture

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Half of the nitrogen applied to arable-fields is lost through several processes linked to soil moisture. Low soil moisture limits nitrogen mobility reducing nitrogen-uptake while wetter conditions can increase nitrogen leaching. Rainfall ultimately governs soil moisture and the fate of nitrogen in soil. However, the interaction between rainfall and nitrogen use efficiency (NUE) remains poorly understood.

We developed a field-scale modelling platform that describes coupled water and nitrogen transport, root growth and uptake, rainfall, the nitrogen-cycle and leaching to assess the NUE of split fertilisations with realistic rainfall patterns. The model was solved for every possible split fertilisation timing in 200+ growing seasons to determine optimal timings. Two previous field trials regarding rainfall and NUE had contrasting results: wetter years have enhanced fertiliser loss and drier years reduced plant nitrogen uptake. By choosing appropriate fertilisation timings in the model we could recreate the two contrasting trends and maintain variability in the data. However, we found by choosing other fertilisation timings we could mitigate the leaching in wetter years. Optimised timings could increase plant nitrogen uptake by up to 35% compared to the mean in dry years. Plant uptake was greatest under drier conditions due to mitigated leaching, but less likely to occur due to low nitrogen mobility. Optimal fertilisation timings varied dramatically depending on the rainfall patterns. Historic and projected rainfall patterns from 1950-2069 were used in the model. We found optimal NUE has a decrease from 2022-2040 due to increased heavy rainfall events and optimal fertilisation timings are later in the season but varied largely on a season-to-season basis.

The results are a step towards achieving improved nitrogen efficiency in agriculture by using the ‘at the right time’ agronomic-strategy in the ‘4Rs’ of improved nitrogen fertilisation. Our results can help determine nitrogen fertilisation timings in changing climates.

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# The extended transfer function model for the simulation of pesticides transport along the unsaturated zone

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The scope of this work is to present the extended transfer function model (TFM-ext) that allows to simulate the spatio-temporal distribution of nonpoint-source pollutants, e.g., pesticides, along the unsaturated zone, till the groundwater table depth.

The model is based on the transfer functions approach, i.e., on the travel time probability density functions (TT pdfs), which describe the leaching behavior in a given soil profile. The strength of the model, despite the important assumptions on time-invariant TT pdfs and steady-state input fluxes, is that it derives the TT pdfs from a physical quantity, i.e., the unsaturated hydraulic conductivity function k(θ). Moreover, the model extends the transport process to the generic depth z, where information on hydraulic properties could not be available, assuming a lognormal travel time pdf, whose parameters are scaled according to the generalized transfer function model. In the case of reactive solutes, the model considers both the mass decay and the retardation factor.

The TFM-ext was validated in Valle Telesina, a hilly area of around 200 $km^2$ in Italy. Forty-six soil profiles, completely characterized from the hydrological point of view, were used to evaluate the mean travel times and the breakthrough curves at the groundwater depth and then compared with the results of a physically based model, Hydrus 1D. Results gave very high correlation coefficients (above 0.8), a mean absolute error of around 40 days and a percent bias of -16%.

Moreover, a comprehensive sensitivity analysis to evaluate to which parameters the TFM-ext is more sensitive, was performed. Results shown that τ anf $\theta_s$ parameters related to the slope of the k(θ) are those affecting more the travel time.

The model was implemented as an operative tool for the specific groundwater vulnerability assessment within the geospatial Decision Support System developed for LANDSUPPORT H2020 project.

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# Soil functions modelling at global scale using SoilGrids 2.0

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Soils provide a variety of goods and services and are a key natural resource, non-renewable on the time scale of a human life-span, to realise several UN-Sustainable-Development–Goals, including zero hunger (SDG2), climate action (SDG13) and life on land (SDG15). Consistent soil information is required to underpin a large range of global assessments, such as soil and land degradation, sustainable land management, and environmental conservation. In this study, we present an application addressing the modelling of soil functions at global scale, using erosivity risk and soil carbon sequestration potential as examples. We used SoilGridsv2.0, as set of soil property maps at 250m resolution, derived from a large set of standardized soil profile observations (WoSIS), an updated set of environmental covariates, and improved machine learning models. It provides global assessments of prediction uncertainty, quantified with a 90% prediction interval, and considers an evaluation procedure that provides more realistic metrics of map accuracy. We used simplified models to derive soil functions (e.g. erosivity or carbon sequestration potential) from basic soil properties, meaningful for different pedo-climatic regions. We provide an indication of areas of low/high risk of soil degradation to support sustainable soil management planning. The uncertainty limits of the input soil layers were used to provide a preliminary assessment of the uncertainty of the derived layers. The present modelling framework, using soil properties maps to derive soil functions, offers great flexibility and may be applied to a diverse set of models to generate soil information products tailored to specific applications. We highlight some of the challenges of assessing soil functions at global scale.

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# Source apportionment of heavy metal pollution in farmland soils on a regional scale using geographically weighted PCA

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Source apportionment of soil heavy metals is an challenge and urgent work as the result of the rapid development of industrialization and urbanization. The common approach is multivariate statistical analysis, such as PCA and APCS/MLR, which infers only a single pattern of sources of heavy metals in entire study area. Due to complicated pathways and processes, patterns of pollution sources in a whole region may include two or more. Hence, we developed an analytical framework based on GWPCA to explore multiple patterns of sources of soil heavy metals on a regional scale. Xiangtan county, an important grain-producing area in China, was taken as a case study, which suffers the problem of heavy metal pollutions. Our results revealed the pollution situations of five soil heavy metals(Pb, Cd, As, Cr and Hg) in farmland soils and suggested that there exists various pollution patterns of these heavy metals in Xiangtan county. In each pattern, the structure of contamination sources is different. Our study also indicates that the analytical framework considering the spatial heterogeneity of pollution sources can help take more precise practices to solve this vital problem.

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# Using digital soil hydraulic maps to simulate water balance at the regional scale (southern Portugal) - impact of spatial resolution and modelling approach

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Modelling of soil physical, chemical, and biological processes is critical to improve the understanding of soil functions, the effect of agricultural practices on soil degradation, and appropriate soil management strategies. However, the use of such tools at the regional scale is largely limited by the lack of accurate mapping of soil texture and soil hydraulic properties (SHP). To overcome this limitation, SHP digital maps were obtained using two modelling approaches. One used a national harmonized soil texture database and geostatistical simulation to create soil texture maps which were further used as input data to derive SHP maps using local pedotransfer functions (PTFs). The other approach used SHP maps produced by Tóth et al (2017) using soil texture from the product SoilsGrids (Hengl et al, 2017). The SHP maps from both approaches were produced at two spatial resolutions: 250 m and 1000 m. This study aims to evaluate the usefulness of such SHP maps to simulate soil water dynamics and biomass growth at the regional scale using the MOHID-Land model. This model describes the movement of water in the porous medium based on mass and momentum conservation equations that are computed in a 3D grid domain using a finite volume approach. Crop development is simulated using a modified version of the EPIC model. The SHP maps produced using the two modelling approaches and considering two spatial resolutions (250 and 1000 m) were used as inputs for the hydraulic characteristics of soils. Simulations were compared for an irrigation area (Roxo Irrigation District), located in southern Portugal. Results revealed the differences in the components of the soil water balance, with soil inputs from local data being able to better portray landscape heterogeneity.

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# Using a combined global and local scaling 3D segmentation method to calculate pore connectivity measures in CT soil images

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The study of the spatial characteristics of soil pore networks is essential to obtain different parameters that will be useful in developing simulation models for a range of physical, chemical, and biological processes in soils. Over the last decade, major technological advances in X-ray computed tomography (CT) have allowed for the investigation and reconstruction of natural porous soils at very fine scales. Delimiting the pore network (pore space) from the CT soil images applying image binarization methods is a critical step. Different binarization methods can result in different spatial distributions of pores influencing the connectivity metrics used in the models.

A combined global & local 2D segmentation method called "Combining Singularity-CA method" was successfully applied improving pore space detection. This method combines a local scaling method (Singularity-CA method) with a global one (Maximum Entropy method). The Singularity-CA method, based on fractal concepts, creates singularity maps, and the CA (Concentration Area) method is used to define local thresholds that can be applied to binarize CT soil images. Combining Singularity-CA (2D) method obtains better performance than the Singularity-CA and the Maximum Entropy method applied individually to the soil images.

A new three dimensional binarization method is presented in this work. It combines the 3D Singularity-CV (Concentration Volume) method and a global one to improve 3D pore space detection. Porosity and connectivity metrics of soil pore spaces are calculated and compared to other segmentation methods.

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# Recent developments in the HPx-codes for coupled reactive transport in porous media

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Coupled reactive transport codes are indispensable tools for simulating the fate of solutes in porous media for both environmental and engineering applications. HP1 and HP2/3 are some of the most versatile tools for coupled processes of variably-saturated water flow, multicomponent solute transport, heat transfer, and equilibrium-kinetic chemical reaction networks (Jacques et al., 2018). To date, multiple extensions are included that significantly increase the flexibility of the HPx codes. In addition to the default PHREEQC geochemical solver, HPx provides alternatives for the geochemical step: the geochemical solver ORCHESTRA (Meeussen, 2003) or direct scripting. The ORCHESTRA solver is relatively small and efficient and comes with a large set of user definable adsorption models, including the NICA-Donnan model. The choice of the scripting language has been extended from the classical BASIC scripting language to the structured, prototype-based programming variant of BASIC and Python. The latter gives the possibility to include several libraries of Python immediately in the HPx based models. For example, machine learning techniques can replace computationally expensive geochemical calculations to speed up the calculations. The HPx code is also coupled to the MT3D-USGS code, the groundwater solute transport simulator for MODFLOW. Via the MODFLOW-HYDRUS1D integration, soil flow and transport processes can be integrated as an unsaturated zone component into MODFLOW and MT3D-USGS. The last change is the updated graphical user interface (GUI) for the geochemical model input and post-processing output, incorporated in the standard HYDRUS GUI. Besides, a stand-alone GUI version is available as an advanced interface for geochemical calculations with PHREEQC.

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# Regional risk assessment of acid sulfate soil acidification under climate change based on mechanistic modelling of pyrite oxidation during prolonged drought events

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Under changing climate conditions with expected higher risks on long periods of severe drought events, acid sulfate soils have a higher risk for acidification when exposed to oxygen under a falling water table. A regional or continental risk map for acidification under possible future climate scenarios is one of the tools for evaluating agricultural, economic and environmental impacts of acidification. The starting point is a simulation model with the relevant processes accounting for (i) the effect of changing meteorological boundary conditions on the water dynamics inside the soil and the ground water depth, (ii) diffusion of oxygen inside the soil profile, and (iii) kinetic dissolution of pyrite and geochemical alterations. The simulation tool HPx (Jacques et al., 2018) couples all these processes and enables to evaluation of different model structures. Numerical results were compared to an extreme drought event in the lower Murray River region, Murray-Darling Basin South Australia, between 2007 and 2010. A second step was the implementation of the mechanistic model in a spatial framework using python. As a proof of principle, we started with 5 x 5 km grid in areas with high probability of acid sulfate soils. Soil spatial data was pre-processed to determine model hydraulic parameters using pedotransfer functions. Climate and soil data were defined for each grid cell and formatted at run time for input into HPx. HPx simulations are controlled for the specific data for each grid cell. The final step is to perform the simulations on large spatial and temporal scales using supercomputing for which a linux-version of HP1 was developed. These developments open up new opportunities for coupled soil-climate modelling.

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# Coupling unsaturated and saturated zone reactive transport : Development and benchmarking of the MTHP tool

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MTHP stands for **M**odflow **T**ransport **H**ydrus **P**hreeqC and aims to provide an effective coupling tool for simulating reactive transport in the unsaturated and saturated zones. It builds upon the existing codes HYDRUS-1D (Šimůnek et al., 2013) / HP1 (Jacques et al., 2018), MODFLOW (Harbaugh, 2005), MT3D-USGS (Bedekar et al., 2016) and PhreeqC (Parkhurst and Appelo, 2013).

Two-way coupling between HYDRUS 1-D and MT3D-USGS has been implemented. HYDRUS-1D provides a mass flux of solute to the topmost saturated cell in MT3D-USGS. After one time step of solute transport has been solved in groundwater, the resulting solute concentration profile in the saturated zone is updated in HYDRUS. The code has been benchmarked against HYDRUS for a 1-D case but still requires to be adapted for 2 and 3-D cases when solute concentrations change in the unsaturated zone following lateral transport in groundwater.

Coupling PhreeqC to HYDRUS 1-D was already implemented within HP1. Simulating geochemical reactions in the aquifer required coupling MT3D-USGS to PhreeqC. This has been implemented by adding a new module MCP (**M**ulti**C**omponent **P**ackage) to the MT3D-USGS code using a similar versatile approach as in HPx. MCP has been successfully benchmarked against examples from the similar PHT3D code (Prommer and Post, 2010).

An application of this new module MCP for the simulation of redox plume development from a landfill, is presented. In this case study, reactive transport in the unsaturated zone is not included (i.e. only the MT3D-USGS – PhreeqC coupling is used), as the contamination source is suitably conceptualized to be at the water table surface. Kinetic degradation of dissolved organic carbon (DOC) in the presence of several electron acceptors is simulated. Observations of ion concentrations at different points in space and time are used to calibrate the MTHP simulations and investigate what is the acceptable level of process and parameter simplification.

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# Simulating Preferential Flow by A Multi-dimensional Process-based HYDRUS Model

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Preferential flow (PF) processes are controlled by subsurface structures with a hierarchical organization across scales, but there is a lack of multiscale model validation using field data. In this study, a comprehensive dataset collected in the forested Shale Hills catchment was used to test and validate PF simulations with the 2-dimensional HYDRUS-2D model at the hillslope scale. The simulations were also compared with the 1-dimensional results at the pedon scale (HYDRUS-1D) and 3-dimensional results at the catchment scale (HYDRUS-3D). There was a good agreement between the 1D simulations and soil moisture measurements, which were mainly affected by the vertical change in porosity/permeability with depth and precipitation characteristics. However, short-term fluctuations due to PF were poorly captured. Notably, 2D and 3D simulations, accounting for PF controlled by slope position and shallow fractured bedrock, provided better results than the 1D simulations. The dual-porosity or anisotropic model provided more accurate soil moisture predictions than the single-porosity or isotropic model due to the more realistic representation of local soil and fractured shale. Consequently, our study shows the importance of multi-dimensional model approaches and the need to adequately represent the bedrocks' soil structure and fractured nature for the PF simulation. The multi-dimensional modeling approaches can represent PF pathways to the first-order stream and shows the benefits of the 3D simulation with detailed information to identify the dominant hydrological process.

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# Modelling soil carbon under diverse cropping systems and farming management in contrasting climatic regions in Europe

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Sustainable agriculture has been identified as key to achieve the 2030 Agenda for Sustainable Development Goal aiming at ending poverty and hunger, and addressing climate change, while maintaining natural resources. Soil organic carbon (SOC) sequestration is an important soil functions for the ecosystems service, and storing carbon (C) in soil by changing traditional management practices can represent an important step towards the development of more sustainable agricultural systems in Europe. Within the European project *Diverfarming,* the process-based ecosystem model ECOSSE was modified and evaluated in three long term experiments to assess the impact of crop diversification and agricultural management in SOC dynamics. ECOSSE was able to simulate SOC under Mediterranean regions in Spain and Italy after changing the minimum value of the decomposition rate modifying factor for soil moisture and allowing a higher soil moisture deficit. In Spain the addition of manure and cover crop in the diversified systems produced an increase in SOC compared to the conventional management (6% in simulations, 2% in measurement) in eight years. The effect of tillage on SOC stock in the Italian dry soil was also modelled, and a positive impact on SOC was predicted when no tillage is practised. Finally, ECOSSE was used to understand the impact of diversifications in Finland where different proportions of legumes and grass were considered in four-year crop rotations compared to conventional cereal rotations. Experiments and modelling showed that the loss of SOC in conventional cereal was compensated when grass was introduced in the rotations. A good agreement (RMSE <10%) and a non-significant bias were observed between model and data for all sites. The modified ECOSSE was able to predict SOC under diverse cropping systems and farming management in contrasting climatic regions. Further studies linking SOC simulations to indicator of sustainability across various European pedoclimatic regions is ongoing.

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# Impact of Land Management on Available Water Capacity and Water Storage of Peat

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In Germany, more than 95% of peatlands have been drained for agriculture and forestry leading to water as well as carbon storage loss, soil degradation, and water eutrophication. Soil available water capacity (AWC) is one of the most important soil properties regulating the water balance and plays a pivotal role in plant growth. Compared with that of mineral substrates, our understanding of the impact of land management on water storage and the AWC of peat is limited. In this study, we aimed to deduce possible alterations of the AWC and water storage of peat following land drainage and rewetting. We analyzed a comprehensive database (674 measurements from boreal and temperate peatlands) to seek relations between bulk density (BD), field capacity, wilting point, and AWC. Bulk density was used as a proxy for soil degradation. The AWC increases with BD up to a value of 0.2 g $cm^{-3}$; a further increase in BD leads to a considerable decrease in AWC. The derived function between BD and AWC enables us to upscale the AWC to a regional scale. The average AWC of agricultural peatlands in Germany is estimated to be 37 ± 11 vol% (mean ± standard deviation). Currently, the water storage of agricultural peatlands in Germany is approximately 1.0 $m^3$ per $m^2$. We estimated that water storage in the natural peatlands in Germany was 33.8 $km^3$ prior to drainage. Converting natural peatlands into agricultural land resulted in a water storage loss of approximately 18.6 $km^3$. Several decades of peatland rewetting have a limited effect on water storage recovery due to a substantial loss of peat thickness because of former drainage and a low porosity of degraded peat.

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# Simulation of shale weathering by seasonal $O_2$ diffusion in a variably saturated soil

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A HPx model that jointly considered the flow, transport, gas diffusion and reactivity processes induced by exposure to the atmosphere of a recently excavated shale was used for the interpretation of a weathering experiment in a lysimeter. The lysimeter was filled with a mechanically disaggregated shale presenting preferential pathways for water and a hydraulic conductivity at saturation of 100 cm/day. The water content and the seasonal saturation and desaturation cycles were identified as the main driving mechanisms of shale alteration. The water content determined the diffusion of gaseous oxygen in the shale's unsaturated porosity, which gave rise to a zonation of the oxidation of pyrite, contained at 1 wt% in the shale. The oxidation of pyrite induces a release of sulphates, cations, iron and trace metals (Pb, Ni, Zn, Co, Cu and As). The acidification due to pyrite oxidation is buffered by calcite dissolution. While the formation of iron (oxy-)hydroxide is efficient for sorbing trace metals, whose content remained at low concentrations in the drainage water. Seasonal precipitation of gypsum during the summer desaturation at the top of the lysimeter was also identified. The hydraulic, chemical and mineralogical observations made in the lysimeters were reproduced using HPx reactive transport code under unsaturated conditions. It was possible to account for the gas diffusion where $O_2$ availability controlled the reactivity with the shale, depending on the meteorological conditions and the drainage at the base of the lysimeter.

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# Simulation of vegetation-soil water feedback in nemoral forests on hydromorphic soils with Hydrus-1D

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It is hypothesized that northern nemoral forests on hydromorphic soils in lowland settings can enter a feedback loop were enhanced evapotranspiration led to better soil aeration enhancing root water uptake and further increase of evapotranspiration. Opposite feedback could be possible as well – poor soil aeration due to water saturation hinders the root water uptake, resulting in overall decreased evapotranspiration and preservation of waterlogged state of the soil. The feasibility of the feedback loop is explored by a Hydrus-1D simulation using artificial climate forcing. It is suggested that wet or dry years can shift the vegetation-soil water system from wet to dry state and back. The research is supported by project No. 1.1.1.2/VIAA/3/19/524.

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# Modeling soil erosion with evolving rills on hillslopes

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Whereas current erosion models are successful in quantitative estimates of soil erosion by water flow, modeling the coevolution of geomorphological features, particularly rill network properties and soil erosion on hillslopes, is still a major challenge. In this study, we propose a rill evolution modeling approach, and combine it with a rainfall-runoff and soil erosion model to simulate the feedback loop of hillslope geomorphic development and soil erosion processes. Rill evolution is mainly characterized by three rill network attributes, comprised of rill density, orientation angle, and rill width, all modeled with physical equations. The entire rainfall-runoff-erosion and rill evolution model is tested against a set of rill network evolution and soil erosion data from an experimental hillslope subjected to successive rainfall events. The simulated spatial and temporal variations of rill network characteristics and soil erosion agree well with the measured data. The results demonstrate that the three rill network characteristics continually alter the partitioning of interrill and rill flows and affect the interrill and rill flow erosivity and soil erosion, which in turn modify the rill geometry and rill network planform. Comparatively, existing approaches such as WEPP that ignore the rill evolution processes largely underestimate the hillslope soil erosion when using time independent model parameters. Moreover, a sensitivity analysis indicates that both the rill evolution and soil erosion processes are sensitive to the rill evolution parameters, rainfall intensity, and slope angle. These results can inform the development of general geomorphic evolution and soil erosion models on evolving rilled hillslopes.

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# Tracer vertical movement and its affecting factors in karst soil profiles using the simulated leaching method

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Soil erosion is a severe issue in Southwest China due to complex karst geomorphology and excessive farming activities. It is also difficult to observe and evaluate using traditional research methods. Fortunately, as a supplement to traditional methods, the $^{137}Cs$ tracing technique has strong potential to monitor and evaluate soil loss in karst regions. However, $^{137}Cs$ might move downward with tiny particles under adequate rainfall conditions. This is critical because it directly affects accuracy of using the $^{137}Cs$ conversion model to evaluate soil erosion. Thus, in our study, in order to explore whether tracers actually moved vertically and to evaluate the movement distance and the factors influencing the movement, magnetic powder ($Fe_3O_4$) and rare earth oxides ($CeO_2$ and $La_2O_3$) were used as the substitute tracers under different conditions (rainfall and leaching area) of a simulated leaching experiment, which possess similar properties as $^{137}Cs$ and have no toxicity problems in humans and the environment. The results showed that tracers moved downward 6 cm when water was added to simulate 1-10-year rainfall conditions and 8 cm when water was added to simulate 15-20-year rainfall conditions. The movement distance of tracers increased slowly with increasing water input, and the concentration of the tracers that moved related indirectly to the leaching area. Tracer movement at the edge of the simulated profile was affected by tracer type and concentration since there was no transition layer between soil and plastic column. Our field observations in two karst watersheds showed that ignoring the vertical movement of tracer can cause the overestimation of soil loss amount by 6.90% and 22.22% respectively. This study proved that in the karst area of Southwest China with abundant rainfall, $^{137}Cs$ would move vertically, and the soil loss will be overestimated if the vertical movement distance of the tracer is ignored.

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# A thousand-year erosional and sedimentation history in karst watersheds based on OSL dating and palynological techniques

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Rocky desertification is a serious environmental issue in karst regions that restricts food production and hinders local economic development. Generally, soil loss is known as a dominant factor driving rocky desertification. However, it is difficult to couple rocky desertification with the soil loss rate based on a database from short-term field plot observations. Hence, it is imperative to reconstruct the history of soil loss over long-term periods and to correlate the rocky desertification process with the soil loss rate. In karst regions, the most common geomorphic landforms are closed peak-cluster depressions. Researchers have shown that estimating soil loss from hillslopes based on a sediment deposition rate in a peak-cluster depression is possible. In this study, two typical peak-cluster depressions with different degrees of rocky desertification were selected, and sediment cores with lengths of 2 m were sampled from the depressions to determine pollen taxa, soil properties and sediments dating at different depths.The results showed that the burial ages of the sediments in the depressions were different in the time series. During the past millennium, soil loss in the LJWD watershed showed an overall decreasing and then increasing trend. While the change in soil erosion was more complex in the DJT watershed, high and low rates appeared alternately in the 748±100 – 2018 period. The alluvial pollen analysis demonstrated that the soil erosion changes in both watersheds were closely related to human farming activities and vegetation landscape changes. The soil loss history over the past 1000 years was insufficient to reveal the evolution of rocky deserts in karst areas, indicating that the formation of rocky deserts should have occurred over a longer historical period. Overall, the optically stimulated luminescence (OSL) dating and palynological techniques were reliable in the investigation of local erosional history in karst regions.

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# The Effect of Hillslope Geometry on Hortonian Rainfall-Infiltration-Runoff Processes

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Topography, one of the main factors in hillslope rainfall-runoff processes, is related to many environment problems initiated by rainfall, such as flash flood, soil erosion, and landslides, and crucial in hillslope hydrological models and large-scale hydrological-hydrodynamic models. This research investigated the effects of topography abstracted by the combination of longitudinal profile curvature and plan shape on the Hortonian rainfall-runoff processes. The results show that different profile curvature and plan shape leads to more than 10% difference in cumulative runoff and runoff rate and more than 20% difference in ponding time. Similar infiltration and runoff processes can occur on different hillslopes because of the similar slope gradient distributions, and partial area runoff can also occur in these hillslopes. The run-on effect causes more infiltration on convex hillslope topography. The soil property and rainfall temporal variability do not change the trends but can alter the magnitudes of the hillslope geometry effect. The study provides insights into the rainfall runoff processes on natural hillslopes that could benefit studies related to hillslope hydrology and geomorphology.

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# Multiscale local connections of deforestation process in the Ecuadorian Amazon

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The deforestation process is nowadays recognized as a global concern due to a variety of environmental issues associated with forest loss. Exacerbated deforestation rates in basins such as the Amazon river basin is contributing tremendously to environmental global degradation and climate change. Previous studies regarding the deforestation process suggest that soils and forest loss are correlated exhibiting non-linear and multi-scale behaviors. Based on this, we conduct a novel approach based on image analysis of the deforestation process to improve the understanding of local connections of this process in a Biosphere reserve in the Ecuadorian Amazon. Understanding the connections between deforested patches and how they are strengthening the deforestation process could provide new features for understanding forest loss associated with agricultural expansion. Thus, these map features can be used for modeling purposes of agricultural expansion and forest loss impact. This work is based on the assessment of cumulative images of deforestation in the *Sumaco* biosphere reserve in the Ecuadorian Amazon from 1985 to 2018. For this, we rigorously sampling every deforested pixel of the images through the moving window technique to calculate the fractal dimension of the connected pixels at different scales. Once fractal dimensions are calculated, we classify these values to mapping the existing relations. The mapping results show different complexity levels in local connections of the deforestation process. These spatial relations can improve the understanding of deforestation patterns and provide relevant information for decision-making to conservation programs.

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# Timely Decision Support for Watershed Management with WEPPcloud

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Since the development and availability of GIS-based software and satellite imagery, there has been a vision that watershed managers would have near-real-time, three-dimensional hydrologic and soil erosion models that could easily assess impacts of watershed management decisions at high spatial resolutions across multiple scales. Our research team has made significant advances to address this challenging problem especially in the forest environment. The technology and data retrieval and access has dramatically improved to the point where it is possible to provide useful, near-real-time, geospatial decision support for watershed managers. This talk describes an online watershed model called WEPPcloud, widely used by the Forest Service and one of the FSWEPP suite of watershed tools, which is based fundamentally on a process-based hydrologic, soil erosion model (WEPP, Water Erosion Prediction Project). WEPPcloud is driven by discoverable, data-rich geospatial mapping products (e.g. soils, topography, satellite-based vegetation characteristics) and management libraries. It accesses daily grid-based historical and future projected climatic data to provide a comprehensive spatially and temporally explicit assessment of the impacts of management decisions on hydrologic response and sediment transport. Currently, WEPPcloud can be applied throughout the continental US, and beta versions are available for Australia and Europe. We will demonstrate this tools' development and application to guide pre-fire fuel management and post-fire mitigation, flood risk for communities where drinking water supplies and water resources are vulnerable to wildfire. We will discuss the ongoing limitations, challenges and opportunities towards more fully incorporating geospatial hydrologic and soil erosion models into watershed management decisions.

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# Effects of a check dam system on the runoff generation and concentration processes of a catchment on the Loess Plateau

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As important soil and water conservation engineering measures, there are more than 100,000 check dams constructed on the Loess Plateau; these dams play a vital role in reducing floods and sediment in watersheds. However, the effects of check dams on hydrologic process are still unclear, particularly when they are deployed as a system for watershed soil and water management. This study examined the watershed hydrologic process modulated by the check dam system in a typical Loess Plateau catchment. By simulating scenarios with various numbers of check dams using a distributed physical-based hydrological model, the effects of the number of check dams on runoff generation and concentration were analyzed for the study catchment. The results showed that the presence of check dams reduced the peak discharge and the flood volume and extended the flood duration; the reduction effect on peak discharge was most significant among the three factors. The system of check dams substantially decreased the runoff coefficient, and the runoff coefficient reduction rate was greater for rainstorms with shorter return periods than for rainstorms with longer return periods. The check dams increased the capacity of the catchment regulating and storing floods and extended the average runoff concentration time in the catchment that flattened the instantaneous unit hydrograph. This study reveals the influencing mechanism of check dams on the hydrological process of a watershed under heavy rainstorm conditions and provides a theoretical basis for evaluating the effects of numerous check dams on regional hydrology and water resources on the Loess Plateau.

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# Spatially uniform surface runoff as a result of erosion-induced high hydrolocial conncenctiviey over an extremelydegraded catchment

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Previous studies have suggested that runoff reduces with slope length, and the scaling trend diminishes with the degree of land degradation. This study further hypothesized that runoff is scale-independent and spatially uniform in extremely degraded landscapes. We tested the hypothesis on the Chinese Loess Plateau. Runoff data were collected from a densely rilled and gullied loess headwater with soil erosion intensity close to 20,000 t km-2 yr-1. The data included observations from seven arable experimental plots of various lengths (20 to 164 m) and gradients (9 to 32°), as well as the headwater outlet. The results showed that the erosion-induced network of rills and gullies lowered runoff reinfiltration and resulted in exceptional high flow connectivity, thus obscuring the effects of other environmental conditions (mainly topography) and contributing to uniform runoff from the upper hillslope to the headwater outlet. The observations held at the event, annual, and mean annual time scales, implying that the investigated watershed is simply the sum of individual slopes. This study highlights the effect of erosion processes on the ensuing runoff yield. The effect should be fully addressed in studies of runoff yield in semi-arid areas, which are among the most erodible landscapes due to sparse land cover.

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# Quantifying paleosol development during three interglacial periods in the Chinese Loess Plateau by soil-climate modeling.

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The Quaternary loess-paleosol deposits in the Chinese Loess Plateau (CLP) provide complete records of paleoclimates for better understanding differences in paleosol development. However, soil properties are overwritten due to climatic conditions in later periods; therefore the true paleosol development cannot easily be quantified. Only a calibrated soil model allows interglacial soil simulation in the CLP over long timescales. Therefore, our objective is to quantify the degree of paleosol development in three different paleosols in the CLP: S2, S4 and S5-1 using a calibrated process-based soil development model, SoilGen2.

The variations of paleosol development were compared by clay% and calcium carbonate content% and anorthite content (kg/m$^2$) in the simulated paleosol.

Our results show that paleosol development is stronger in S5-1, S4, S2 in the studied paleosols in decreasing order of intensity. Each paleosol showed distinct variations in clay migration and decalcification processes under varying climate and dust deposition at the time of development. The model correctly simulated the two-sub paleosol units in paleosol S2. In conclusion, the results indicate that the (calibrated) SoilGen2 model combined with modeled climate can quantify and describe the paleosol development in the CLP fairly.

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# Influence of climate change on soil erosion in high mountain area: a case study of upper Heihe river basin

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The impact of climate change on soil erosion is pronounced in high mountain area. In this study, the revised universal soil loss equation (RUSLE) model was improved for better calculation of soil erosion during snowmelt period by integrating a distributed hydrological model in upper Heihe river basin (UHRB). The results showed that the annual average soil erosion rate from 1982 to 2015 in the study area was 8.1 t $ha^{-1}$ $yr^{-1}$, belonging to the light grade. To evaluate the influence of climate change on soil erosion, detrended analysis of precipitation, temperature and NDVI was conducted. It was found that in detrended analysis of precipitation and temperature, the soil erosion of UHRB would decrease 26.5% and 3.0%, respectively. While in detrended analysis of NDVI, soil erosion would increase 9.9%. Compared with precipitation, the effect of temperature on total soil erosion was not significant, but the detrended analysis of temperature showed that the effect of temperature on soil erosion during snowmelt period can reach 70%. These finding were helpful for better understanding of the impact of climate change on soil erosion and provide a scientific basis for soil management in high mountain area under climate change in the future.

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# Soil erosion impacts on nutrient deposition in a typical karst watershed

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Soil erosion has a significant influence on nutrient redistribution and deposition. However, the effect of soil erosion on nutrient deposition remains unclear in karst areas such as southwest China, which represents an ecologically fragile zone experiencing severe soil erosion. The objective of this study was to investigate the characteristics of soil organic carbon (SOC), total nitrogen (TN), and total phosphorus (TP) deposition in a karst watershed of southwest China over the past 60 years and evaluate the relationship between soil erosion and nutrient deposition. The peak-cluster depressions in southwest China are typical for the geomorphological type, which is an ideal place to determine the sediment chronology, and the estimation of sediment and nutrient deposition rates. Three soil profiles were excavated in a typical karst depression. The characteristics of $^{137}Cs$, $^{210}Pb_{ex}$, particle size distribution, and nutrients at different soil depths were investigated to evaluate the effect of soil erosion on nutrient deposition. Results showed that there was a significant negative correlation between nutrient concentrations and clay content ($P$<0.001). Generally, compared with $^{137}Cs$, $^{210}Pb_{ex}$ had a higher correlation with SOC and TN. In an undisturbed sediment profile, Pb/Cs can reflect nutrient dynamics better than a single nuclide. The nutrient deposition rates increased before 1953, reached its maximum in 1954-1956, and then dropped rapidly from 1957 to 2015. The sediment deposition rates were negatively correlated with nutrient concentrations ($P$<0.01), but had a positive influence on nutrient deposition rates ($P$<0.01). This implies that the temporal variation in nutrient deposition rates over the past 60 years was dominated by soil erosion rather than nutrient concentrations. This study provides a new insight to explore the historical nutrient deposition rates in a peak-cluster karst depression, and may help effectively control soil erosion and sustainable development of agro-ecosystems.

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# Modelling soil erosion on unpaved road surface with process-based model and terrestrial laser scanning

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Unpaved roads are common man-made features that distributed in agricultural or forest watersheds. Road construction will change the underlying topography and alter the surface hydrology, in turn would enhance runoff generation and result in high soil loss risk. Therefore road erosion should be considered as one of the main sediment sources and should be properly evaluated. Process-based erosion models provide efficient tools to precisely evaluate soil loss along unpaved roads. This study was performed using the hillslope version of the Water Erosion Prediction Project (WEPP) to estimate soil loss from 20 typical road segments in the red soil region of South China. The terrestrial laser scanning (TLS)-measured soil losses were used to validate the model simulations. The results showed that the WEPP model could reasonably predict the total soil loss in relatively short (less than 100m) and gentle (slope gradient lower than 10%) road segments. On the contrary, the WEPP simulated soil loss would result in underestimation for long or steep road segments. Detailed WEPP plot outputs along roads revealed that most of the peak soil loss rates cannot be adequately calculated as comparing with the TLS-measured values. The linear critical shear stress theory in WEPP model for soil detachment simulation might responsible for the underestimation of non-linear peaked soil losses in long or steep road segments. Meanwhile, the lack of upslope flow and the curved road tortuosity were also found to be connected to the relatively low efficiency of the model outputs. Nevertheless, the WEPP simulation could accurately fit the detailed trend of soil loss variation along road segment despite the underestimation. Furthermore, the simulated results could provide a reliable prediction of the maximum soil loss positions. Therefore, the WEPP model could be adopted to evaluate erosion risk of unpaved roads in red soil region of China.

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# Using four different approaches to separate the effects of climate change and human activities on sediment discharge in karst watersheds

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Quantifying the relative contributions of climate and human activities to changes in sediment discharge is closely related to regional water resources, soil management and even the healthy operation of ecosystems. However, few studies used different methods to decompose influences of climatic variability and human activities on sediment discharge change, especially in karst regions of southwest China where experiencing severe soil erosion. This study systematically reviewed four different methods including simple linear regression method, double mass curve method, sediment identify factor analysis, and elastic coefficient method to separate the contribution of climate change and human activities to sediment discharge variation in four karst watersheds of southwest during 1955 to 2015. The trend and abrupt change year of sediment discharge in four watersheds were obtained by nonparametric Mann-Kendall test. Result showed that the sediment discharge in four watersheds all decreased significantly ($P$<0.05), and the abrupt change years were 2003, 2003, 2004 and 2004 for Wujiang, Yujiang, Hongshui, and Xijiang watersheds, respectively. The simple linear regression method, double mass curve method and elastic coefficient method all indicated that the sediment discharge was mainly influenced by human activities, with the contribution rate ranging from 73% to 101%. For the sediment identify factor analysis method, the sediment concentration is the principal factor influencing sediment discharge variation, and the contribution rate of sediment discharge varied from 100% to 154%. The results can provide good reference value for evaluating the influence of the climate and human activities on sediment discharge, and is significance for proper formulation of regional soil conservation policy in karst watersheds.

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# PROcess-guided deep learning and DAta-driven modelling (PRODA) uncovers key mechanisms underlying global soil carbon storage

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Soil carbon storage is a vital ecosystem service. Yet mechanisms that regulate global soil organic carbon (SOC) dynamics remain elusive. Here we explicitly retrieve the spatial patterns of key biogeochemical mechanisms and their regulation pathways on SOC storage using the novel PROcess-guided deep learning and Data-driven modelling (PRODA) approach. PRODA integrates data assimilation, deep learning, big data with 54,073 globally distributed vertical SOC profiles, and the Community Land Model version 5 (CLM5) to best represent and understand global soil carbon cycle. The PRODA-optimised CLM5 can represent 56±2% spatial variation of SOC across the world. Among all the mechanisms we explored in this study, microbial carbon use efficiency (CUE) emerges as the most critical regulator of global SOC storage. Increasing CUE, where more carbon flow is channelled into stabilisation, coincides with decreasing temperature and favours SOC accrual. Global sensitivity analysis further confirms the CUE, surpassing carbon input and decomposition, as the primary driver to SOC storage and its spatial variation. An increase of CUE by 1% from its standing value will lead to an additional 76±3 petagrams global SOC accumulation. We conclude that how efficiently soil microorganisms utilise organic carbon in metabolism is central to global SOC stabilisation. Understanding detailed processes underlying CUE and its environmental dependence will be critical in accurately describing soil carbon dynamics and its feedbacks to climate change.

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# On the mechanistic foundation and limit of Liebig's law of the minimum

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In ecosystem biogeochemistry, Liebig's law of the minimum (LLM) is one of the most widely used rules to model and interpret biological growth. Although it is intuitively accepted as being true, its mechanistic foundation has never been clearly presented. We here first show that LLM can be derived from the law of mass action, the state of art theory for modeling biogeochemical reactions. We further show that there are (at least) another two approximations (the synthesizing unit (SU) model and additive model) that are more accurate than LLM in approximating the law of mass action. We then evaluated the LLM, SU, and additive models against growth data of algae and plants. For algae growth, we found all three models are equally accurate, albeit with different parameter values. For plants, LLM failed to accurately model one dataset, and achieved equally good results for other datasets with very different parameters. We also find that LLM does not allow flexible elemental stoichiometry, which is an oft-observed characteristic of plants, when an organism's growth is modeled as a function of substrate uptake flux. In summary, we caution the use of LLM for modeling biological growth if one is interested in representing the organisms' capability in adapting to different nutrient conditions.

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# Soil carbon persistence governed by plant input and mineral protection at the regional and global scales

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Elucidating the processes underlying the persistence of soil organic matter (SOM) is a prerequisite for projecting soil carbon feedback to climate change. However, the potential role of plant carbon input in regulating the multi-layer SOM preservation over broad geographic scales remains unclear. Based on large-scale soil radiocarbon ($\Delta^{14}C$) measurements on the Tibetan Plateau, we found that plant carbon input was the major contributor to topsoil carbon destabilisation despite the significant associations of topsoil $\Delta^{14}C$ with climatic and mineral variables as well as SOM chemical composition. By contrast, mineral protection by iron–aluminium oxides and cations became more important in preserving SOM in deep soils. These regional observations were confirmed by a global synthesis derived from the International Soil Radiocarbon Database (ISRaD). Our findings illustrate different effects of plant carbon input on SOM persistence across soil layers, providing new insights for models to better predict multi-layer soil carbon dynamics under changing environments.

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# Increasing soil organic carbon stocks in croplands: a multi-modelling analysis evaluating the carbon inputs required to maintain and increase soil organic carbon stocks in Europe

**Elisa Bruni**

Soils represent the largest terrestrial reservoir of organic carbon on land and have the ability to sequester carbon dioxide from the atmosphere. Increasing soil organic carbon (SOC) stocks also improves soil fertility, water holding capacity and prevents erosion. Maintaining SOC stocks is particularly relevant in agricultural soils, where they have been depleted through historical land use. Simulation models representing the dynamics of carbon in the soil are used for predicting the impact of future climate change on SOC dynamics. It is necessary to reduce the uncertainties related to SOC predictions and increase confidence on long-term model simulations. Multi-modeling simulations allow predicting the evolution of SOC stocks, while estimating the uncertainty related to different modeling approaches.

In this study, we used a multi-modeling ensemble (ICBM, AMG, RothC and Century) to estimate the amount of carbon inputs required to maintain and increase SOC stocks in 17 agricultural experiments around Europe. Models were run once without calibration and once fitting SOC stocks to long-term observations though parameters' optimization. Outputs were significantly different among the models and, although no effect of the optimization was found, we observed a significant interaction effect between models and parameters' optimization. We found that maintaining and increasing SOC stocks is realistic for some experimental conditions, but might be hard to implement at a larger scale.

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# Site-level simulations of measurable soil fractions with Millennial Version 2

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Soil carbon (C) models are used to predict C sequestration responses to climate and land use change. Yet, the soil models embedded in Earth system models typically do not represent processes that reflect our current understanding of soil C cycling, such as microbial decomposition, mineral association, and aggregation. Rather, they rely on conceptual pools with turnover times that are fit to bulk C stocks and/or fluxes. As measurements of soil fractions become increasingly available, soil C models that represent these measurable quantities can be evaluated more accurately. Here we present Version 2 (V2) of the Millennial model, a soil model developed to simulate C pools that can be measured by extraction or fractionation, including particulate organic C, mineral-associated organic C, aggregate C, microbial biomass, and dissolved organic C. Model processes have been updated to reflect the current understanding of mineral-association, temperature sensitivity and reaction kinetics, and different model structures were tested within an open-source framework. We evaluated the ability of Millennial V2 to simulate total soil organic C (SOC), as well as the mineral-associated and particulate fractions, using three soil fractionation data sets spanning a range of climate and geochemistry in Australia (N=495), Europe (N=176), and across the globe (N=730). Millennial V2 (RMSE = 1.98 – 4.76 kg, AIC = 597 – 1755) generally predicts SOC content better than the widely-used Century model (RMSE = 2.23 – 4.8 kg, AIC = 584 – 2271), despite an increase in process complexity and number of parameters. Millennial V2 reproduces between-site variation in SOC across a gradient of plant productivity, and predicts SOC turnover times similar to those of a global meta-analysis. Millennial V2 updates the conceptual Century model pools and processes and represents our current understanding of the roles that microbial activity, mineral association and aggregation play in soil C sequestration.

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# Improving modelling estimations of soil organic carbon sequestration in manure-amended croplands

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Carbon sequestration reduces GHG emissions while improving soil fertility. In order for carbon sequestration through agriculture to be viable, however, accurate estimations of sequestration values are crucial in order to guide policy-making. Currently, Ontario's provincial Ministry of Agriculture, Food and Rural Affairs (OMAFRA) uses sequestration values from the federal government's farm-level greenhouse gas emission model (Holos), however these estimates fall short in one respect: a 2018 analysis demonstrated that manure application is not completely considered in the government's estimates, which is a critical gap.

The main purposes of our study were 1) to assess the accuracy of soil organic carbon estimations of process-based soil carbon models (Century and RothC) which were calibrated with data from long-term manure addition experiments in Ontario, and 2) to modify these models such that they were able to fully take manure application into account when estimating carbon sequestration in Ontario's croplands, and determine whether this substantially increases model accuracy.

The models' estimations for soil organic carbon sequestration were respectively calibrated and validated using data from two long-term manure addition experiments in Ottawa and Harrow. By calibrating multiple models using multiple datasets, model-specific and site-specific biases were minimized. The statistical analyses consisted of a suite of tests that assess the modelling accuracy compared to baseline measured data: the coefficient of determination (R2), root mean square error (RMSE), average relative error (ARE), and the Nash-Sutcliffe efficiency statistic (NSE).

As a result of these improved provincial estimates, Canadians will be better-informed about the greenhouse gas mitigation potential of long-term manure addition to croplands, which will help guide decisions made by policymakers as well as farmers. These improved provincial estimates will also be reported to Canada's national greenhouse gas inventory, and will be ultimately disclosed to the UN's Intergovernmental Panel on Climate Change (IPCC) in their global GHG summary report.

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# Whole-soil profile carbon dynamic in response to climate change modulated by vertical carbon transport

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Vertical carbon transport along the soil profile redistributes soil carbon fractions in soil layers, which may have significant consequences on whole-soil profile organic carbon (SOC) dynamics. We developed three varieties of vertically resolved SOC models to simulate SOC dynamics (down to 2 m). The three models took into account mechanisms underpinning the increased persistence of SOC in deeper soil layer depths by explicitly simulating microbial processes and the interactions between old and new carbon pools. Model sensitivity analyses indicated that vertical carbon transport must to be considered; otherwise the profile distribution of SOC stock cannot be captured by the models. The models were further constrained by global data sets of whole-soil profile observations of vertical distribution of SOC stocks and carbon inputs, and then were used to predict the spatial pattern of the depth-specific amount of vertically transported organic carbon ($V$, g C $m^{-2}$ $yr^{-1}$) across the globe. The $V$ showed great variability across the globe as well as across different depths. Precipitation was the most important for influencing the global pattern of $V$; and soil texture and organic carbon content for the profile pattern. Applying the models across the global, we assessed the response of SOC to 2□ global warming at the resolution of 1 km. The results suggested that without considering the vertical carbon transport, SOC loss under warming would be underestimated by 10%, particularly in the deeper layers. In wetter areas or areas with stronger soil profile disturbance such as bioturbation and cryoturbation, SOC was more sensitive (i.e., more SOC loss) to climatic warming due to the stronger vertical carbon transport and/or carbon-mixing. Our modelling demonstrates the vital role of vertical carbon transport in controlling whole-soil carbon dynamics, which is a key determinant of whole-soil profile SOC persistence under warming.

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# Estimation and spatio-temporal analysis of soil organic carbon stock in China using machine learning algorithms from 2000 to 2014

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Soil is the largest carbon pool in terrestrial ecosystems, storing up to 2 or 3 times the amount of carbon present in the atmosphere, and a small change in soil carbon stock could have profound effects on atmospheric $CO_2$ and climate change. However, an accurate estimate of soil organic carbon (SOC) stock is still challenging. Previous studies on SOC stock prediction across China were mainly from biogeochemical models and national soil inventories, and large uncertainties still remained. In this study, we predicted SOC stock at 0 – 20 cm and 0 – 100 cm with 3419 and 2479field observations using artificial neural network (ANN), extreme gradient boosting (XGBoost), random forest (RF), and gradient boosting regression trees (GBRT) across China with the linkage of climate, vegetation and soil variables. Results showed that RF performed best among the four machine learning approaches with model efficiency of 0.61 for 0 – 20 cm and 0.52 for 0 – 100 cm. The trained RF model was used to predicted the temporal and spatial patterns of SOC stock at a spatial resolution of 1 km from 2000 to 2014 across China. Temporally, SOC stock at 0 – 20 cm ($p = 0.07$) and 0 – 100 cm ($p = 0.3$) did not change significantly. However, SOC density showed strong spatial patterns, the mean value of SOC density at 0-20 cm and 0-100 cm increased firstly, then decreased and then increased with the increase of latitude, and the minimum density was 39.83° and 41.59°, respectively. The total SOC stocks across China were 33.68 and 95.01 Pg C for 0 – 20 cm and 0 – 100 cm, respectively. The developed SOC stock could serve as an independent dataset that could be used for decision-making and help with baseline assessments for inventory and monitoring SOC stocks for global biogeochemical models in China.

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# Challenges of using microbial explicit models for evaluating organic matter decomposition in predominantly organic soils

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Models of soil organic matter (SOM) decomposition are critical for predicting the fate of soil carbon (and nutrient) under changing climate. Traditionally, models have used a simple set-up where the substrate is divided into conceptual pools to represent their resistance to microbial degradation, and decomposition rates are often proportional to the amount of substrate in each pool. Emerging models now consider explicit microbial dynamics and show that SOM loss under warming may be fundamentally different from the classical models. Microbial explicit models use reaction kinetics, represented on a concentration basis. However, when the substrate makes up most of the volume of soils (e.g., the organic horizon in forest soils or peat), an increase or decrease in SOM does not, or only very little, affect concentrations of microbes and substrate. Consequently, reduction in SOM does not reduce the amount of substrate the microbial biomass encounters. This problem does not occur in classical models like CENTURY. We incorporated the effect of organic matter on soil volume in several microbial models. If microbes are solely limited by enzymes, organic soils or peats are decomposed very quickly as there is no mechanism that stops the positive feedback between microbial growth and SOM concentration until the substrate is gone. Alternative formulations that account for carbon limitation or microbial 'cannibalism' display a sweet spot of soil carbon concentration. Interestingly, a response to warming will depend on the amount of organic vs. mineral materials. Apparent $Q_{10}$ was higher in fully organic soil than in mineral soils, which was pronounced when small to moderate amounts of the mineral matter was present that diluted the substrate for microbes. We suggest that model formulations need to be clear about the assumption in key processes, as each of the steps in the cascade of biogeochemical reaction can produce surprising results.

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# A climate-soil-vegetation-human interaction analysis for SOC change monitoring over 30 years across the National Ecological Observatory Network, USA

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Previous studies of long-term soil change have been focusing on the impacts of climate and land-use change, while neglecting the impacts of soil taxonomy on soil's response to vegetational and human disturbance. In this study, a spatial-temporal framework was used to study the change in soil organic carbon (SOC) across National Ecological Observatory Network (NEON), USA over 30 years. We hypothesize that: 1) on the continental scale, the hot-spots and cold-spots of SOC change vary with soil orders across different eco-climatic domains, controlled by all soil forming factors that affect carbon input and output; 2) within the same eco-climatic regime, the effects of disturbance on SOC change are controlled by physical and biogeochemical processes, represented by varying soil properties including clay, bulk density, pH, and CEC. To separate the effects of disturbance under different land-use scenarios on SOC change, space-for-time substitution was used in combination with the Continuous Change Detection and Classification algorithm and structural equation models. Results suggested that 1) under natural vegetation, Ultisols, Spodosols, and Inceptisols showed a large SOC accumulation especially in the eastern coast, while Inceptisols, Andisols, and Aridisols in the western US showed a large SOC loss; 2) compared with the same reference soils under natural vegetation, Mollisols and Alfisols showed a large SOC decrease due to human disturbance (e.g., farming and grazing); 3) Inceptisols (+6.2 g/kg) and Gelisols (+27.5 g/kg) in Alaska presented the largest SOC increase among all the soil orders within the subsoil (B horizon); 4) clay content and pH were the most dominant factors that affected SOC content across the NEON sites. This empirical analysis of the 30-years SOC change across eco-climatic regimes could be used for ecosystem modelers to benchmark the models across biomes and study the physical and biogeochemical controls on SOC change under different land management scenarios.

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# Carbon sequestration in agricultural soils as potential climate change mitigation strategy for Germany

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The limitation of global warming to +1.5°C compared to preindustrial levels requires net-zero $CO_2$ emissions globally by mid-century and substantial removal of $CO_2$ thereafter. Carbon sequestration in agricultural soils has been proposed as a potential mitigation strategy. Aim of this study is to quantify current carbon storage and emission reduction potential in agricultural soils, and assess the impact of mitigation measures in a prognostic modeling approach. The land surface model Community Land Model 5.0 (CLM) is used to assess soil carbon changes in agricultural soils in Germany. The simulation domain was set up with an 8 x 8 km grid across Germany using recent land use and soil texture maps, and parameters for major field crops. The model was spun up for ~1500 years with a 30-year climate dataset. Preliminary results show that spinup-derived organic carbon density (OCD, 0-188 cm) was significantly related to Soil Grid v2 OCD ($R^2$ = 0.82), but only weakly related to field-measured OCD ($R^2$ = 0.21). The simulated OCD values in the upper 32 cm soil layer were lower in Northwestern Germany compared to Soil Grids. This is probably due to the intensive use of organic amendment application in the region, and CLM5 lacks a subroutine for simulating organic carbon application. In a next step, carbon storage for different climate projections (regional EUR11 RCP2.6 and RCP8.5 scenarios) and management systems from 2020 - 2100 will be investigated. We will present preliminary results and discuss improvements of CLM5 to better represent agricultural soils.

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# Predicting Anaerobic Microsites in Soils

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Anaerobic microsites in soils are critical features in the Earth system as they are prime locations for generating powerful greenhouse gases. These processes occur in hot spots and hot moments and are therefore difficult to capture in mean-field approaches. Typically, they are captured as empirical functions of soil moisture.

We present a mechanistic upscaling of microsites from single soil particles to the soil column, by considering existing formulations that link the processes of solute diffusion, pore sizes and particle size distributions, and water retention. The upscaling allows to predict probability density functions of volume and surface area of anaerobic microsites, which can then be integrated to the scale of a laboratory soil sample or a field site. Our goal was to make these predictions based on variables typically measured in soils and are routine diagnostic or prognostic variables in Earth system model. While the detailed expressions can only be solved numerically, we found closed-form solutions with little loss of accuracy. Our result have the necessary hooks for direct implementation of anaerobic microbial carbon processing, methane production and nitrification-denitrification processes in Earth System models. A first application yields two soil moisture-CO2 efflux hypotheses that could potentially be tested and which set this upscaling apart from empirical formulations 1) the degree of temperature sensitivity and dependence of carbon concentration in anaerobicity and 2) different CO2 response to soil moisture if measured in laboratory jars vs. measured in the field.

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# Simulation of soil carbon dynamics in Australia with {\sc Roth C}

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We simulated soil organic carbon (C) dynamics across Australia with the Rothamsted carbon model ({\sc Roth C}) by connecting new spatially-explicit soil measurements and data with the model. This helped us to bridge the disconnection that exists between datasets used to inform the model and the processes that it depicts. We compiled publicly available continental-scale datasets and pre-processed, standardised and configured them to the required spatial and temporal resolutions. We then calibrated {\sc Roth C} and run simulations to estimate the baseline soil organic C stocks and composition in the 0--0.3~m layer at 4,043 sites in cropping, modified grazing, native grazing, and natural environments across Australia. We used data on the C fractions, the particulate, mineral associated, and resistant organic C (POC, MAOC and ROC, respectively) to represent the three main C pools in the {\sc Roth C} model's structure. The model explained 97--98\% of the variation in measured total organic C in soils under cropping and grazing, and 65\% in soils under natural environments. We optimised the model at each site and experimented with different amounts of C inputs to simulate the potential for C accumulation under constant and chainging climate in a 100-year simulation. Soils under native grazing were the most potentially vulnerable to C decomposition and loss, while soils under natural environments were the least vulnerable. An empirical assessment of the controls on the C change showed that climate, pH, total N, the C:N ratio, and cropping were the most important controls on POC change. Clay content and climate were dominant controls on MAOC change. Consistent and explicit soil organic C simulations improve confidence in the model's estimations, contributing to the development of sustainable soil management under global change.

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# Projecting long-term soil organic dynamics in Australia's rangelands

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Rangelands in Australia are vast and occupy more than 80% of the continental land area. They extend across arid, semi-arid, and the tropical regions with seasonal, variable rainfall in the north. They include diverse, relatively undisturbed grasslands, shrublands, woodlands and tropical savanna ecosystems. They represent Australia's largest terrestrial carbon sink as they account for almost 70% of Australia's total soil organic carbon stock (Viscarra Rossel et al., 2014), more than all above-ground sources of carbon (native grasses, trees and shrubs) in these regions (Gifford et al., 1992). Here we have developed a novel space-time approach for projecting the long-term C dynamics of rangelands soils using Long Short-Term Memory (LSTM) deep learning neural networks. We further demonstrate how the networks might be interpreted and quantified the influence of explanatory variables on the spatiotemporal dynamics of soil C in these regions. Our results provide an improved ability to accurately model long-term carbon dynamics, which is needed to confidently predict changes in soil C from change in climate or anthropogenic disturbance. The information is critical for improving our understanding of soil C in these regions and for understanding the potential for sequestering C in the rangelands.

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# Wavelet Analysis of Soil Water State Variables for Identification of Lateral Subsurface Flow: Lysimeter versus Field Data

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Preferential and lateral subsurface flow may be responsible for the accelerated transport of water and solutes in sloping agricultural landscapes; however, the process is difficult to observe. One idea is to compare time series of soil moisture observations in the field with those in lysimeters, where flow is vertically oriented. This study aims at identifying periods of deviations in soil water contents and pressure heads measured in the field and in a weighing lysimeter with the same soil profile. Wavelet Coherency Analysis (WCA) was applied to time series of hourly soil water content and pressure head data (15, 32, 60, 80, and 140 cm depths) from Colluvic Regosol soil profiles in summer 2017. The phase shifts and periodicities indicated by the WCA plots reflected the response times to rain events in the same depth of lysimeter and field soil. For many rain events and depths, sensors installed in the field soil showed a faster response than those in the lysimeters soil. This could be explained by either vertical preferential flow or lateral subsurface flow from upper hillslope positions. Vice versa, a faster sensor response in the lysimeter soil could be indicative for vertical preferential effects. The WCA plots comprise all temporal patterns of time shifts and correlations between larger data time series in a condensed form to identify potentially relevant periods for more detailed analyses of subsurface flow dynamics.

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# The relationship between thermal conductivity and matric suction of soils

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The soil thermal conductivity (λ) and matric suction of soil water (h, the negative of matric potential) relationship has been widely used in land surface models for estimating soil temperature and heat flux following the McCumber and Pielke (1981, MP81) λ-h model. However, few datasets are available for evaluating the accuracy and feasibility of the MP81 λ-h model under various soil and moisture conditions. In this study, we developed a new λ-h model and compared its performance with that of the MP81 model using measurements on 18 soils with a wide range of textures, water contents and bulk densities. The heat pulse technique was used to measure λ, and the suction table, micro-tensiometers, pressure plate device, and the dew point potentiometer were applied to obtain soil water retention curves at the appropriate suction ranges. In the range of pF (the common logarithm of h in cm)≤3, the λ-h relationships were highly nonlinear and varied strongly with soil texture and bulk density. In the dry range (i.e., pF > 3), there existed a universal λ-h relationship for all soil textures and bulk densities, and an exponential function was established to describe the relationship. Independent evaluations using λ-h data on five intact soil samples showed that the new model produced accurate λ data from pF values with root mean square errors (RMSE) with the range of 0.03–0.18W $m^{-1}$ $K^{-1}$. While, large errors (RMSEs within 0.17–0.36W $m^{-1}$ $K^{-1}$) were observed with λ estimates from the MP81 model.

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# Exploring the Long-Term Soil Moisture Predictability with FLUXNET Site Data using Circulating Learning Model

**Qingliang Li**, Zhongyan Li, Wei Shangguan, Yifei Yao, Xuezhi Wang, and Fanhua Yu

The skillful long-term (from 3 days delay) prediction of soil moisture can provide more help than the short-term prediction of soil moisture for many practical applications including ecosystem management and precision agriculture. It presents great challenges because the far future variation of soil moisture has more uncertainties than the near future on soil moisture. Therefore, a novel circulating learning deep learning (DL) model based on Long Short-Term Memory (LSTM), is developed in this study as an alternative data-intelligence tool. This model includes two layers: the encoder-decoder LSTM layer and LSTM with a fully connected layer, which were used to enhance the long-term prediction ability by considering the intermediate time-series data between the input timestep and the predictive timestep. We applied this model by using FLUXNET2015 tie1 and tie2 subset data product over seven sites in different countries. The result shows that our model predicts soil moisture with better accuracy in average state and fluctuation pattern and amplitude when compared with other state-of-the-art DL methods, such as Multiple Linear Regression (MLR), Long Short-Term Memory (LSTM) and encoder-decoder LSTM models. Furthermore, the different-term (short-term, medium-term and long-term) predictability of soil moisture over various conditions (i.e., different hyper-parameters in our model, different predictive models, different climate regions and different sites) has been widely discussed in this paper. The code of our model is publicly available at https://github.com/ljz1228/CLM-LSTM-soil-moisture-prediction. We hope that this work will accelerate the research for long-term soil moisture prediction.

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# A data-driven approach for mapping global surface soil moisture at 100 m using high-resolution remote sensing data and land surface parameters

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Current in situ soil moisture monitoring networks are sparsely distributed while remote sensing satellite soil moisture maps have a very coarse spatial resolution. In this study, an empirical global surface soil moisture (SSM) model was established via fusion of in situ continental and regional scale soil moisture networks, remote sensing data (SMAP and Sentinel-1) and high-resolution land surface parameters (e.g., soil texture, terrain) using a quantile random forest (QRF) algorithm. The model had a spatial resolution of 100m and performed moderately well under cultivated, herbaceous, forest, and shrub soils ($R^2$ = 0.524, RMSE = 0.07 $m^3$ $m^{-3}$). It has a relatively good transferability at the regional scale among different continental and regional networks (mean RMSE = 0.08–0.10 $m^3$ $m^{-3}$). The global model was then applied to map SSM dynamics at 30–100m across a field-scale network (TERENO-Wüstebach) in Germany and an 80-ha irrigated cropland in Wisconsin, USA. Without local training data, the model was able to delineate the variations in SSM at the field scale but contained large bias. With the addition of 10% local training datasets ("spiking"), the bias of the model was significantly reduced. The QRF model was also affected by the resolution and accuracy of soil maps. It was concluded that the empirical model has the potential to be applied elsewhere across the globe to map SSM at the regional to field scales for research and applications. Future research is required to improve the performance of the model by incorporating more field-scale soil moisture sensor networks and high-resolution soil maps as well as assimilation with process-based water flow models.

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# Soil properties: their prediction and feature extraction from the LUCAS spectral library using deep convolutional neural networks

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Soil, as a non-renewable resource, should be monitored continuously to prevent its degradation and promote sustainable agricultural management. Soil spectroscopy in the visible-near infrared range is a fast and cost-effective analytical technique to predict soil properties. The use of large soil spectral libraries can reduce the work needed to reliably estimate soil properties and obtain robust models capable of widespread applicability. Deep learning is apt for big data analysis, and this approach could herald a profound change in the way we model soil spectral data generally. Accordingly, we explored the modeling potential of deep convolutional neural networks (DCNNs) for soil properties based on a large soil spectral library. The European topsoil dataset provided by the Land Use/Cover Area frame Survey (LUCAS) was used without any pre-processing of spectra or covariates added. Two 16-layer DCNN models (ResNet-16 and VGGNet-16) were successfully used to make regression predictions of seven soil properties and classification predictions of soil texture into four groups and 12 levels. Our results showed that the ResNet-16 and VGGNet-16 models produced highly accurate predictions for most soil properties, being superior to either a shallow convolutional neural network and traditional machine learning approaches. Soil organic carbon content, nitrogen content, cation exchange capacity, pH, and calcium carbonate content were well predicted, having a ratio of performance to deviation (RPD) > 2.0. Soil potassium content was adequately predicted ($1.4 \leq RPD \leq 2.0$) and phosphorous content was poorly predicted ($RPD < 1.4$). The overall classification accuracy of soil texture was 0.749 (four groups) and 0.566 (12 levels). The position of feature wavelengths differed among the soil properties, for which multiple characteristic peaks were common. This study fully demonstrates the modeling potential of deep learning with soil hyperspectral data, which could bring us closer to achieving precision agriculture.

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# Soil nutrient estimation and mapping in agriculture land based on improved ELM and UAV imaging spectrometry

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Soil nutrient is one of the most important properties to support farmland quality and product. Imaging spectrometry has the potential for rapid acquisition and real-time monitoring of soil characteristics. The goal of this study was to explore the preprocessing and modeling method of hyperspectral image acquired from UAV platform for soil organic matter (SOM) and soil total nitrogen (STN) content estimation in farmland. The results showed that: 1) Multiple Scattering Correction method performed better in reducing image scattering noise rather than Standard Normal Variate transformation or spectral derivatives with higher correlation and lower signal-to-noise ratio; 2) The proposed feature selection method, which was combined with Competitive Adaptive Reweighted Sampling algorithm (CARS) and Successive Projections Algorithm (SPA), could provide selective preference for hyperspectral bands with final 24 feature bands for SOM estimation and 22 feature bands for STN estimation; 3) The particle swarm optimization (PSO) algorithm was selected to optimize input weights and hidden biases of extreme learning machine (ELM) model for SOM and STN prediction. The PSO-ELM model with input selective preference bands produced higher prediction accuracy with the $R^2$ of 0.73, RPD of 1.91 for SOM and $R^2$ of 0.63, RPD of 1.53 for STN respectively rather than ELM model. These outcomes provided a technical support for wider application of soil properties estimation using imaging spectrometry in agriculture precision monitoring and mapping.

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# Semi-supervised learning for increasing transferability of machine learning in digital soil mapping

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The most critical aspect of application of digital soil mapping is its limited transferability. Modelling soil properties for regions where no or only sparse soil information is available is highly uncertain, when using the low-cost geo-spatial environmental covariates alone. To overcome this drawback, transfer learning has been introduced in different environmental sciences, including soil science. The general idea behind extrapolation of soil information with transfer learning in soil science is that the target area to transfer to is alike, e.g. in terms of soil-forming factors, and the same machine learning rules can be applied. Supervised machine learning, so far, has been used to transfer the soil information from the reference to the target areas with very similar environmental characteristics between both. Hence, it is unclear how machine learning can perform for other target regions with different environmental characteristics. Semi-supervised learning is an approach to machine learning that combines a small amount of labeled data (reference area) with a large amount of unlabeled data (target area) during training. In this study, we explored if semi-supervised learning could improve the transferability of digital soil mapping relative to supervised learning methods. Soil data for two arid regions and associated environmental covariates were obtained. Semi-supervised learning and supervised learning models were trained based on the data in the reference area and then tested based on the data in the target area. The results of this study indicated the higher power of semi-supervised learning for transferring soil information from one area to another in comparison to the supervised learning method.

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# Soil sampling design optimization by using conditioned Latin Hypercube sampling

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One of the most critical steps in digital soil mapping is finding a sampling approach to cover a good spatial coverage of the area regarding the soil spatial variation. In this matter, environmental variables can aid in taking samples in more innovative and more precise locations while reducing the soil sampling efforts such as time and costs. Conditioned Latin hypercube sampling (cLHS) is a stratified random design strategy that perfectly represents the variability of auxiliary variables in feature space. This study applied this method and compared it to simple random sampling to optimize sampling designs for mapping in the agricultural study site in Hungary. The covariates were indices extracted by the digital elevation model and Landsat images. The principal component analysis (PCA) was applied to reduce the data overlap and select the most important variables as the model's inputs. By computing the statistical criteria (mean, variance, standard deviation, etc.) for covariates and comparing these results between the sampling populations and the entire one, we may conclude that both designs gave almost similar predictions. However, for most covariates, statistical means of cLHS provide the closest approximation compared to the random approach sampling method, but the statistical variances and SDs retrieved similar results. Furthermore, the histogram distribution of most variables in the cLHS was following more closely to the original distribution of the environmental covariates. Overall, considering the type of the study site and the chosen variables, it seems that cLHS is a more applicable method.

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# A two point machine learning method for spatial prediction for soil : overcoming the spatially heterogeneous distribution and relationship of soil heavy metal concentration

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The soil heavy metal contamination has becoming a serious problem worldwide. An accurate prediction of soil heavy metal concentration at un-sampled locations using a small sample remains a challenge, because of many natural and human factors and resulted complex heterogeneous pattern, and the relationship between influencing factors are also not homogeneous. To overcome those heterogeneities and improve the prediction accuracy, a two point machine learning method is proposed in this paper by fully leveraging the spatial relationship and similarity relationship of high dimensional ancillary variables. It firstly models the difference between paired points using machine learning model, then predict the concentration differences between sampling points and the un-sampled points, and finally utilize the predicted differences to choose near neighbors to obtain the final concentration prediction. In this method, an innovative way to search near neighbors for local model from the difference of response variable was put forward to overcome the Curse of Dimensionality. Its performance was illustrated in two diverse case studies and it is demonstrated that proposed method can dramatically improve the prediction accuracy for soil heavy metal. Besides spatial prediction of soil pollution, it can also be applied to spatial prediction of other other elements of the earth system. And in further the machine learning method in this paper can be replaced to any other supervised learning model according to specific situations.

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# Spatial heterogeneity of temperature sensitivity of soil respiration across China

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Soil respiration (RS), consisting of soil autotrophic respiration (RA) and heterotrophic respiration (RH), is the largest outflux of $CO_2$ from terrestrial ecosystems to the atmosphere. The temperature sensitivity ($Q_{10}$) of RS is a crucial role in benchmarking the intensity of terrestrial soil carbon-climate feedbacks. However, the heterogeneity of $Q_{10}$ of RS has not been well explored. To fill this substantial knowledge gap, gridded long-term $Q_{10}$ datasets of RS at 5 cm with a spatial resolution of 1 km were developed from 515 field observations using a random forest algorithm with the linkage of climate, soil and vegetation variables. $Q_{10}$ of RA and RH were estimated based on the linear correlation between $Q_{10}$ of RS and RA/RH. Field observations indicated that regardless of ecosystem types, $Q_{10}$ of RS ranged from 1.54 to 4.17 with an average of 2.52. $Q_{10}$ varied significantly among ecosystem types, with the highest mean value of 3.18 for shrubland, followed by wetland (2.66), grassland (2.49) and forest (2.48), whereas the lowest value of 2.14 was found in cropland. RF could well explain the spatial variability of $Q_{10}$ of RS (model efficiency = 0.5). Temporally, $Q_{10}$ of RS, RA and RH did not differ significantly ($p$ = 0.386). Spatially, $Q_{10}$ of RS, RA and RH varied greatly. In different climatic zones, the plateau areas had the highest mean $Q_{10}$ value of 2.88, followed by tropical areas (2.63), temperate areas (2.52), while the subtropical region had the lowest $Q_{10}$ on average (2.37). The predicted mean $Q_{10}$ of RS, RA and RH were 2.52, 2.29, 2.64, respectively, with strong spatial patterns, indicating that the traditional and constant $Q_{10}$ of 2 may bring great uncertainties in understanding of soil carbon-climate feedbacks in a warming climate.

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# Digital soil mapping using machine learning techniques in a varied tropical environment

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Environmental models often require soil maps to represent the spatial variability of soil attributes. However, mapping soils using conventional in-situ survey protocols is time-consuming and costly. As an alternative, digital soil mapping offers a fast-mapping approach that might be used to monitor soil attributes and their interrelationships over large areas. In Brazil, conventional survey methods are still widely used, and thus maps still in development are considered as the state-of-the-art products for decades. In this study, we address this lack of updated spatial information on many soil attributes by producing regional statistical soil models using an innovative framework. This new framework attempts to reduce prediction redundancies due to high multicollinearity, by implementing a Feature Selector algorithm. This is expected to improve a model's strength by decreasing its unexplained variance. The framework's core is composed of the Soil-Landscape Estimation and Evaluation Program (SLEEP) and a calibrated Gradient Boosting Model capable of modelling the spatial distribution of soil attributes at multiple soil depths. These models allowed us to explain the spatial distribution of some basic soil attributes (physical and chemical), and its environmental drivers. The model training and testing approach used 30 environmental attributes, and data from 223 soil profiles for the state of Pernambuco, Brazil. Our models demonstrated a consistent potential to perform spatial extrapolations with $r^2$ ranging from 0.8 to 0.97, and PBIAS from -0.51 to 2.03. The properties related to topographic and climatic conditions were dominating when estimating the number of horizons, percentage of silt and the sum of bases (a measure of soil fertility). We believe that our framework features high flexibility, while reducing capital investments when compared to *in situ* surveys and traditional mapping protocols. These findings also have implications for the improvement and testing of pedotransfer functions. We thank FACEPE for funding this through APQ 0646-9.25/16.

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# Machine learning to automate rapid soil health assessment using infrared spectroscopy

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Soil infrared spectroscopy has great potential for estimating soil properties, but reference soil measurements are typically required in combination with multivariate statistical models to estimate soil properties. User-friendly predictive tools based on open-source statistical environment remain one of the main limitations to enable technology diffusion to non-specialist users. Our aim is to build capacity for an automated machine learning routine for rapid and robust prediction of soil health indicators using lab acquired soil infrared spectra. This intelligent system runs on R statistical environment and includes (1) a diverse soil spectral library comprising main physiographic regions from the USA Midwest region under diverse land uses and various sampling depths, (2) a classification process to detect potential outliers in newly acquired spectra using supervised machine learning techniques, and (3) a multi-model optimized prediction process based on linear and non-linear statistical procedures (partial least squares, support vector machines, and neural network). This prediction system works at the intersection of soil and data science and high-performance computing to enable efficient parallel processing of spectral data on multi-core coprocessors. Using artificial intelligence to automate soil infrared spectroscopy is a fundamental demand that will make this technique an effective routine in soil laboratories to estimate soil health.

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# An empirical soil water retention model based on probability laws for pore-size distribution

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Knowledge of the soil water retention curve (SWRC) is critical to mathematical modeling of soil water dynamics in the vadose zone. Traditional SWRC models were developed based on bundles of cylindrical capillaries (BCCs) using a residual water content, which fail to accurately describe the dry end of the curve. This study improved and expanded on the traditional BCC models. Specifically, the total water retention was treated as a weighed superposition of capillary and adsorptive components.We proposed a mathematical continuous expression for
water retention from saturation to oven dryness, which also allowed for a partition of capillary and adsorptive retention. We further evaluated six capillary retention functions using different probability laws for pore-size distribution - namely, the log-logistic, Weibull, lognormal, two-parameter van Genuchten (VG), three-parameter VG (or Dagum), and Fredlund–Xing (FX) distributions. Model testing against 144 experimental data showed better agreement of the proposed model with experimental observations than the traditional approaches that use the residualwater content. The Dagum and FX distributions, which have one more degree of freedom, provided better agreement with experimental data than the other four distributions. The log-logistic and lognormal distributions fitted the experimental data better than the Weibull and VG distribution for loam soils. In addition, the fitted weighting factor w using the log-logistic and lognormal distributions better correlated to soil clay content than the other four distributions. Our study suggests that the log-logistic and lognormal distributions are more suitable to model soils' pore-size distribution than other tested distributions.

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# Global Mapping of Soil Saturated Hydraulic Conductivity Combining Legacy Data, Spatial Covariates and Machine Learning

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Saturated soil hydraulic conductivity (Ksat) is a key parameter in many hydrological and climatic modeling applications, as it controls the partitioning between precipitation, infiltration and runoff. Values of Ksat are often deduced from Pedotransfer Functions (PTFs) using maps of soil attributes. To circumvent inherent limitations of present PTFs (heavy reliance of arable land measurements, ignoring soil structure, and geographic bias to temperate regions), we propose a new global Ksat map at 1–km resolution by harnessing technological advances in machine learning and availability of remotely sensed surrogate information (terrain, climate and vegetation). We compiled a comprehensive Ksat data set with 13,258 data geo-referenced points from literature and other sources. The data were standardized and quality-checked in order to provide a global database of soil saturated hydraulic conductivity (SoilKsatDB). The SoilKsatDB was then applied to develop a Covariate-based GeoTransfer Function (CoGTF) model for predicting spatially distributed Ksat values using remotely sensed information on various environmental covariates. The model accuracy assessment based on spatial cross-validation shows a concordance correlation coefficient (CCC) of 0.16 and a root meansquare error (RMSE) of 1.18 for log10 Ksat values in cm/day (CCC=0.79 and RMSE=0.72 for non spatial cross-validation). The generated maps of Ksat represent spatial patterns of soil formation processes more distinctly than previous global maps of Ksat based on soil texture information and bulk density. The validation indicates that Ksat could be modeled without bias using CoGTFs that harness spatially distributed surface and climate attributes, compared to soil information based PTFs. The relatively poor performance of all models in the validation (low CCC and high RMSE) highlights the need for the collection of additional Ksat values to train the model for regions with sparse data.

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# An automated machine learning based ensemble approach for improving estimates of soil water retention parameters

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Accurately mapping soil water retention parameters is vital for modeling atmosphere-land interactions but is challenged by limited measurements and simulations globally. Ensemble pedotransfer functions (PTFs) have been highly recommended for use due to the higher reliability of ensemble models and the error compensation among ensemble members. However, conventional ensemble approaches assign a fixed weight to each PTF and may not fully utilize the strengths of individual PTFs. In this work, we developed a new ensemble approach based on an automated machine learning workflow to assign varying weights to assemble 13 widely used PTFs. The AutoML-assisted ensemble approach (AutoML-Ens), as well as the simple average (MEAN), Bayesian Model Average (BMA), and the hierarchical multi-model ensemble approach (HMME), were evaluated using the global coverage National Cooperative Soil Surbey (NCSS) Soil Characterization Database. Results indicate that AutoML-Ens approach performs better than the conventional approaches in terms of the coefficient of determination ($R^2$) and root mean square error (RMSE). Three soil hydraulic parameters, i.e., saturated water content, field capacity, and wilting points, and their corresponding uncertainties, were further derived through the AutoML-Ens approach at a 30″×30″ geographical spatial resolution based on a global soil composition database (SoilGrids), which can be applied in the Earth System Modeling. This study demonstrated the necessity of dynamic weights assigning in ensemble approaches and the great potential of coupling data-driven (here, the AutoML) and modeling (empirically or physically-based PTFs) approaches in mapping global soil water retention-like parameters.

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# An analytic representation of the total soil carbon trajectory implied by the general mathematical framework of most soil carbon models

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Most models of soil C dynamics can be expressed by the differential vector equation:

**dC(t)/dt = f(t).K.C(t) + b(t)**

where each element of the vector C(t) represents a carbon compartment with intrinsic decomposition rate (usually fast, slow and passive); K is the transition matrix between the compartments (decomposition rates and decomposition partitioning); the scalar function f(t) is a forcing function of the decomposition rates modifiers (e.g. soil moisture and temperature); and b(t) is the vector with rates of external C inputs for each compartment. Considering the case where only total soil carbon is measured, only the sum of C in all compartments can be used for model evaluation, calibration and data assimilation. Also, in most compartmental models there are too many parameters to be adjusted, leading to identifiability problems. Although some parameters can be constrained according to the model's assumptions, identifiability is still problematic except for the simplest compartmental models. By working on the differential equation, it is possible to deduce an explicit representation of the total carbon trajectory, in a way that the number of necessary empirical parameters is reduced, without loss of generality or need of further assumptions. In this work we propose such a representation for the total carbon trajectory whose generality embraces implicitly the mechanism of models as Century, RothC and CQESTR. The solution requires less parameters than the original models do but still allows mapping the original model parameters and decomposition modifiers functions onto the solution. Additionally, we show how the main processes of decomposition of soil organic matter can be represented by the terms of the solution found. Finally, we present the solution behavior under extreme conditions of temperature, humidity and initial stocks. We expect our general framework to help improving model's calibration and data assimilation procedures.

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# Prediction of Total Nitrogen Distribution in Surface Soil Based on Multi-source Auxiliary Variables and Random Forest Approach

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Soil total nitrogen is closely related to soil quality and fertility. It is of great significance to know the spatial distribution characteristics of soil total nitrogen for the implementation of precision agriculture management. The spatial distribution of total nitrogen in the surface soil of Xunwu County was predicted and mapped by using two methods: random forest and random forest plus residuals kriging. These methods were combined with multi-source auxiliary variables such as (i) terrain factors, (ii) geographical coordinate, (iii) remote sensing factors, (iv) climate factors, (v) distance factors, and (vi) soil physical or chemical factors. Also, the prediction accuracy of the two models was compared after 100 times of repeated operation. Our results show that the mean values of the decision coefficient ($R^2$ = 0.6291) and concordance correlation coefficient (CCC = 0.7613) of the random forest model were higher than those of the random forest plus residual kriging method ($R^2$ = 0.5719, CCC = 0.6881). Also, the mean values of the mean absolute error (MAE = 0.1570 g·kg$^{-1}$) and root mean squared error (RMSE = 0.2108 g·kg$^{-1}$) were lower than those of the random forest plus residual kriging method (MAE = 0.1682 g·kg$^{-1}$, RMSE = 0.2267 g·kg$^{-1}$). Importantly, adding residual to the random forest model did not improve its accuracy. These results suggest that the random forest model can be used as a new method for predicting soil properties, and it provides technical support for the implementation of agricultural management.

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# Deep neural networks: a flexible framework for soil modelling

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Since the first applications of machine learning (ML) methods in the 80s, ML adoption in soil science has increased considerably. In parallel, the size of the soil datasets has also increased. However, current soil modelling is mostly based on "traditional" ML approaches, not taking full advantage of large datasets or the multiple opportunities provided by more advanced modelling methods. Here I present the latest examples in the use of ML for soil predictive modelling, specifically the use of deep learning models in the context of soil spatial modelling and soil spectroscopy. Additionally, I will show less traditional ML applications that allow the use of field data into numerical workflows, and some advanced training techniques that showcase the flexibility of neural networks and open new, exciting opportunities to solve soil modelling challenges.