Storyline „Exploring paths towards multifunctional landscapes modelling"

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Introduction to simulating multi-functional landscapes

Terrestrial landscapes need to maintain functioning ecosystems, halt biodiversity loss, and provide fresh water and food as essential resources for society. Fulfilling these competing needs will become even more challenging due to climate change and the associated increases of extreme events and lead to trade-offs. For example, intensely managed landscapes use fertilizers, pesticides and intense tilling methods, which not only decreases biodiversity and water quality but also increases eutrophication and erosion.
Models allow to thoroughly analyze these multiple trade-offs and various options of actions. Existing impact models simulate only specific landscape functions. Additionally, they are not easily transferable from one location to another. Our approach goes beyond the state-of-the-art: we develop cross-sectoral models, that allow to investigate the effect of human management and climate change on multiple landscape functions combinedly. Our models run efficiently to cover nations and continents, have a long-term perspective and are able to quantify uncertainties to assess risk and probabilities. With this new generation of robust and high-resolution compositional models, we will develop sustainable management options aimed at securing multifunctional landscapes.

In the following, we want to illustrate with two **use cases** as example how research questions on multifunctional landscapes could look like:
(i) How does a **change in agricultural management** affect plant nutrient and water use efficiency and in consequence aboveground processes and biodiversity?
To analyze this, we apply different management scenarios with varying crop rotation and usage of cover crops, organic and mineral fertilization strategies, pesticide application, irrigation and tillage practices and simulate the effects on plant productivity, water and nutrient use efficiency and leachate within the rooting zone on the farm scale. Furthermore, we simulate the fate and transport of nutrients and water flow in the unsaturated zone and the groundwater, and consequently to the river system. The combined results are used to investigate the effects on aboveground biodiversity.
(ii) How does the **forest dieback in the Harz** mountains affect the water quality and how can this be restored by specific reforestation practices?
Here, the complete effect chain from forest growth via transport of water and nutrients in the soil, nutrient inflow in streams and reservoirs is modeled. We simulate the current state of the forest after drought-induced dieback and different alternative reforestation scenarios with the aim to enable a resilient forest growth while maintaining a high water quality.

To answer these research questions, models that simulate specific environmental systems (e.g., forests, rivers, agricultural fields) at different spatial scales and the ability to efficiently couple these are needed. Over the past years, we have successfully developed different environmental models that we will now use to address the above use cases. Some of which are described in the next paragraphs.

The UFZ environmental model portfolio

At UFZ, we develop models to simulate different compartments of the terrestrial **water cycle.** The mesoscale Hydrologic Model (**mHM**, mhm-ufz.org) is a grid-based hydrologic model. Recently, we focused on adding anthropogenic components, in particular reservoirs (Shrestha et al., submitted). Building on top of the widely known German drought monitor, an operational sub-seasonal soil moisture forecasting system is also developed (Najafi et al., in prep.). Based on the drought monitor, we gained extensive experience with stakeholder interaction to provide tailored information on agricultural drought for decision making. We also investigate the impact of climate change on low flow using high-resolution EURO-CORDEX simulations (Chandrasekar et al., in prep).

Complementing the water quantity calculations provided by mHM, we are currently developing a multi-scale water quality model (**mQM**, Kumar et al. in prep., Sarrazin et al.). To apply mQM at continental scale, we have evaluated long-term trends in soil-nitrogen data (Batool et al., 2022).

While mQM and mHM focus on surface water, we are also simulating deeper groundwater using the OpenGeoSys model (**OGS**, https://www.opengeosys.org/). We have already created a regional-scale groundwater model for the Danube (Pujades et al. 2023) and also investigate the interaction of surface and groundwater by creating a one-way coupling between mHM and OGS (Jiang et al. 2018). We have also performed a spectral analysis on the interface between the unsaturated and saturated zone (Houben et al. 2022). We also studied the impact of climate change on groundwater recharge at European scale (Kumar et al., in prep.).

To simulate long-term effects of management and climate change on soil functions in **agricultural systems**, we developed the process-based model **BODIUM** (https://www.bonares.de/bodium) integrating different processes in soil and at the soil-plant interface (König et al., in press). This includes a dynamic soil structure (Weller et al., in prep), and a microbial component based on stoichiometric theory (König et al., in prep) to better represent biological processes (Vogel et al., under review). It further serves as a basis for a decision support tool for farmers and farmers advisors - the BODIUM4Farmers – and is developed in co-design with the respective stakeholders. Although BODIUM is currently extended to grasslands (Kanagarajah et al., in prep), it is mainly built for croplands.

The individual- and process-based dynamic grassland model **GRASSMIND** (https://formind.org/) simulates plant growth and dynamics of species-rich **grasslands** including management. It was recently applied to investigate the relevance of plant trait variability (Hetzer et al. 2021, Schmid et al. 2021) and effects of climate change and mowing frequency on multifunctionality of grasslands (Schmid et al. 2022, Leins et al. 2022).

The model **BEEHAVE** (https://beehave-model.net/) simulates the development of a honeybee colony and its nectar and pollen foraging behavior. It was applied to analyse the effects of crop diversity and farm structure (Horn et al. 2021), insecticides (Reiner et al. 2022) and alternative management practices (Schödl et al. 2022) on honey bee colonies.

The individual-based **fores**t gap model **FORMIND** simulates the growth of forests including processes of mortality, recruitment, and competition for environmental resources, and related carbon dynamics. It was applied to analyse climate change effects on forest and carbon storage in Africa (Fischer 2021; Hiltner et al. 2021), China (Wu et al. 2023), the Amazon (Bauer et al. 2021) and on a global basis (Fischer et al. 2021). It can be coupled to remote sensing data for biomass estimation (Bruening et al. 2021, Hiltner et al. 2022).

Towards multifunctional modelling

We have created the **LandTrans initiative** to combine the strengths of our individual modelling branches**.** Within this initiative, we simulate multifunctional landscapes and address our use cases outlined above. We will be able to simulate landscapes at large scales under climate, land use change and various management schemes. We developed the coupling framework **FINAM** (Müller et al. in prep., https://finam.pages.ufz.de/) to exchange data between the models both effectively and efficiently. One unique selling point of our modelling activities is that we are targeting multiple scales. Within mHM, we have developed the multiscale parameter regionalization (**MPR**) for this purpose (Samaniego et al. 2010). This technology was limited to mHM, but we have now created a model agnostic implementation (Schweppe et al. 2022) that is applicable to any model and will also be implemented in the **LandTrans** initiative. We are also working on the theoretical foundation of how subsurface flow has to be simulated at different spatial scales (Didato et al. submitted) that will be later implemented in MPR. The **LandTrans** modelling system constitutes a next-generation modelling system that will allow us to study multifunctional environmental systems from a holistic perspective.

References:

Batool, M., Sarrazin, F.J., Attinger, S., Basu, N.B., Van Meter, K., Kumar, R. (2022): Long-term annual soil nitrogen surplus across Europe (1850–2019). Sci. Data **9**, art. 612.

Bauer, L., **Knapp, N.**, **Fischer, R.** (2021): Mapping Amazon Forest productivity by fusing GEDI lidar waveforms with an individual-based forest model. Remote Sens. **13** (22), art. 4540.

Bruening, J.M., **Fischer, R.**, **Bohn, F.J.**, Armston, J., Armstrong, A.H., **Knapp, N.**, Tang, H., **Huth, A.**, Dubayah, R. (2021): Challenges to aboveground biomass prediction from waveform lidar. Environ. Res. Lett. **16** (12), art. 125013.

Chandrasekar et al., Changes in snow dynamics are the major source for low flow changes in Germany in a 1.5K, 2K, and 3K warmer world, in prep.

Fischer, R. (2021): The long-term consequences of forest fires on the carbon fluxes of a tropical forest in Africa. Appl. Sci. **11** (10), art. 4696.

Fischer, R., **Taubert, F.**, **Müller, M.S.**, **Groeneveld, J.**, **Lehmann, S.**, **Wiegand, T.**, **Huth, A.** (2021): Accelerated forest fragmentation leads to critical increase in tropical forest edge area. Sci. Adv. **7** (37), eabg7012.

Hetzer, J., **Huth, A.**, **Taubert, F.** (2021): The importance of plant trait variability in grasslands: a modelling study. Ecol. Model. **453**, art. 109606.

Hiltner, U., **Huth, A.**, Hérault, B., **Holtmann, A.**, Bräuning, A., **Fischer, R.** (2021): Climate change alters the ability of neotropical forests to provide timber and sequester carbon. For. Ecol. Manage. **492**, art. 119166.

Hiltner, U., **Huth, A.**, **Fischer, R.** (2022): Importance of the forest state in estimating biomass losses from tropical forests: combining dynamic forest models and remote sensing. Biogeosciences **19** (7), 1891 – 1911.

Horn, J., Becher, M.A., **Johst, K.**, Kennedy, P.J., Osborne, J.L., Radchuk, V., **Grimm, V.** (2021): Honey bee colony performance affected by crop diversity and farmland structure: a modeling framework. Ecol. Appl. **31** (1), e02216.

Houben, T., Pujades, E., Kalbacher, T., Dietrich, P., Attinger, S. (2022): From dynamic groundwater level measurements to regional aquifer parameters – Assessing the power of spectral analysis.Water Resour. Res. **58** (5), e2021WR031289.

Kanagarajah, L., Reitz, T., Schädler, M., Taubert, F., Vogel, H.-J., Weller, U., König, S. (in prep.): Modelling the effects of global change on soil functions in different land-use types

König, S., Weller, U., Betancur-Corredor, B., Lang, B., **Reitz, T.**, Wiesmeier, M., **Wollschläger, U., Vogel, H.-J.** (in press): BODIUM - a systemic approach to model the dynamics of soil functions, Eur. J. Soil Sci..

König, S., Reitz, T., Weller, U., Vogel, H.-J. (in prep).: Accounting for microbial dynamics to simulate soil functions under agricultural management.

Kumar et al. The multi-scale water quality model (working title), in prep.

Leins, J.A., **Grimm, V.**, **Drechsler, M.** (2022): Large-scale PVA modelling of insects in cultivated grasslands: The role of dispersal in mitigating the effects of management schedules under climate change. Ecol. Evol. **12** (7), e9063.

Pujades, E., Kumar, R., **Houben, T.**, Jing, M., Rakovec, O.R., Kalbacher, T., Attinger, S. (2023): Towards the construction of representative regional hydro(geo)logical numerical models: Modelling the Upper Danube basin as a starting point. Front. Earth Sci. **11**, art. 1061420.

Reiner, D., Spangenberg, M.C., **Grimm, V.**, **Groeneveld, J.**, Wiegand, K. (2022): Chronic and acute effects of imidacloprid on a simulated BEEHAVE honeybee colony. Environ. Toxicol. Chem. **41** (9), 2318 – 2327.

Sarrazin, F. J., Kumar, R., Basu, N. B., Musolff, A., Weber, M., Van Meter, K. J., & Attinger, S. (2022). Characterizing catchment-scale nitrogen legacies and constraining their uncertainties. Water Resources Research, 58, e2021WR031587. https://doi. org/10.1029/2021WR031587

Samaniego, L., Kumar, R., Attinger, S. (2010): Multiscale parameter regionalization of a grid-based hydrologic model at the mesoscale. Water Resour. Res. **46**, W05523.

Schmid, J.S., **Huth, A.**, **Taubert, F.** (2021): Influences of traits and processes on productivity and functional composition in grasslands: A modeling study. Ecol. Model. **440**, art. 109395.

Schmid, J.S., **Huth, A.**, **Taubert, F.** (2022): Impact of mowing frequency and temperature on the production of temperate grasslands: explanations received by an individual-based model. Oikos **2022** (9), e09108.

Schödl, I., Odemer, R., Becher, M.A., Berg, S., Otten, C., **Grimm, V.**, **Groeneveld, J.** (2022): Simulation of Varroa mite control in honey bee colonies without synthetic acaricides: Demonstration of Good Beekeeping Practice for Germany in the BEEHAVE model. Ecol. Evol. **12** (11), e9456.

Schweppe, R., **Thober, S.**, **Müller, S., Kelbling, M., Kumar, R., Attinger, S.,** and **Samaniego, L.** (2022): MPR 1.0: a stand-alone multiscale parameter regionalization tool for improved parameter estimation of land surface models. Geosci. Model Dev., 15, 1–24. https://doi.org/10.5194/gmd-15-1-2022, 2022.

Shrestha et al., Towards Improved Simulations of Disruptive Reservoirs in Global Hydrological Modelling, submitted.

Vogel, H.-J., Amelung, W., Blagodatsky, S., Bonkowski, M., Grosch, R., Herbst, M., Kiese, R., Koch, S., **König, S.**, Kuhwald, M., Lang, B., Lennartz, B., Leinweber, P., Müller, C., Pagel, H., Rillig, M., Russell, D., Schulz, S., Siebers, N., **Vetterlein, D.**, Wachendorf, C., **Weller, U.**, **Wollschläger, U.**, (under review.): How to adequately represent biological processes in modeling multifunctionality of arable soils. Biol. Fertil. Soils

Weller, U., König, S., Vogel, H.-J. (in prep.): Soil hydraulic modeling with flow driven potentials.

Wu, M.M., Liang, Y., **Taubert, F.**, **Huth, A.**, Zhang, M., Wang, X. (2023): Sensitivity of forest composition and productivity to climate change in mixed broadleaved-Korean pine forest of Northeastern China. Ecol. Model. **483**, art. 110434.