Exploring paths towards multi-functional landscapes: perspectives from modelling and observations

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Climate change presents significant threats to terrestrial landscapes, which are essential for maintaining functioning ecosystems, mitigating biodiversity loss, and ensuring a reliable supply of water and food for society. To effectively respond to these threats, we need reliable model predictions at operationally relevant resolutions. The grand challenge we are facing is to develop modelling systems that account for the relationship between multiple landscape functions. This holistic approach will enable us to investigate management options that will not only account for one landscape function, but for all of them.

We want to discuss the case of agricultural systems as an example here. Agricultural landscapes in Germany need to provide the basis for food production, maintain or improve biodiversity, and maintain high water quality among others. For this case, our research questions are: (1) How can we use the existing modelling strengths at UFZ combinedly to analyse agricultural systems from a multifunctional perspective? (2) What kind of observations will we need to create a high-performing modelling system? (3) Eventually, which management practices will secure sustainable agriculture under global change?

To address these questions, we need a coupled modelling framework considering water quantity and quality, vegetation phenology, soil processes, etc.. One unique selling point of UFZ is that various environmental models reaching from plant dynamics to the deep subsurface are developed at UFZ. One focus of our research in the past years was to add processes to our models that represent anthropogenic influences in the environment. We have added reservoirs to the mesoscale Hydrologic Model **mHM** to improve the representation of water use and abstraction in natural rivers (Shrestha et al., 2023). Complementing the water quantity calculations provided by mHM, we are currently developing a multi-scale water quality model **mQM** to also understand how long-term nitrate soil storage affect water quality (Sarrazin et al., 2022; Nguyen et al., 2022). We have developed the process-based soil model **BODIUM** that simulates various physical, biological and chemical processes at the field scale (König et al., 2023). It serves as a basis for a decision support tool for farmers and farmers advisors. The individual- and process-based dynamic grassland model **GRASSMIND** simulates plant growth and dynamics of species-rich grasslands including management (Hetzer et al., 2021, Schmid et al., 2021). We have recently applied to investigate the effects of climate change and mowing frequency on multifunctionality of grasslands. We are able to create regional-scale groundwater models using the open geosys model **OGS** (Pujades et al., 2023) and also investigate the interaction of surface and groundwater by creating a one-way coupling between mHM and OGS. While we are constantly adding new features to our models and are pushing the research frontier further, we are also using them to create services for society fulfilling the mission of the

Helmholtz Association. For example, the German Drought Monitor (GDM) operationally provides agricultural drought information powered by mHM. Over the past years, the GDM has become the number one information system for drought in Germany with countless national coverage media outlets. To simulate the various functions in the case of agricultural systems, we will make use of a subset of the UFZ model portfolio. We will use the grassland model **GRASSMIND**, the agricultural soil model **BODIUM**, the mesoscale Hydrologic Model **mHM**, the multiscale water quality model **mQM**, and the groundwater model **OGS**. We have developed a light-weight model coupler **FINAM** to exchange state variables and fluxes between these models. This will allow us to combine the strengths of the individual models without the need to reimplement them. In detail, we will represent each environmental process exactly once and use the representation of the model that is focused on this process. We will analyze the numerical behaviour by answering the question: how sensitive is a coupled modelling system to individual process representation and how can a process-balanced sensitivity be achieved?

The model building process requires high-quality Earth Observations to make reliable model simulation and predictions. We are contributing to Helmholtz's long-term operated environmental observatories and platforms like TERENO, MOSES, and eLTER (Zacharias, et al., 2011; Mollenhauer et al., 2018). One key variable in the environmental system that is also of highest importance to agricultural systems is soil moisture. Representative data on the spatial and temporal variability of soil moisture are an indispensable prerequisite for the development and application of environmental models. Reliable monitoring of soil moisture is a big challenge: it varies widely in space, time, and at different scales. The non-invasive and regional-scale monitoring technique "Cosmic-Ray Neutron Sensing" (CRNS) has been in the focus of UFZ research strategies in the past. Today, the UFZ is one of the world's leading centers of excellence for the theory and application of this technology. At the same time, satellite remote sensing has become another pillar of UFZ for monitoring even global-scale soil moisture dynamics (Peng et al., 2021 a, Peng et al., 2021 b). The combined multi-scale soil moisture monitoring activities bring together several departments at the UFZ as well as collaborations across other Helmholtz centres (e.g., DLR, FZJ, GFZ). This includes works (i) on the robust methodological foundation for CRNS (Köhli et al., 2015, 2023; Schrön et al., 2017, 2023), (ii) on innovative approaches to real-time acquisition of regional soil moisture using mobile CRNS applications (Schrön et al., 2018, 2021; Heistermann et al., 2022; Altdorff et al., 2023), (iii) on the near-realtime integration, quality control, provisioning, and visualization of incoming measurement data (Schmidt, L. et al., 2023), (iv) on methods for testing and improving satellite data products using CRNS (Schmidt et al., 2023), and (v) on European and global scale high-resolution soil moisture data and products (Bogena and Schrön et al. 2022; Fan et al., 2023). We are experienced in using these data sets for the validation of large-scale hydrologic models through incorporation of CRNS and remote sensing data. The "observation to model" process is of fundamental interest. We will address: How can we integrate earth-observation based datasets (e.g., soil moisture, evapotranspiration, plant traits) into our coupled modelling framework that couples various models? In particular, how can individual process representations in models be improved using observation-based datasets.

It is important to highlight that the case of agricultural system serves only as an example here. Our future work will not be limited to this case. We will also focus on other sectors like forestry and water supply. These will require other configurations of coupled models and observation-based datasets for calibration/validation. For example, the forest gap model **FORMIND** (Fischer et al., 2021) used to investigate management strategies to reforestrate the Harz Mountain region. The Forest Monitor project is providing observation-based evidence on forest health conditions over Germany. Additionally, **mHM** contributes to the Destination Earth climate-adaptation Digital Twin to quantify future water resource availabilities. Our long-term goal is to understand the effect of different management strategies within these sectors. We want to provide a comprehensive analysis of management strategy that provide the best compromise among competing landscape functions. Given that the dimension of climate change is inherently uncertain because it depends on human decisions, we will relate optimal management strategy to different degrees of future global warming.

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