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A Methodology for Implementing a Digital Twin of the Earth's Forests to Match the Requirements of Different User Groups

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Abstract

Europe has acknowledged the need to develop a very high precision digital model of the Earth, a Digital Twin Earth, running on cloud infrastructure to bring data and end-users closer together. We present results of an investigation of a proposed submodel of the digital twin, simulating the worlds' forests. We focus on the architecture of the system and the key user needs on data content and access. The results are based on a user survey showing that the forest-related communities in Europe require information on contrasting forest variables and processes, with common interest in the status and forecast of forest carbon stock. We discuss the required spatial resolution, accuracies, and modelling tools required to match the needs of the different communities in data availability and simulation of the forest ecosystem. This, together with the knowledge on existing and projected future capabilities, allows us to specify a data architecture to implement the proposed system regionally, with the outlook to expand to continental and global scales. Ultimately, a system simulating the behaviour of forests, a digital twin, would connect the bottom-up and top-down approaches of computing the forest carbon balance: from tree-based accounting of forest growth to atmospheric measurements, respectively.

Keywords: Digital Twin Earth, forest, carbon, modelling

1 Introduction

Forests make up approx. 1/3 of the Earth's land surface (FAO, 2020). They influence climate through physical, chemical, and biological processes that affect planetary energetics, the hydrologic cycle, and atmospheric composition (Bonan, 2008). Forest biomass is a central component in the terrestrial carbon balance: together with agriculture, it contributes close to

10% of the total greenhouse gases (Tubiello et al., 2015). European countries have agreed to take carbon emissions under meticulous political attention with the Paris agreement. Furthermore, forests are an important economic resource and provide ecosystem services to communities. The global forest sector had a direct contribution of more than US$539 billion and a total contribution of more than US$1298 billion to the world GDP (Li et al., 2019).

The value of Earth Observation (EO) for forestry is widely accepted: if certain baseline requirements on data availability and technology are fulfilled, the technology can provide forest area and deforestation rate, and also on more in-depth information, e.g., biodiversity (Anderson et al., 2017). Currently, information on forests is available, for example, as a part of Copernicus Core Services; the EU has also launched a new Forest Information System for Europe, based heavily on remote sensing. Recently, high-level EU documents, the Green Deal and EU Data Strategy called for bringing together European scientific and industrial excellence to develop a very high precision digital model of the Earth. The Digital Twin Earth (DTE) will provide a leading-edge capability to "visualize, monitor and forecast natural and human activity on the planet in support of sustainable development thus supporting Europe's efforts for a better environment". The Destination Earth (DestinE) policy document (European Commission, 2021) specifically foresees the creation of a Digital Twin on Climate Change Adaptation, which will also include specialised DTE's of Earth system components.

Here, we present a methodology for a spatially explicit EO data analysis and modelling tool supporting the top-level policy goals to create a specialized DTE of Earth's forests. We start with describing user needs based on a Europe-wide user survey. We consider the spatial and temporal resolutions needed by the users, and the resulting requirements of the DTE. Finally, we present a layout of the DTE, fitting the structure of DT on Climate Change Adaptation.

2 Methods

We performed 30 one-hour interviews with leading data users in forestry and forest science. As the DestinE policy targets European entities, the addressed entities were chosen from Europe, many with an international scope. They were, somewhat subjectively, divided into categories such as forest enterprises, scientific and institutional users, etc. (Table 1). We also assigned home countries to the entities, which represented their main location or home market. Many of the users are international and work with global data (e.g., most science users) or treat Europe, or even the entire globe, as their home market, but only European and international intergovernmental institutions are classified as international in Table 1.

We asked all users eleven questions, including both open-ended and multiple-choice ones (Table 2). The answers to the questions were used to determine the key estimation and prediction needs, as well as spatial and temporal resolutions and ranges for the DTE. Finally, we analysed the requirements on the available forest models and computing infrastructure to address the needs determined in the survey. The analyses were constrained by the requirements of openness and interoperability set out in the policy documents, and the key European infrastructures foreseen to be used for the tasks.

Table 1: User categeries involved in the user needs study. Country codes: DE – Germany, ES – Spain, FI – Finland, GB – United Kingdom, PL – Poland, RO – Romania, SE – Sweden, INT – international (acting at European or global scales only).

User category	number	countries
Forest enterprises	5	DE,FI,RO
Governmental bodies & international organizations	9	DE,FI,PL,RO,INT
Forest and Wood Industry	3	FI,SE
Service Companies	1	DE
Scientific users	7	DE,FI,GB, RO
Public research institutes	5	DE,ES,FI,RO
total	30	

Table 2: The questions guiding the interview. The column "Open" indicates whether the question was open-ended.

no.	Question text	Open
1	What is the key question to be answered by a forest modeling system?	yes
2	What are further priorities to be simulated?	no
3	How should the results be presented?	no
4	What is the spatial unit of the analysis you would like to carry out?	yes
5	What is the temporal scope of the analysis you would like to carry out?	yes
6	In what region on Earth do you typically carry out analyses?	yes
7	What is the size of the study area you are focusing?	yes
8	What kind of data could you contribute?	yes
9	When using the platform, would you contribute your data to the digital twin?	no
10	What systems do you have in place for analyzing the status of forests and the future development of the forests?	yes
11	At which spatial dimension could you provide data?	yes

3 Results and Discussion

The question most commonly asked to be addressed by the digital twin was forest carbon stocks and their changes (**Figure 1**). Due to the role of forests in the carbon cycle, its relevance to institutional and scientific users is not a surprise. However, this topic was also relevant for commercial entities, as indicated by the high importance of "organizational carbon balance", which quantifies the carbon footprint of the activities of an entity, including its forest-related products. Next in line were topics related to hazards and risks, including shifts in the geographic area of the climatic conditions suitable for specific overstory species. "Sustainable timber productivity" was not very high on the list, but considering the small share of commercial users in the survey, it cannot be ignored by the digital twin.

Open-ended questions included those related to carbon and climate (*What does climate change mean for the entire forest carbon cycle? How can we mitigate the effects of the wood industry to global warming?*); species and risk mitigation (*Which tree species will still occur in 100 years and where will they occur? What will be the natural borders of tree species in 2050 or 2100? What does climate change mean for individual tree species? What species to plant now in order to guarantee a continuous forest cover?*), and forestry (*Which forest type will retain its forest function in the long run? Where can forests be secured in the future, and where can timber still be produced? Where will trees still grow old enough in order to harvest timber?*).

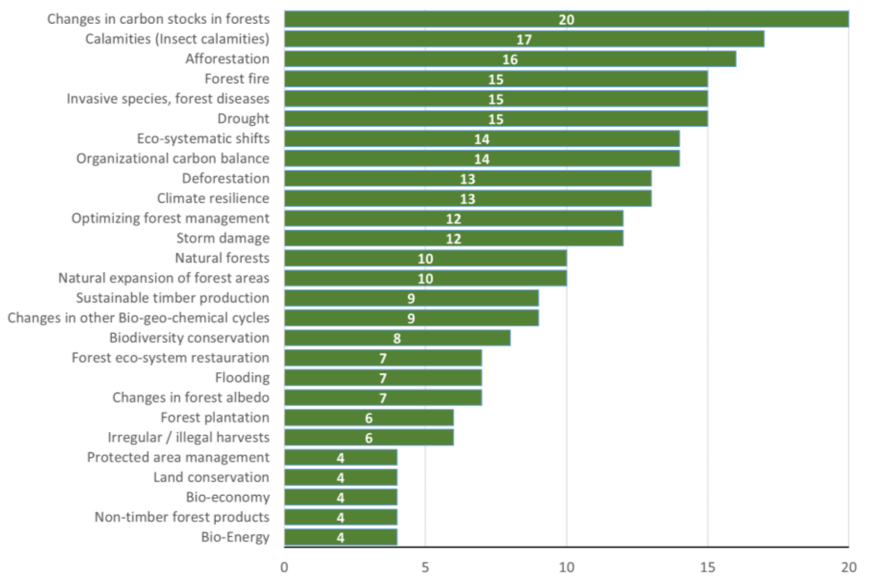

Figure 1: The number of times a need was mentioned by users. Each user was asked for three priorities.

On average, the time to be simulated was 54 years. National research centres interviewed by us are legally obliged to provide long-term simulations between 10 and 40 years. 45% of the interviewed stakeholders mentioned the need for seasonal or yearly forecasts, with one request for near real-time operations. The required time step varied from weekly and bi-weekly to monthly. Shorter steps were mentioned regarding hazards such as bark beetle disturbances or drought and fire threats. The required modelling scale varied largely between the interviewed users, ranging from a single tree to 16×16 km^2, with possible aggregation to regional/country level. A specific requirement stated by commercial users is the need to enforce access rights to data: to achieve their requirements for accuracy and reliability, commercial users need to use their privately-owned forestry data for simulations, which should not be accessible to other users of the digital twin. The visualisation and data output requirements for almost all users included geographically tagged rasters (e.g., geotiffs; NetCDF was explicitly mentioned once). More enhanced visualisations, including a fully realistic 3D and interactive representation of the forest, was not a high priority but mentioned as a tool for outreach (non-commercial users) or attracting customers (commercial users).

To answer the different tasks raised by the potential users and to match the definition of the DTE as expressed in the DestinE policy ("digital replicas of various aspects of the Earth system"; European Commission, 2021), the following modelling components need to be used: (1) forest structure retrieval, (2) forest growth model, (3) forest disturbance risk prediction, (4) forest management and scenario model, (5) wood product life cycle model, and (6) estimation of direct climate forcing of forest. As dictated by the policy documents, the digital twin will need to interact with the foreseen Digital Twin on Climate Change Adaptation, which will provide the forest twin with the scenarios to simulate, weather and climate data, parts of a user interface, etc. (**Figure 2**). Visualization will form a natural part of the DTE, implemented on the landscape scale, displaying the spatial variation in predicted key forest properties.

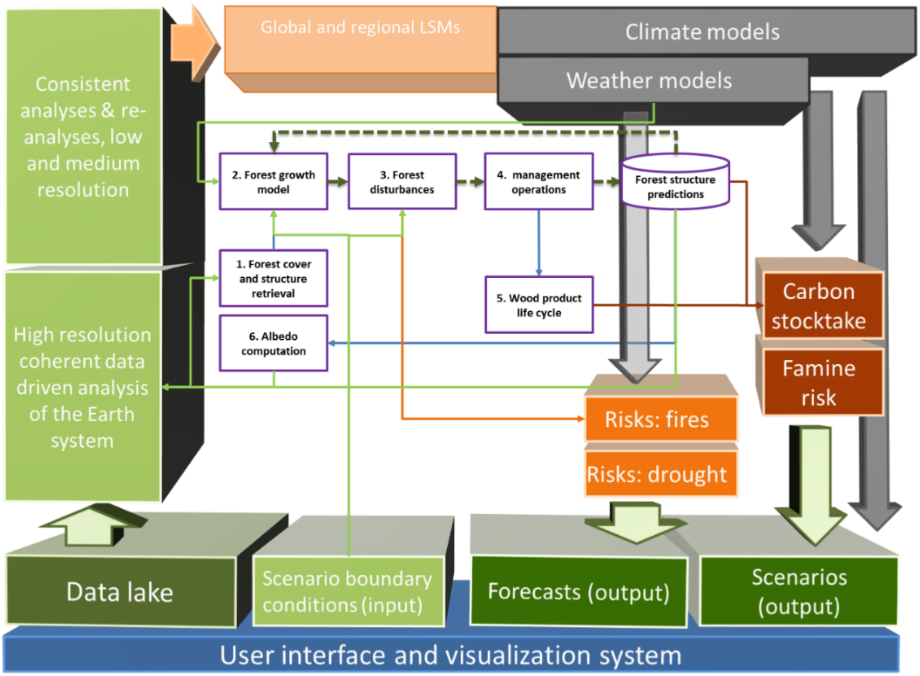

Figure 2: Positioning of the digital twin of forests (represented as a set of numbered blocks) inside the Digital Twin on Climate Change Adaptation to be implemented according to the DestinE policy.

To start the simulations, existing forests need to be mapped in the simulation area. Next, the forest productivity model needs to predict the productivity (e.g., net ecosystem exchange and the distribution of assimilated carbon in the different pools in the forest) and translate this into forest growth. In interaction with forest management and disturbance models, the forest structure should be altered in time steps required by users, quantify the side flows of carbon (e.g., into wood products), and determine the status of the forest for the next iteration. A single forest productivity and growth model can be adopted, calibrated for different biomes (e.g., Tian et al., 2020) or several biome-specific models could be combined. Great attention must be paid to model validation: model prediction errors consist of inherent model errors and model calibration (parameterization) errors, with the former contributing up to 50% of model performance (Dietze et al., 2014). Forest management models need to be up-to-date regarding national forest policies and regulations, while forest damage assessment still requires expert knowledge (e.g., Jactel et al., 2012).

Due to the nature of the models, optical multispectral data is recommended (Sirro et al., 2018) for estimating the forest variables and initializing the modelling process. For global coverage and unlimited accessibility, Sentinel-2 and Landsat are the preferred sources. Auxiliary data (field plot measurements, airborne laser scanning, very high resolution imagery, future hyperspectral and chlorophyll fluorescence imagery, etc.) should be included where and when available. In addition to providing the required EO data, the computing environment should support the implementation of the forest models mentioned above and provision of environmental and weather data required by the forest growth model. Such infrastructure in Europe is provided by the Copernicus Data and Information Access Services (DIAS), initially funded by the European Commission.

The key components and competences for a successful implementation of a digital twin of the Earth's forests exist in Europe. The biggest challenge is to implement the system at the very high resolution required by the forestry sector, while still achieving compatibility with the global estimates of carbon fluxes from the variations in the CO_2 concentration in the atmosphere (i.e., merging bottom-up and top-down approaches of carbon flux estimations). Based on the work presented here, the policy-driven enthusiasm in Europe is supported by real user-side interest and technological readiness.

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