High-performance computing for mechanistic predictions of biome distribution

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1. Background

- Biomes are vegetation assemblages that are shaped by the convergent evolution of plant forms that adapt to similar climatic conditions, regardless of species ancestry.
- Modeling at the biome level allows us to understand how entire ecosystems, not just individual species, respond to their environmental niche and how these responses may shift over time.

BIOME4

- In the face of climate change, we can no longer assume that current biome distributions will align with their climatic niches in the future. This calls for a shift from correlative models based on observed distributions to process-based models that incorporate the physiological mechanisms driving vegetation dynamics.
- A **biogeophysical model** like BIOME4 [1],[2] addresses this need by simulating both the potential natural distribution of vegetation types (biogeography) and the biogeochemical fluxes of carbon and nutrients within ecosystems (biogeochemistry). It uses plant functional types with distinct physiological responses to climate variables, allowing for a mechanistic understanding of biomass production and competitive interactions under changing environmental conditions.

Why is it useful to have High-Resolution models?

- They capture ecological variation in complex terrains such as mountainous regions/ecotones

Historical Constraints to High-Resolution Modeling

- Limited computational capacity in the past
- Absence of reliable, high-resolution climatic input / validation dataset

2. BIOME4.jl

- **Resolution**: Increased from 55 km to 1 km (over 3,000× more pixels).
- **Parallelization**: Runs on up to 300 CPU threads; full global simulations parallelized by pixel blocks.
- **Memory Handling**: Capable of processing more than 400 GB of input climate data without exceeding HPC memory limits.
- **Modularity**: Separated modules for input handling, core processes, and output. New scenarios, PFTs, biome types, biophysical limits or ecological processes can be integrated independently.
- **Performance**: Just-in-time (JIT) compilation yields speeds comparable to Fortran for numerical operations.

Climate change scenario

- Input data: climatological monthly mean timestep with a minimum of ca. 30 years average extracted from CHELSA-1km for temperature, precipitation and cloud cover for 1951-1981, 1980-2010 climatologies and CHELSA-CMIP6 variables for SSP3.7-0: regional rivalry for the period 2041-2070 with the model GFDL-ESM4 (realistic vegetation-climate feedbacks, nutrient limitation processes) [3],[4]. The input data for soil saturated conductivity and water holding capacity is extracted from SoilGrids using the ARVE-Research program makesoil (available on GitHub) [5].
- Atmospheric CO_2 concentrations in ppm globally averaged for the climatological periods [6]:
    - 1951-1980: 322.4, 1981-2010: 373.8, 2041-2071: 570.9

3. BIOME4.jl for High-Resolution Predictions Over Mountain Terrain

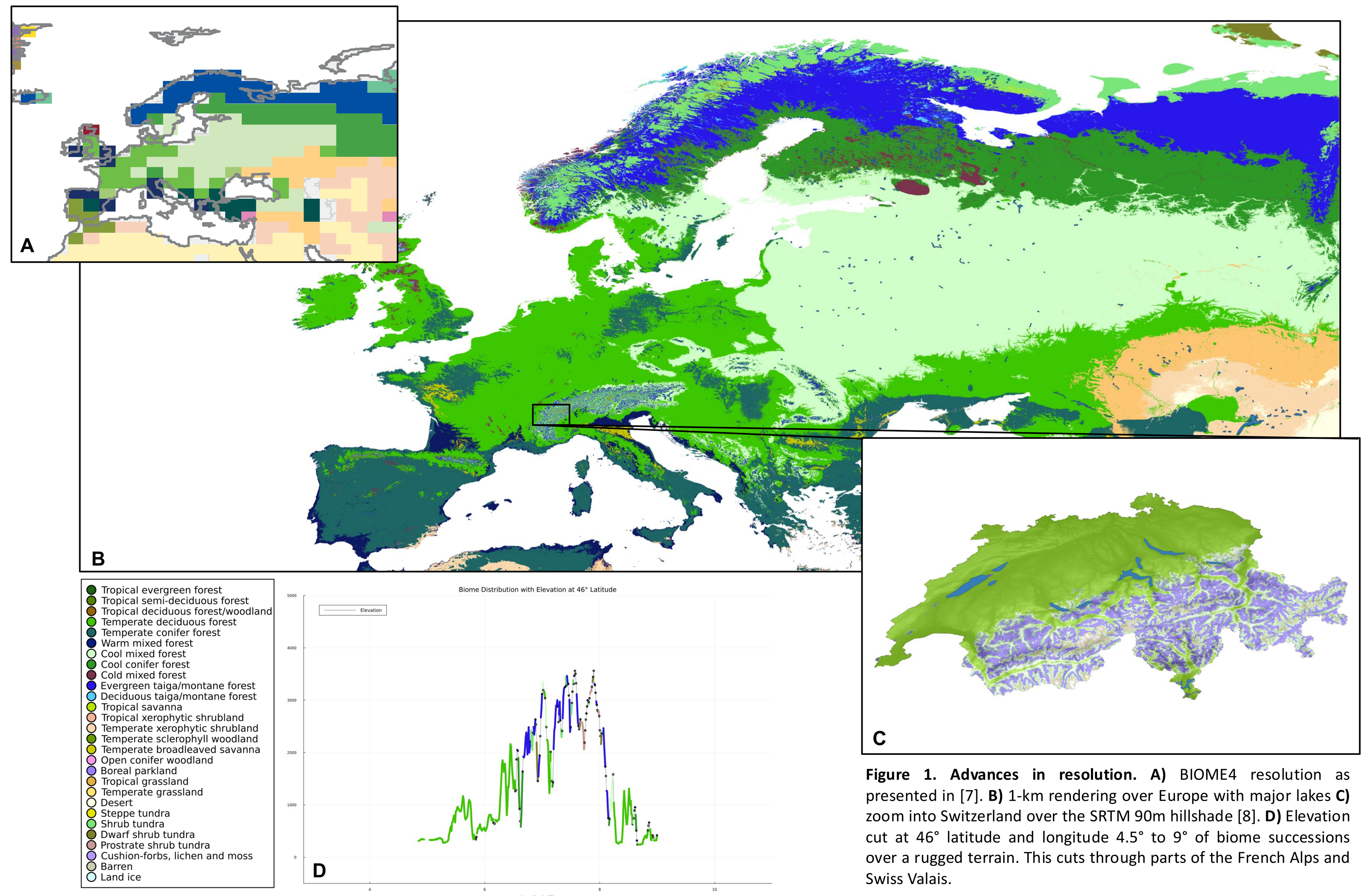
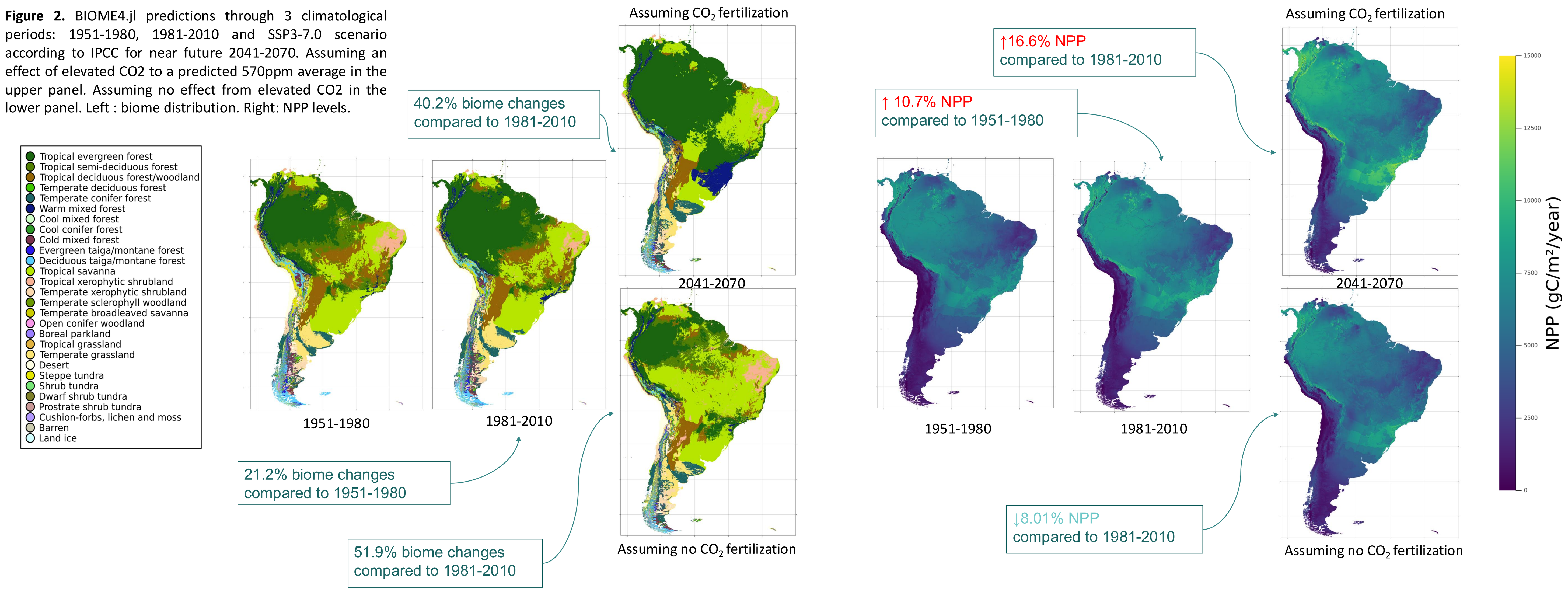


Figure 1. Advances in resolution. A) BIOME4 resolution as presented in [7]. **B)** 1-km rendering over Europe with major lakes **C)** zoom into Switzerland over the SRTM 90m hillshade [8]. **D)** Elevation cut at 46° latitude and longitude 4.5° to 9° of biome successions over a rugged terrain. This cuts through parts of the French Alps and Swiss Valais.

4. Using BIOME4.jl to Predict Vegetation Change and Isolate the Role of CO_2

Figure 2. BIOME4.jl predictions through 3 climatological periods: 1951-1980, 1981-2010 and SSP3-7.0 scenario according to IPCC for near future 2041-2070. Assuming an effect of elevated CO2 to a predicted 570ppm average in the upper panel. Assuming no effect from elevated CO2 in the lower panel. Left : biome distribution. Right: NPP levels.



- **CO_2 fertilization** refers to the enhancement of photosynthesis and reduction of leaf and ecosystem transpiration with rising atmospheric CO_2 concentrations. This effect is considered one of the most important negative feedback process to mitigate global warming through the enhancement of the land carbon sink [9]. Notably, CO2 is known to increase plant water use efficiency, possibly palliating drought effects from warming [10].
    - Because one cannot link the empirically measured physiological responses of plants to the equilibrium state of an ecosystem, **we cannot evaluate the extent to which CO_2 fertilization will increase productivity**, and its long-term effect on community structure [11].
- Regarding this limitation and our findings, in the SSP3.7-0 scenario there is a **high uncertainty in biome response** to climate change in terms of forest cover and biomass depending on the actual effects of elevated atmospheric CO_2 on photosynthesis.
    - The results suggest that the historical increase in productivity is likely to continue due to increase in temperatures and decrease in cloud cover only in the CO_2 fertilization scenario.
    - Where CO_2 does not affect plant growth, we expect to see enhanced drought effects and the loss of forest in the Amazon and Brazilian Sul and Sudeste.
    - A plateau in productivity with CO_2 increase has been suggested to be reached at 700ppm in plants grown at low nitrogen levels [12]. With 570.9ppm average over 2041-2070, BIOME4.jl should be able to accurately predict equilibrium biomes for SSP3.7-0 but its scope may be limited by the absence of a nutrient cycling module in projected future scenarios.

5. Outlook

- The parallelized and hyper-computing version of BIOME4.jl will allow for further tuning of biophysical parameters of plant functional types, particular attention will be given to mountain areas and ecotones.
- BIOME4.jl combined with high resolution data for climate change scenarios allow to identify regions that are the most subject to change, uncertainty, and shift in productivity.

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