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Assessing forest management practices across Europe under climate scenarios: insights from the 3D–CMCC–FEM model in the OptFor–EU Project

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Forest modeling is essential for understanding ecosystem dynamics, evaluating future scenarios, and supporting informed decision–making, mainly given the long–life cycles of trees. Within the 4–year project (2023–2027) "OPTimising FORest management decisions for a low–carbon, climate–resilient future in Europe" (OptFor–EU), several model types, including forest, climate, and land surface vegetation models, are used to simulate forest dynamics under climate scenarios. A primary project effort includes developing and testing new Forest Management Practices (FMPs), building on widely used management practices such as clearcut, shelterwood, and continuous forest cover using single tree harvesting. These FMPs are crucial for generating accurate forest future representation, as most European forests undergo active management (State of Europe's forests, 2020).

The 3D–CMCC–FEM model plays a central role in the OptFor–EU project. It is a process–based model simulating forest eco–physiological, and biogeochemical processes, developed to simulate different forest management scenarios. It accounts for species differences, age classes, and tree dimensions, modeling carbon and water cycles on a daily basis at a hectare scale (Collalti et al., 2014, 2018, 2024; Dalmonech et al., 2022). It has been widely applied in European forests, making it perfectly fitting for OptFor–EU purposes (i.e., Collalti et al., 2016; Marconi et al., 2017; Morichetti et al., 2024; Vangi et al., 2024a).

The simulations focus on three case study areas: Austria, Romania, and Italy, representing alpine, temperate, and Mediterranean ecosystems, respectively. Climate data from the EURO–CORDEX regional models HIRHAM5 and RACMO22E, aligned with CMIP5 scenarios (RCP2.6, 4.5, and 8.5), are used to drive the simulations (Jacob et al., 2020). Forest stands are grouped by species composition and 20–year age classes to ensure heterogeneity. Simulations target a minimum of 50 plots per European Forest Type (EFT), ensuring statistical robustness.

Different FMPs are tested under the same climate conditions to isolate the impacts of management on forest carbon stocks. For instance, considering the EFT 6 (*Fagus sylvatica* L.), for

AC1 (i.e., Age Class 0–20), NOMAN results in the highest biomass carbon stocks in the end of simulation (250 tC ha^{-1}) due to the absence of harvesting. Shelterwood management (BAU), involving periodic thinnings and final harvesting, achieves near–NOMAN carbon levels. Variants like BAU^{+} (increased thinning) target larger products, whereas BAU^{-} (reduced thinning) promotes denser forests with higher carbon stocks. Continuous cover systems apply single–tree harvesting every decade, fostering uneven–aged stands. These methods sustain carbon stocks between 100–200 tC ha^{-1}. In contrast, low–intensity harvesting (5 m^3 ha^{-1} per year), suitable for protecting forests prone to disturbances, leads to moderate carbon storage trends.

This comparative approach provides valuable insights for decision–makers, enabling the development of tailored forest management strategies that consider ecological and climatic contexts. By integrating diverse FMPs and climate scenarios, OptFor–EU supports sustainable forest management for a low–carbon, and climate–resilient future in Europe.