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Evaluating management and climatic scenarios on *Eucalyptus* plantations using a new ecophysiological model of water dynamics and wood production

Guerric le Maire[1]
Ivan Cornut[1]
Joannès Guillemot[1]
Yann Nouvellon[1]
Otavio Campoe[2]
José-Luiz Stape[3]
Jean-Paul Laclau[1]
Nicolas Delpierre[4]

[1] CIRAD, UMR Eco&Sols, guerric.le_maire@cirad.fr
[1] CIRAD, UMR Eco&Sols, ivan.cornut@cirad.fr
[1] CIRAD, UMR Eco&Sols, joannes.guillemot@cirad.fr
[1] CIRAD, UMR Eco&Sols, yann.nouvellon@cirad.fr
[2] Federal University of Lavras – UFLA, otavio.campoe@ufla.br
[3] UNESP-FCA, jlstape@gmail.com
[4] Université Paris Saclay, UMR ESE, nicolas.delpierre@universite-paris-saclay.fr

ABSTRACT: *Water availability is a critical factor affecting the growth of Eucalyptus plantations, particularly in tropical and subtropical regions where droughts are expected to increase in frequency and intensity due to climate change. Managing water resource sustainably is thus essential for the long-term viability of plantations and other water use in the watershed. We developed a new ecophysiological model, CASTANEA-MAESPA, to simulate the interactions between plantation growth, soil water dynamics, and water-table balance over multiple rotations. We parameterized and validated the model using 12 years of time-series data on soil water content, water-table levels, and evapotranspiration obtained from eddy covariance measurements. We also tested the model's ability to predict changes in wood production resulting from a 33% reduction in rainfall during a rainfall exclusion experiment. Our model provides a valuable tool for evaluating the impacts of climate and management scenarios, including rotation length, planting density, and the duration between harvest and planting, on water use, water-table discharge, and wood production.*

keywords: process-based model, water use, water table depth, wood production

Introduction

Fast-growing tropical plantations are highly susceptible to drought and rainfall variability (Allen, 2009), necessitating a reevaluation of management strategies to enhance plantation drought tolerance. Silvicultural adaptations to improve plantation drought tolerance include: (i) selecting drought-tolerant species and hybrids through breeding programs, (ii) reducing stocking densities, rotation lengths, or increase the duration between harvesting and replanting to promote soil water recharge after clear-cutting, (iii) prioritizing afforestation on deep soils, and on soils where the water table is not too deep, and (iv) reducing fertilizer applications. These strategies have been proposed by various studies and may help sustain fast-growing tropical plantations under changing climatic conditions, and should be carefully analyzed.

In particular, deep soil water storage is critical for tree survival and functioning in tropical regions, enabling trees to withdraw water from depths greater than 8-10 m during dry periods (Costa et al., 2023; Stocker et al., 2023). This is also the case in some eucalypt plantations: if a water table is present on the site, the water uptake in the capillary fringe is likely to play a critical role for the tree functioning during severe drought when soil profile is drier (Christina et al., 2017).

Forest ecophysiological process-based models that couple the water and carbon cycles are crucial for improving our understanding of forest functioning. Indeed, these models are based on fundamental mechanisms and can predict the carbon and water balance under different climatic and management scenarios. While several forest ecophysiological models exist that account for soil water dynamics and its impact on growth, such as Gday (Marsden *et al.*, 2013), they do not consider the presence of a water table, or do so only in a simplistic manner (Attia et al., 2019). Other models, such as HYDRUS (Simunek et al., 2005) or MAESPA (Duursma and Medlyn, 2012), can simulate water flow in soil and the presence of a water table, but are not specifically adapted to modeling rapid forest plantation growth or the retroactions between water availability and tree growth.

The present study introduces a new model, CASTANEA-MAESPA, which accounts for the presence of a water table in deep sandy soils and the interactions between the growing forest plantation and the water table dynamic. This model represents an important advance in the field of forest ecophysiological - ecohydrological modeling and provides a valuable tool for assessing the sustainability of forest plantations under various climatic and management scenarios.

Material and methods

CASTANEA-MAESPA model

CASTANEA-MAESPA is a process-based model that couples carbon and water cycles to simulate forest growth at the stand level. The model is an adaptation of the original CASTANEA model (Dufrêne et al., 2005). In order to simulate the water-plant-atmosphere hydraulic continuum, CASTANEA was coupled with the MAESPA model and adapted to eucalypt plantations (Christina et al., 2018). This was necessary since CASTANEA was not originately simulating the hydraulic continuum, and the assumption of a fixed root depth made by CASTANEA was not valid in the studied system. Details on the development of the CASTANEA-MAESPA coupled model can be found in (Cornut et al., 2022a; Cornut et al., 2022b). A schematic overview of the model is given in Figure 1.

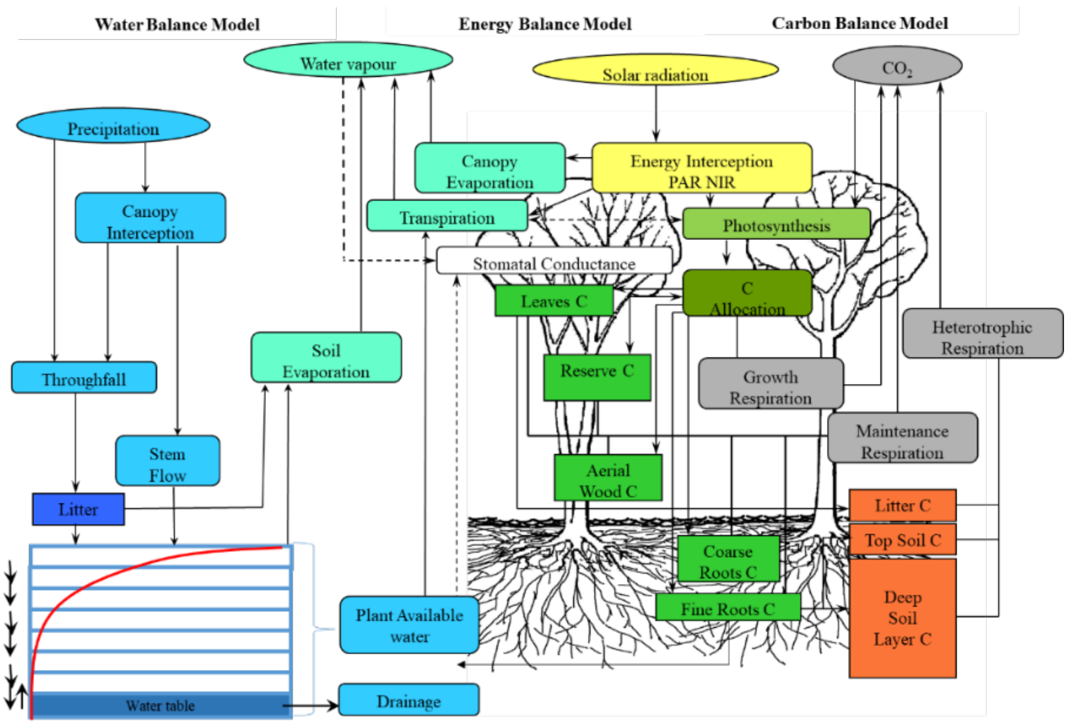

Figure 1: Schematic representation of CASTANEA-MAESPA model

Model parameterization and validation

To ensure the accuracy and applicability of the CASTANEA-MAESPA model to specific sites and species, a comprehensive parameterization process is necessary. While some model parameters can be obtained from literature, we conducted dedicated experiments to measure more than 50 critical parameters, including leaf photosynthetic parameters, plant hydraulic conductivities, and root profiles. This study presents the parameterization and test of the model for two different sites in Itatinga, São Paulo state, southeastern Brazil. The first site was a 200-hectare commercial plantation, which was part of the Eucflux project. The model was parameterized for the two successive genotypes and for the hydraulic profile of the soil. To validate the model, we compared 11 years of simulated soil water content and water table depth with the same 11 years of measured data, among other variables.

The second site was a large experiment of rainfall exclusion, crossed with potassium (K) fertilization omission trial. We parameterized the model for the Eucalypt genotype and the soil of this experiment, and tested the impact of a one-third reduction in rainfall on biomass production under K omission. Simulations were compared with measured biomasses for a five-year rotation. Notably, the CASTANEA-MAESPA model also simulates the K cycle, as described in (Cornut et al., 2022a) which also allowed to test the impact of rainfall reduction on biomass production under K omission.

Model simulation of different climate and management scenarios

The validated model was then applied on different scenarios of climate and management at the Eucflux site. Climate scenarios were constructed : i) we reduced the rainfall by 15 and 30 % ; ii) we randomly inverted the years of meteorological data to explore the potential impact of inter-annual variability in climate; iii) we randomly selected years with increased frequencies of drier years to explore the impact of more extreme and frequent drought events; iv) we tested the impact of changes in management practices by altering the timing and duration of the inter-planting period; and v) we evaluated the sensitivity of the model to changes in genotype parameter sets.

Results and discussion

Test of the model on in situ long-term measurements

The CASTANEA-MAESPA model accurately represents water flows in the soil and the dynamics of the water table depth (Figure 2). The model was not directly calibrated using these measurements; rather, the simulation of soil water content and water table dynamics arises from several interacting processes. It accurately captures the dynamic of the soil water content and water table depth, exhibiting a significant rise at the beginning of the rotation followed by a continuous decrease over time. Our model also successfully reproduces the decrease in biomass production resulting from reduction in rainfall, as observed in both the normal fertilization and K omission trials (Figure 3).

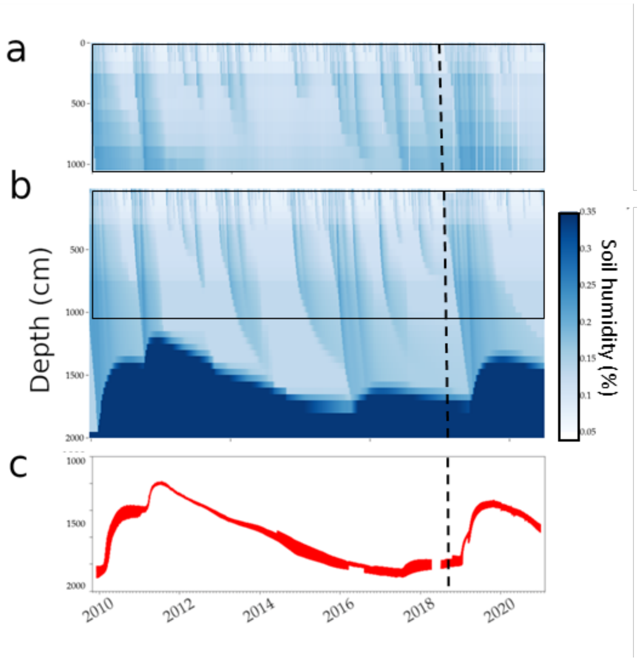

Figure 2: Measured (a) and simulated (b) soil water profiles. Black boxes show same soil depth. Dashed lines show harvest date. The dynamics between the simulated water table (b) and measured water table depth (c) are similar.

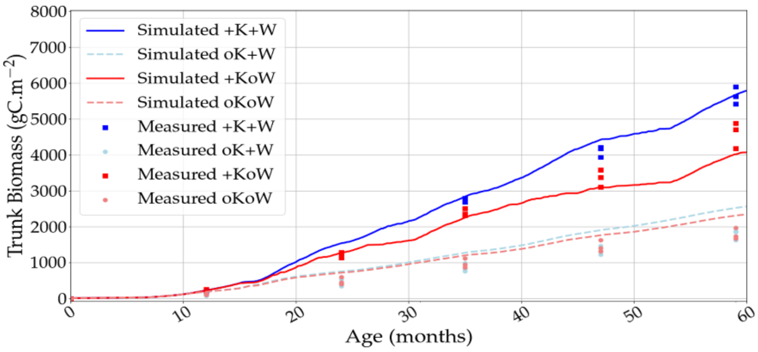

Figure 3: Measured (points) and simulated (lines) trunk biomass in an experiment with partial (33%) rainfall exclusion (oW, red) crossed with potassium omission (oK, dashed)

Application to climatic and management scenarios

Figure 4 shows the result of one of the scenario (scenario i): the simulations reveal the long term influence of rainfall reduction, where the water table height decreased, but also its recovery during the inter-planting period. Our study highlights the applicability of the CASTANEA-MAESPA model to diverse scenarios and management strategies.

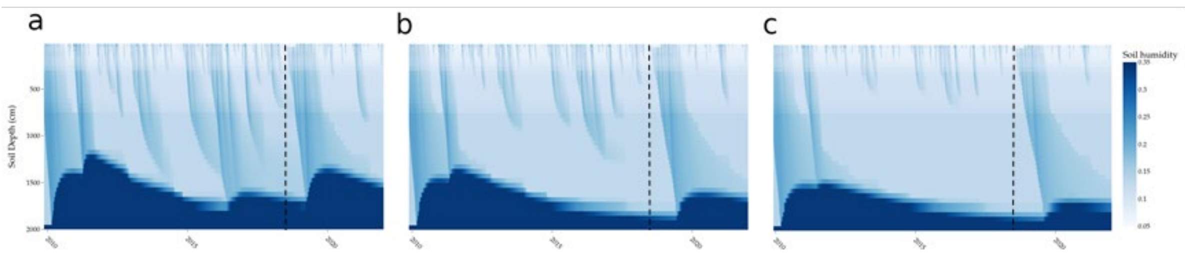

Figure 4: Simulated soil water profile under different water regimes: measured precipitation (a), reduced precipitation by 15% (b) or by 30% (c).

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