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SurEau-Ecos-FMC: mechanistic modelling of fuel moisture content (FMC) at leaf and canopy scale under extreme drought

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Forest flammability, plant-water relations, fuel modeling, fire-vegetation interactions

Abstract

Understanding and predicting fuel moisture content (FMC) is a crucial prerequisite to increase our knowledge of forest's vulnerability to fires in a changing climate. While live fuel moisture content (LFMC) is a main driver of fire behavior and activity in crown fires in forests and shrublands, it remains poorly understood and predicted, especially under extreme drought. A major reason for that is that LFMC sensitivity to climate is mediated by a range of location-specific factors, including soil characteristics and plant response to drought. Another reason is that LFMC is often simulated at the leaf scale while, from a fire danger perspective, canopy scale fuel moisture content (CFMC) is more relevant.

Here we introduced a FMC module in the plant-hydraulic SurEau-Ecos model to simulate the dynamics of both LFMC and CFMC as a function of leaf water potential (ψ_{Leaf}). CFMC integrates the impacts on moisture content of foliage mortality that can occur under extreme drought because of leaf embolism. SurEau-Ecos-FMC relies on two main mechanisms. The relationship between ψ_{Leaf} and leaf relative water content of the symplasm is modeled through pressure volume curves. Percent loss of leaf conductance (PLC) is derived from ψ_{Leaf} through vulnerability curves to cavitation and affects the dynamics of fuel moisture content in two different ways. At the leaf level, PLC dictates the dynamics of the leaf apoplasmic reservoir. At the canopy level, PLC drives the proportion of dead fuel within the canopy.

SurEau-Ecos-FMC accurately reproduced the temporal dynamics of LFMC in a Quercus ilex stand at the Puéchabon site over a three-years period. The model explained 69 % (RMSE = 4.27) and 74 % (RMSE = 4.92) of the variance in the minimum and maximum daily observed LFMC, respectively. The model was also able to capture the dynamics in CFMC resulting from leaf mortality during the summer drought. The years when SurEau-Ecos-FMC predicted leaf mortality were also the ones with the highest anomaly in NDVI. Multi-model projections of fire danger indices based on CFMC showed a general increase of fire danger over the next century. Under RCP8.5, the averaged minimum CFMC reached during the year is expected to decrease from 65 % to 32 % and the fire season length (number of day when CFMC<67%) is expected to increase from 15 to 120 days per year.

SurEau-Ecos-FMC offer new opportunities to improve our comprehension of LFMC's sensitivity to climate and we show that plant embolism might be a growing cause of FMC decrease in a drier climate. We also encourage the use of SurEau-Ecos-FMC to inform fire models in order to increase our understanding of the FMC's effect on fire behavior and activity.

1. Introduction

Fuel moisture content (*FMC*), the ratio of water mass to dry mass of vegetation, governs the amount of time and energy needed to vaporize fuel moisture before ignition can occur. *FMC* is usually separated into dead (*DFMC*) and live (*LFMC*). Declining *LFMC* was associated with an increase in area burned (Pimont *et al.* 2019a), extreme wildfires (Ruffault *et al.* 2018a) and increased fire behavior (Pimont *et al.* 2019b).

Despite its importance, LFMC remains poorly understood and predicted for two main reasons. First, unlike DFMC, the effect of climate on LFMC is regulated by a range of location-specific factors, including plant traits

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and soil characteristics (Ruffault et al. 2018b, Nolan et al. 2020). As a result, models based on meteorological drought indices do not accurately predict LFMC (Ruffault *et al.* 2018b). Second, canopy level moisture content (CFMC) is more relevant for wildfire danger (Rossa and Fernandes 2018) but predicting CFMC requires to take into account the mechanisms that lead to leaf mortality under severe to extreme drought.

Recent advances in our physiological understanding of plant response to drought have led new opportunities to improve our comprehension of leaf-level and canopy-scale FMC sensitivity to climate (see Figure 1). A first theoretical framework, derived from pressure volume (p-v) curves, states that the response of symplasmic water content to leaf water potential essentially depends on cell wall elasticity (ε) and leaf osmotic potential (π_0). Such relationships have recently been adapted to model leaf-level LFMC (Nolan *et al.* 2020). A second framework, inherited from plant hydraulic, allow to derive the water content of the apoplasmic tissue and the ratio of dead to live fuels within the canopy from the percent loss of conductance (PLC).

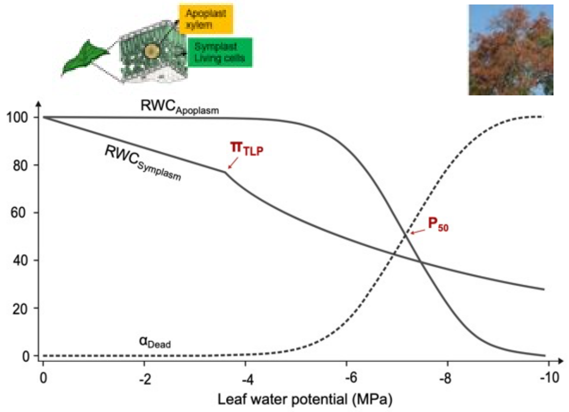
Understanding and anticipating fire hazard requires to improve our current knowledge of fuel moisture response to climate. As compound dry and hot events become more frequent and intense (Ruffault et al. 2020), drought-induced plant defoliation and mortality that affect CFMC are likely to increase in many ecosystems (Allen et al., 2015). Here we developed a FMC module in the plant-hydraulic SurEau-Ecos model (Ruffault et al., 2022) to simulate the dynamics of LFMC and CFMC and compared them with field measurements. We then explored the impact on future climate changes on wildfire danger.

2. Methods

2.1. SurEau-Ecos-FMC

We implemented a fuel moisture content (*FMC*) module into *SurEau-Ecos* to simulate *FMC* dynamics of fine canopy fuels (shoot and leaves), both at the leaf and canopy levels. *SurEau-Ecos* is a plant-hydraulic model that simulates plant water status and fluxes between the soil, plant and the atmosphere. *SurEau-Ecos* draws on the mechanisms developed in *SurEau* (Cochard *et al.* 2021) and an ecosystem-level water balance model (Ruffault *et al.* 2013). It predicts hourly plant water potentials as function of soil properties, plant hydraulic traits, stand structure and daily climatic variables (see a full description in Ruffault *et al.* 2022).

SurEau-Ecos-FMC relies on two main mechanisms (Figure 1). The relationship between ψ_{Leaf} and leaf relative water content of the symplasm is modeled through pressure volume curves. Percent loss of leaf conductance (PLC) is derived from ψ_{Leaf} through vulnerability curves to cavitation and affects the dynamics of fuel moisture content in two different ways. At the leaf level, PLC dictates the dynamics of the leaf apoplasmic reservoir. At the canopy level, PLC drives the proportion of dead fuel within the canopy (α_{Dead}). Dead leaves are assumed to stay on plant until the end of the year.



Main Definitions

$\boldsymbol{CFMC}$: $Canopy\ fuel\ moisture\ content$
α_{Dead} : $Dead\ to\ live\ fuel\ ratio$
$\boldsymbol{LFMC}$: $Live\ fuel\ moisture\ content$
$\boldsymbol{DFMC}$: $Dead\ fuel\ moisture\ content$

Main equations

$$\boldsymbol{CFMC} = \alpha_{Dead}\boldsymbol{DFMC} + (\mathbf{1} - \alpha_{Dead})\boldsymbol{LFMC}$$

$$\alpha_{Dead} = f(embolism)$$

$$LFMC = LFMC_{sat}\left[a_f RWC_{Apo} + (1 - a_f)RWC_{Sym}\right]$$

$$\boldsymbol{DFMC} = f(VPD)$$

Figure 1- Schematic representation of the main processes and equations involved in the dynamics of live fuel moisture content (LFMC) and canopy moisture content (CFMC) in the plant-hydraulic model SurEau-Ecos-FMC.

2.2. Validation datasets

SurEau-Ecos-FMC estimations of ψ_{Leaf}, LFMC and *CFMC* were compared to measurements made on a *Quercus ilex* Mediterranean forest for the period 2016-2018. The study site is located at the Puéchabon forest at 35 *km* north-west of Montpellier (southern France; 270 m ASL). ψ_{Leaf} and *LFMC* were measured at predawn and at midday for five trees during the summer drought (May to October) approximatively once per 3 weeks each year. As a proxy of leaf mortality, we used the Normalized Difference Vegetation Index (NDVI). Continuous NDVI measurements were made using a sensor positioned above the canopy. We computed an index of foliage change during the summer drought as the relative variation in NDVI between leaf maturity (around early July) and the end of the summer.

2.3. Projections of fuel moisture content

Projections of climate variables for the future climate period (2005-2100) and historical periods used as input in FMC projections (section 2.3.5) were obtained from the climate simulation program involved in the 5th phase of the Coupled Model Intercomparison Project (CMIP5) produced as part of the EURO-CORDEX initiative. 13 GCM-RCM couples were selected and extracted for the historical (1990–2005) and future (2006–2099) periods for the RCP4.5 and RCP8.5 scenarios. Model outputs were bias-corrected by a multivariate correction approach (*MBCn*, Cannon, 2018).

3. Results and Discussion

SurEau-Ecos-FMC captured well the variations in predawn (ψ_{pd}) and midday (ψ_{md}) leaf water potentials measured at the Puéchabon site over the three studied years (Figure 2A), explaining 98 % (RMSE = 0.27) and 87 % (RMSE = 0.45) of their variance, respectively. *SurEau-Ecos-FMC* also captured relatively well the temporal dynamics of leaf level LFMC (Figure 2B). The model explained 69 % (RMSE = 4.27) and 74 % (RMSE = 4.92) of the variance in the minimum and maximum daily observed LFMC, respectively. This provides further evidence of the relevancy of p-v curves to estimate LFMC from leaf water potential. However, model performance was lower than that obtained for ψ_{pd} and ψ_{md}. A potential gain of performance in LFMC predictions could be attained by taking into account year-to year osmotic adjustments.

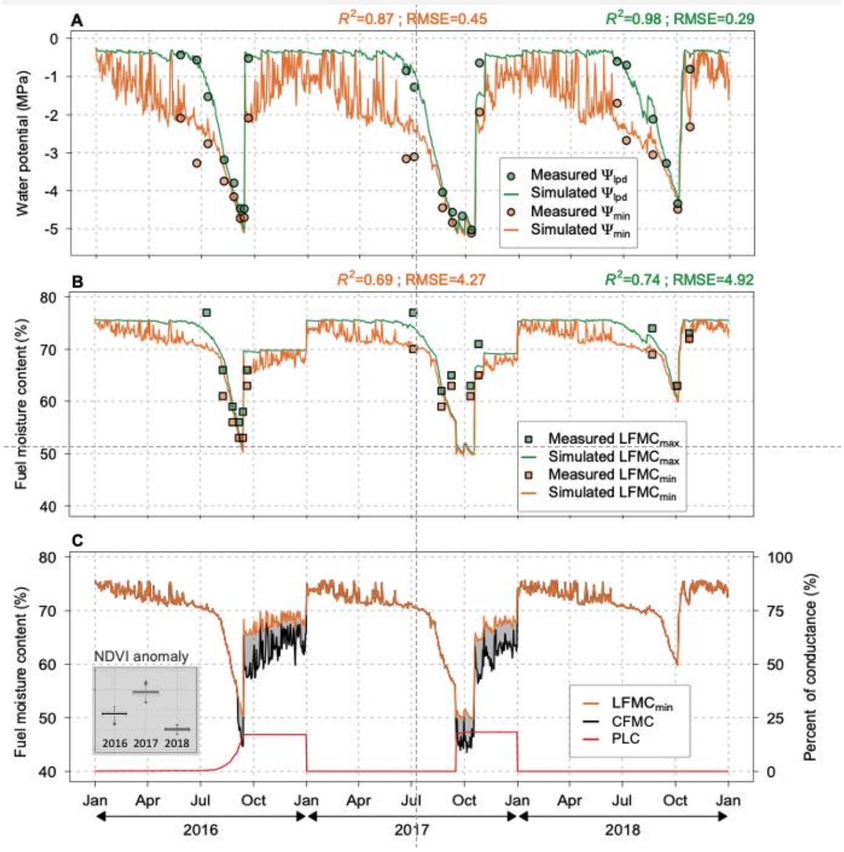


Figure 2- Dynamics of simulated and observed (A) leaf water potential, (B) live fuel moisture content (LFMC) and (C) canopy fuel moisture content (CFMC) for the three studied years. The insert panel in (C) shows the standardized anomaly in NDVI

Our model showed that the conditions observed during the 2016 and 2017 summer droughts (Figure 2C) led to a 20% rate of leaf embolism. This in turn led to a decrease in *CFMC* compared to what was observed at the leaf level. These results are consistent with a higher relative change in NDVI during the year 2016 and 2017 compared to 2018 (insert panel in Figure 2C).

Our projections of fire danger indices based on *CFMC* showed a general increase of fire danger over the next century but with major differences according to the emission scenario (Figure 3A and 3B). *CFMC$_{min}$* decreased from 65% to the 62% for end of the century under RCP4.5 but down to 32% under RCP8.5. Similarly, FSL increased from 15 to 20 days per year under RCP4.5 but up to 120 day per year under RCP8.5. A significant part of these trends was due to the increase in drought-induced leaf embolism (Figure 3C) that contribute to decrease LFMC and increase dead to live ratio of foliage in the canopy. More research is need to assess how long do dead leaves might stay on the trees. Plants are also likely to adapt to drier conditions by a series of mechanisms, including long-term reductions in leaf are index, that were not included in the present simulations, but might be explored in future work.

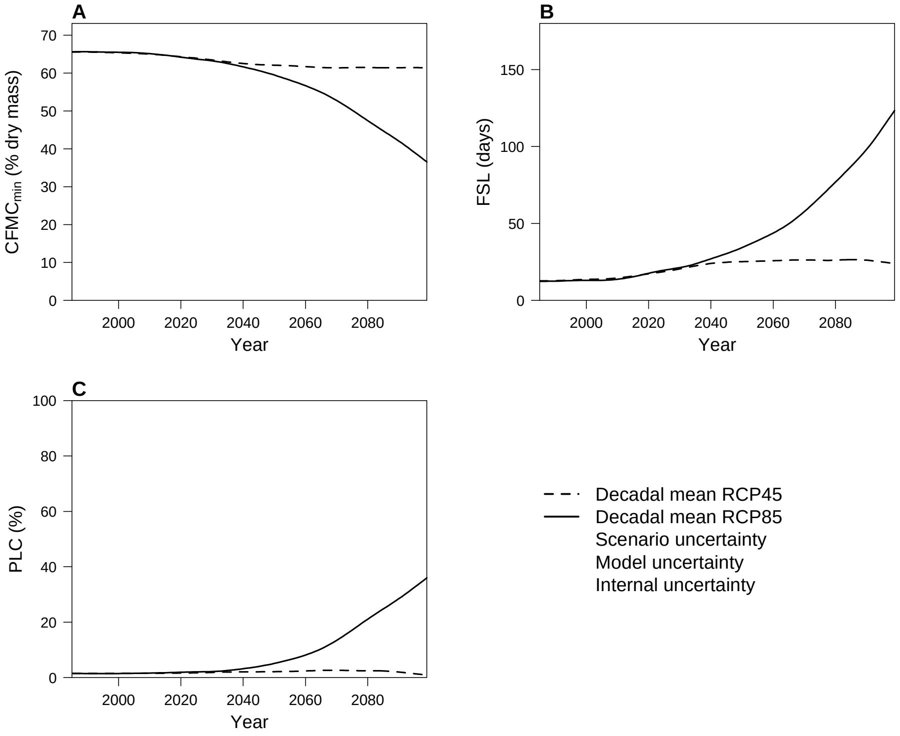


Figure 3- Multi-model projections of fire danger indices and plant cavitation for Quercus ilex at the Puéchabon study site for two emission scenarios (RCP4.5 and RCP8.5). CFMC$_{min}$ is the minimum canopy moisture content reached during the year; FSL is the fire season length, defined as the number of days when CFMC is below the 67% critical threshold.

4. Conclusion

Understanding and predicting FMC is an important prerequisite to increase our knowledge of forest's vulnerability to fires in a changing climate. Here, we developed and validated *SurEau-Ecos-FMC* a mechanistic model predicting *LFMC* and *CFMC* based on plant-hydraulics. We show that leaf embolism might be a growing cause of FMC decrease in a drier climate. We encourage the use of *SurEau-Ecos-FMC* to inform fire models and increase our understanding of the FMC's effect on fire behavior and activity.

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