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Introduction

Climate change challenges agricultural production due to interacting effects of increased atmospheric CO_2 concentration ([CO_2]) and altered temperature and water availability. Anticipating climate change effects on agricultural systems and developing adaptation strategies is a major challenge for the next decades. Plant morphogenesis plays a crucial role in resource capture and is under a complex regulation which is mainly determined by the interplay between environmental factors. Climatic models for Western Europe show that climate change will probably affect water availability (through lower rainfalls) and demand (through increased evapotranspiration due to high temperatures), leading to more frequent water deficits and losses of biomass production (Durand *et al.*, 2010). On the other hand, higher [CO_2] will cause a decrease of the stomatal conductance which will improve water use efficiency. A major challenge therefore lies in our ability to anticipate the integrated response of plant morphogenesis. However, the complex feedback controls involved make it difficult to decipher plant response using only experimental approaches. Functional Structural Plant Models (FSPMs), which account for the interactions between biological processes and environmental factors are better suited to explore plant responses to climate change and possible adaptation mechanisms. Most of FSPMs available mainly focus on the competition for light and carbon acquisition, without considering water relations. In the present work, we describe a comprehensive FSPM, CNW-Grass, encompassing the regulation of leaf growth by water and trophic dynamics in grasses.

Model description

CNW-Grass is defined at individual tiller scale, composed of a series of interconnected laminae, sheaths, internodes and growth zones. Leaf elongation kinetics are split in two phases whose durations depend on coordination rules based on the emergence of successive leaves. During the early phase, which lasts until leaf $_{n-1}$ emergence, the growth of leaf *n* is assumed to be regulated by the carbon and nitrogen concentrations of the growth zone, considering water availability as non-limiting (as a first approximation for this initial version of the model). In the second phase, leaf growth is driven by turgor pressure, which is coupled to leaf water content variations and osmotic pressure (related to C content), thus resulting in elastic deformation and plastic irreversible growth (Coussement *et al.*, 2018). The water flow throughout the hydraulic architecture of the tiller is calculated from organ transpiration and water potential differences. Carbon and nitrogen concentrations, which affect leaf growth and osmotic pressure, are simulated at organ scale using CN-Wheat, a detailed model of the metabolic processes involved in CO_2 and nitrogen acquisition and allocation (Gauthier *et al.* 2020; Barillot *et al.*, 2016). The modelling framework was implemented in OpenAlea platform and uses the MTG formalism as a central data structure for model communication. The model was calibrated for wheat but the formalisms can be extended to many grass species.

Results and Discussion

To illustrate model behaviour, simulations are presented for a wheat plant grown for 800 hours and exposed to a mild drought period arbitrarily imposed at *t=400* hours by decreasing the roots' water potential from -0.1 to -0.2 MPa (Figure 1). Before 400 hours, the water potential of the emerged growing leaf was close to that of the roots and was slightly affected by the diurnal variations of transpiration. At *t=400* h, the water potential of the growing leaf in the 'drought treatment' immediately dropped to -0.2 MPa, which significantly reduced leaf elongation. As a consequence of the coupling between the water and trophic dynamics, CNW-Grass simulated an increase in carbon supply for roots, which positively affected nitrate uptake and the shoot: root ratio (data not shown).

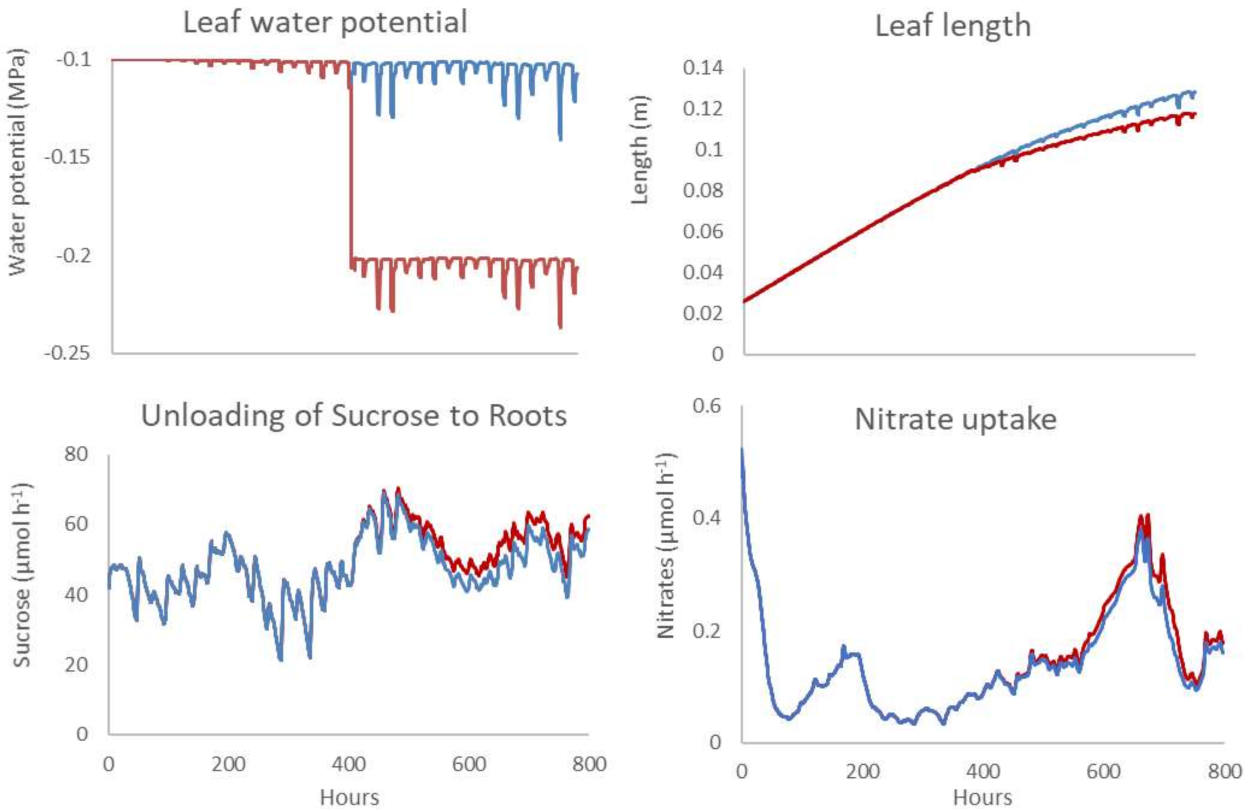

Figure 1: Dynamics of leaf water potential, leaf length, sucrose unloading in roots and nitrate uptake for control plants (blue) and water-stressed plants (red). The water stress was simulated by decreasing the water potential of roots from -0.1 to -0.2 MPa at 400 hours.

Conclusions

The complex feedbacks implemented in CNW-Grass between C, N and water dynamics allowed to account for the effects of drought on leaf growth but also the consequences on resource allocation between shoot organs and roots. CNW-Grass will be used to investigate the integrated response of plants to future climate conditions (*i.e.* combined variations of temperature, water and [CO_2]), which is a rather underexplored field of research. The model will also allow to explore the potential of the available natural variation in crops for improving plant production and resilience *e.g.* through the identification of plant traits useful for the adaptation of plants to climate change.

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