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Hierarchical ODE models for heading date estimation in wheat

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Abstract: Accurate prediction of crop phenology is crucial for tactical management decisions and yield forecasting in agricultural systems. Traditional approaches to estimate crop development often rely fully on the environmental responses of the developmental processes or the data-driven estimations from field phenotyping technologies that may not fully capture the complexities of crop development across varying genotypes and environmental conditions.

In this study, we present a hybrid approach to model wheat dynamics using process-based equations with phenotypic data from field RGB cameras for thermal time accumulation, green area index (GAI), and head emergence data across 24 trials in Australia. Images were first processed with a green-pixel classification to compute the gap fraction and a faster R-CNN with a ResNet 101 backbone for the head detection, trained on the Global Wheat Head Dataset with a custom augmentation pipeline based on YoloV5. From there, an ordinary differential equation (ODE) system was modelled in a hierarchical Bayesian framework to estimate key physiological parameters, including light extinction coefficient, senescence rates, and thermal time requirements for heading.

The ODE model successfully captured the dynamics of GAI and head emergence across diverse environments, with reliable in-season forecasts of heading date (±3 days). We explicitly accounted for measurement uncertainties and provided probabilistic estimates of canopy growth and phenological development. This approach offers an alternative to enhance crop trait estimation from environmental and field trial data, with applications for crop breeding and agronomy by supporting timely management decisions.

Keywords: *Bayesian-ODE modelling; sensor data assimilation; environment; crop phenotyping; decision making*