

Potential role of 3D modelling of canopy architecture to explore G x E x M interactions in wheat

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Abstract

The potential yield of a crop in a specific environment depends on its canopy architecture, which refers to the dynamic changes in size, orientation and spatial arrangement of leaves and other plant organs over time, as driven by the underlying physiology. Canopy architecture is increasingly viewed as a trait to be manipulated by plant breeders as it influences how plants capture resources. However, selection for specific architectural traits has been elusive, partly because architecture is only one of many traits affecting yield and partly because effects of architecture on resource capture are hard to quantify. Advances in modelling of plant architecture and physiological functions using functional-structural plant (FSP) models allow for feedbacks between environmental factors, architecture, and selected physiological processes to be explored. As an example, an FSP model of spring wheat was developed to dynamically simulate the architecture of an expanding wheat crop, taking into account growth and development, size, shape and orientation in space of each organ in relation to thermal time. Here, we show how this model can be used to assess the effects of different planting arrangements (row and grid configurations) on light intercepted by a wheat canopy. We conclude that FSP models could assist in exploring contributions of architectural traits to crop performance to improve understanding of G x E x M interactions.

Introduction

Plant architecture, the three-dimensional organization of the plant body, is a key determinant of light capture in plants. Therefore, architectural traits are interesting targets for breeding. However, effects of architectural traits such as leaf angle and tillering on light capture are difficult to assess. To this end, simulation of plant architecture, termed functional-structural plant (FSP) modelling is a promising tool. FSP modelling is used to simulate “the development over time of the 3D architecture or structure of plants as governed by physiological processes which, in turn, depend on environmental factors” (Vos, Evers *et al.* 2010). A frequently used synonym of FSP modelling is virtual-plant modelling (Room, Hanan *et al.* 1996).

FSP models have a rich history of variation in methods of implementation, in degree of complexity and biological realism, as well as in the associated simulation platforms such as L-Studio (Prusinkiewicz, Karwowski *et al.* 2007), GroIMP (Hemmerling, Kniemeyer *et al.* 2008), and OpenAlea (Pradal, Dufour-Kowalski *et al.* 2008). The common denominator of all FSP modelling approaches is the explicit inclusion of (aspects of) plant architecture, which results from the general philosophy behind FSP modelling that plant architecture is a concept central to plant growth and development. To be able to support research on plant growth and development, FSP modelling has several distinctive properties to offer. Capturing of plant topology, *i.e.* the structure of the network of interconnected organs, allows simulation of transport of compounds such as assimilates or hormones through the plant from source to sink organs, taking into account the number of nodes to travel and the number of ramifications to encounter. Additionally, the simulation of the (3D) geometry of the plant, its leaves and other organs, and the direct and diffuse light coming from any direction enables the calculation of local and whole-plant light absorption. This is vital for the simulation of photosynthesis and photomorphogenetic processes. Simulation of root system geometry can support studies exploring the uptake of water and nutrients from spatially heterogeneous soils (Dunbabin, Postma *et al.* 2013). Finally, a property of FSP modelling crucial for questions related to plant growth and development in the crop and agricultural sciences is the ability to include external factors such as environmental variables (light, water, nutrients, herbivores, volatiles, *etc.*) and management (plant manipulation, planting pattern or density, biocide spraying, *etc.*). The purpose of this study was to demonstrate the applicability of FSP modelling to explore the effects of different planting arrangements on light interception in a wheat canopy.

Methods

To demonstrate the capacity of FSP modelling to simulate crop light interception in relation to architecture and planting arrangement, we used an existing simulation model of wheat architecture (Evers, Vos *et al.* 2005; Zhu, Van der Werf *et al.* 2015), implemented in the simulation platform GroIMP (Hemmerling, Kniemeyer *et al.* 2008). The model simulates, on a daily time step, the development of the aboveground parts of the wheat plant in terms of leaf appearance, expansion, and senescence, tiller appearance and senescence, as well as geometrical properties such as leaf angle and curvature. For details see the aforementioned papers. The model was calibrated for the CSIRO wheat line 7770N (genetic background: Australian cultivar Wyalkatchem) grown at a population density of 125 plants m⁻², using observations of developmental rate, sizes of individual plant organs, and tillering behaviour as model inputs (Moeller, Evers *et al.* 2014).

Light interception by the canopy was simulated using the GroIMP light model, with direct and diffuse light coming from light sources arranged appropriately (Evers, Vos *et al.* 2010). Simulations of canopy light interception were done for three contrasting planting arrangements: 20 cm row spacing, 30 cm row spacing, and a regular, square grid configuration with 9 cm distance between individual plants, all at a plant population density of 125 plants m⁻². The expansion of organs was entirely based on empirical rules, hence the same for each canopy configuration, and the light intercepted was not used to drive growth. To eliminate border effects on light interception, only the central area of the virtual plots was used for the calculation of canopy light interception. Figure 1 illustrates the visual output of the model.

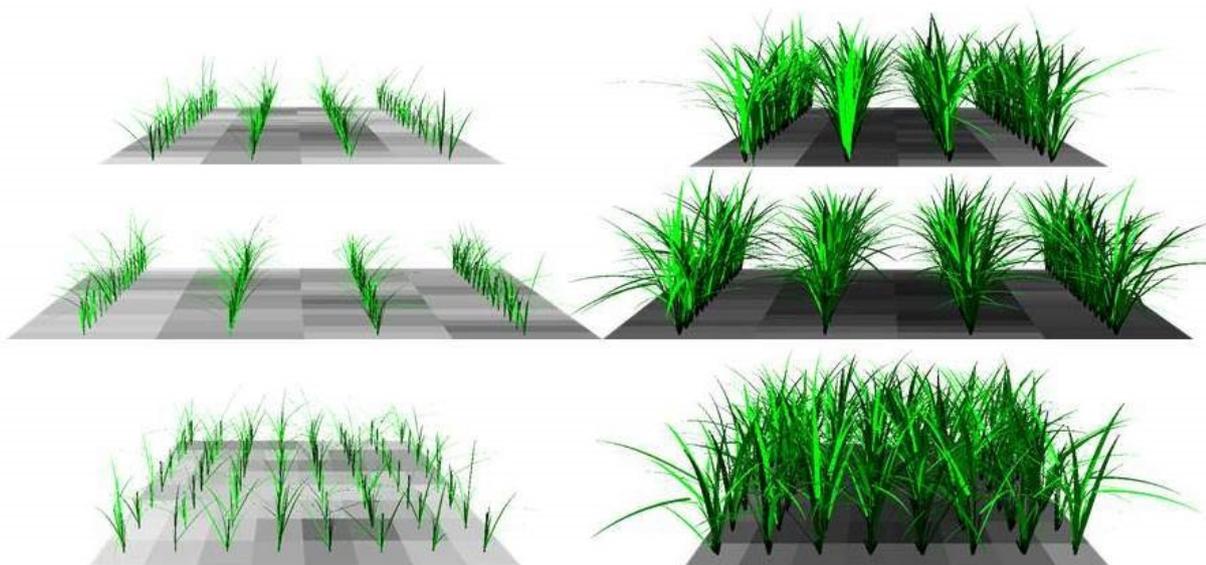


Figure 1. Visual output of simulated wheat canopies at 50 (left) and 80 (right) days after sowing, for three planting arrangements: 20 cm row spacing (top), 30 cm row spacing (middle), and a square-grid configuration (bottom). The population density was 125 plants m⁻² for all configurations. The brightness of the soil tiles and canopy elements indicates the level of radiation reaching the element. The canopies shown here for illustration are smaller than those simulated to explore light interception (see text for details).

Results and discussion

The square-grid canopies intercepted less light than either of the row-based canopies (Figure 2). The average fraction of PAR interception from day 10 to 80 was 0.34±0.005 for the square grid, whereas for the row configurations this average was 0.37±0.006 at 20 cm and 0.38±0.014 at 30 cm row spacing. The simulated leaf area per m² of soil area was identical for all three planting arrangements due to the descriptive nature of the model used in this specific study. From this, we conclude that arranging plants in a square grid by itself reduces canopy light interception. This was unexpected, but may be explained by the more homogeneous distribution of leaf area in the grid configuration, which reduced the penetration of light into the lower canopy thereby reducing the total amount of light intercepted by the canopy compared to the row configurations. Light interception was similar for plants arranged in rows. Due to the fixed population density of 125 plants m⁻², plant-to-plant distance within rows was smaller at 30 cm compared to 20 cm row spacing. Apparently, increasing row spacing while proportionally decreasing plant distance within rows, results in the net effect on light interception being minimal. Similar results have been obtained for maize (Drouet and Kiniry 2008) for relatively narrow row spacing, but not for wider ones.

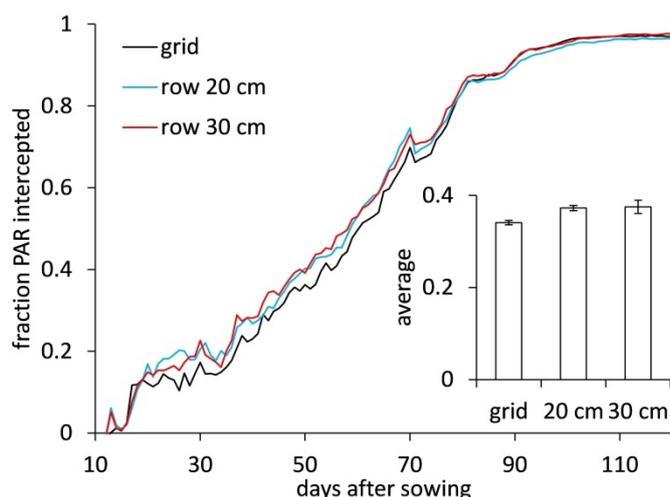


Figure 2. Daily simulated fraction of photosynthetically active radiation (PAR) intercepted by wheat canopies at 20 cm (blue line) and 30 cm (red line) row spacing, and in a square grid configuration (black line). Inset: average fraction of PAR intercepted between 10 and 80 days after sowing (error bars: $2 \times se$; $n = 3$).

In real canopies, plants may adjust their architecture in terms of leaf and branch angles, and tiller numbers, etc. in response to changes in canopy configuration including spatial arrangement and population density (e.g. Maddonni, Otegui *et al.* 2002), which is likely to affect light interception. Such plasticity was not accounted for in the approach taken here, in which fixed parameter values or parameter value probabilities derived from experimental data were used (Moeller, Evers *et al.* 2014). A fully mechanistic model that simulates plant growth and development based on the underlying processes such as photosynthesis and carbon allocation (Evers, Vos *et al.* 2010) will give flexibility in simulation of a range of densities and field configurations. An intermediate implementation in which the leaf area development is simulated empirically but tiller appearance and senescence is simulated based on environmental signals (Evers, Vos *et al.* 2007) may already cover most of the plasticity required for the simulations to provide an adequate representation of reality.

Architectural characteristics of one specific genotype (7770N) were input to the simulations shown here (Figures 1 and 2). However, genotypic differences in architectural attributes such as plant height, tiller number, and leaf size and angle have been described (e.g. Moeller, Evers *et al.* 2014). By including genotype-specific characteristics in a mechanistic model, the benefit of one architectural type over another can be assessed and quantified in respect to resource capture. Such models calibrated for Australian varieties with contrasting canopy architectures are currently being developed (Moeller *et al.* 2015)

Conclusions

The current exercise showed that management choices such as planting arrangement can be evaluated in relation to light interception using an FSP model. The approach can be extended to allow comparison of genotypes as long as genotypic differences in architectural characteristics are represented in the model parameterization. Once mechanistic models of the underlying physiology are included, the predictive power of FSP models could assist in exploring how architectural traits can be exploited in plant breeding by incorporating G x E x M considerations.

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