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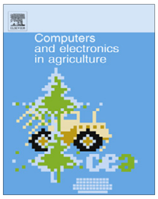

Original papers

Modeling the spatial distribution of plants on the row for wheat crops: Consequences on the green fraction at the canopy level

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ABSTRACT

This work investigates the spatial distribution of wheat plants and its consequences on the canopy structure. A set of RGB images were taken from nadir on a total 14 plots showing a range of sowing densities, cultivars and environmental conditions. The coordinates of the plants were extracted from RGB images. Results show that the distance between-plants along the row follows a gamma distribution law, with no dependency between the distances. Conversely, the positions of the plants across rows follow a Gaussian distribution, with strongly interdependent. A statistical model was thus proposed to simulate the possible plant distribution pattern. Through coupling the statistical model with 3D Adel-Wheat model, the impact of the plant distribution pattern on canopy structure was evaluated using emerging properties such as the green fraction (GF) that drives the light interception efficiency. Simulations showed that the effects varied over different development stages but were generally small. For the intermediate development stages, large zenithal angles and directions parallel to the row, the deviations across the row of plant position increased the GF by more than 0.1. These results were obtained with a wheat functional-structural model that does not account for the capacity of plants to adapt to their local environment. Nevertheless, our work will extend the potential of functional-structural plant models to estimate the optimal distribution pattern for given conditions and subsequently guide the field management practices.

1. Introduction

The plant spatial distribution is obviously initialized at the sowing. The seed drill is pulled by the tractor and the sowing is driven by a combination of gears synchronized with the ground speed of the drill. The variation of seed spacing along the row can arise in seed metering, release, flight from the mechanism to the soil surface and soil covering and pressing (Wilson, 1980). The limitations of the seed metering system can cause misses and bunches from place to place (Karayel et al., 2006). In addition, several factors may contribute to the non–uniformity of seed inter-spacing along the row and deviations from the row direction including variations of the state of the soil surface, changes in the driving speed and vibrations or deviations of the drill from the pre-defined row direction. Further, the germinating process is driven by the seed vigor and seedbed temperature and moisture conditions (Bradford, 2002; Orzolek and Daum, 1984), which impact the rate and the dynamics of emergence (Bradford, 2002; Rowse and Finch-Savage, 2003). All these factors interactively contribute to the final non–uniformity of plant distribution, including the non–even distribution of inter-plant distance along the row and the deviation across the row.

The spatial distribution pattern initializes the environment for individual plants. Then plants have to adapt themselves to the local environment through adjusting physiological functions and structure (Vos et al., 2010). The spatial heterogeneity induced by the non–uniform distribution may exaggerate the inter-plant variability at the stand scale (Pagano et al., 2007) and also reduce the yield of a single plant, due to the presence of competing neighbors (Duncan, 1984), including weed plants (interspecific competition) as well as crop plants (intraspecific competition) (Evers and Bastiaans, 2016). Generally it was considered that evenly spaced stands have higher potential yield than unevenly spaced stands

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(Liu et al., 2004). However, recent work on maize showed mixed effects on maize grain yield of crowding stress induced by non–uniformly spaced plants (Liu et al., 2004; Pagano et al., 2007). Nevertheless for wheat, increasing crop density and spatial uniformity consistently strengthen crop competitiveness across species, resulting in suppression of weed growth and a reduction in yield loss (Olsen et al., 2006, 2005; Weiner et al., 2001). These previous results were mainly derived from the comparison of crop yield or biomass under the uniform pattern achieved by precise seed drill systems and the so-called 'standard' sowing condition. As a matter of fact, the standard sowing pattern may vary greatly among experimental conditions. This may question the generality of the previous work. It is therefore prerequisite to characterize more rigorously the actual plant distribution achieved under standard seeding conditions.

Apart from the experimental approach, modelling may be an alternative to dissect the effect of plant distribution. However, most current crop functioning models are based either on the 'big leaf' concept or are considering the behavior of the canopy as resulting from the functioning of identical plants under a fixed spatial distribution pattern. Therefore these models do not allow describing the possible effect of the plant spatial distribution (Deen et al., 2003; Evers and Bastiaans, 2016). Functional-structural plant models (FSPMs) are the emerging tools to describe canopy response across environments, especially when within-field variability should be taken into account (Vos et al., 2010). For instance Evers and Bastiaans (2016), developed a FSPMs to simulate the crop-weed competition for light. It includes modules to describe plant architecture and the distribution pattern of the crop-weed canopy, and is capable of simulating the dynamics of individual plants while competing for resources in three-dimensional (3D) space. However, the pattern of plant spatial distribution is not well characterized even for the state of the art FSPMs. Simple assumptions on the plant spatial distribution along rows are generally used (Garin et al., 2014; Gigot et al., 2014; Robert et al., 2008): plants are often aligned exactly along the row with strictly equal spacing. Sometimes, random deviations are added subjectively through randomly moving (Feng et al., 2014) or removing plants (López-Lozano et al., 2007) from their original systematic positions. Ideally FSPMs should be driven by physical variables at the organ scale that describe the phylloclimate and its spatial distribution within canopy space along the growth cycle (Chelle, 2005). However, assumptions above were not validated by actual field observations. Therefore, a novel module charactering the plant distribution driven by field observations will be necessary to better the description of canopy structure and improve the model performance. More importantly, this will potentially allow FSPMs to estimate the optimal distribution pattern for given conditions. Further this information can be used to guide the development of seed drills.

The objectives of this study are to document the actual plant distribution pattern based on field measurements at several locations. A statistical module was developed here to describe the distribution along and across the row. Through coupling the plant distribution module with a functional-structural plant model, consequences of the plant distribution pattern was evaluated at the stand scale at different growth stages. Specifically, the ADEL-Wheat model (Fournier et al., 2003) was used here for simulating wheat stands with a range of plant spatial distribution patterns. The impact of the plant spatial distribution pattern was evaluated using the green fraction (GF) under a set of directions. The green fraction in the sun direction corresponds to the light fraction intercepted by green elements which drives photosynthesis and transpiration processes (Baret et al., 1993a, 1993b). GF is also very important for interpreting remote-sensing observations achieved either from the sensors aboard satellite or vectors closer to the ground level (Comar et al., 2012; Verger et al., 2014) for precision agriculture or phenotyping applications.

2. Materials and methods

2.1. Field experiment

The experiment was conducted at three locations in France, Avignon (43.917°N; 4.879°E), Toulouse (43.531°N; 1.500°E) and Grignon (48.849°N; 1.917°E) in 2014. In all the cases, a mechanical seed drill was used, which represents the standard practice for wheat crops. In Grignon, five plots were sampled, corresponding to different cultivars with a single sowing density 170 plt/m^2 (Table 1). In Toulouse, five sowing densities were sampled (100, 200, 300, 400 and 600 plt/m^2) with the same "Apache" cultivar. In Avignon, four sowing densities were sampled (100, 200, 300 and 400 plt/m^2) also with the same "Apache" cultivar. The row spacing was all set as 17.5 cm over three experimental sites. All measurements were taken at around 1.5 Haun stage, when most plants already emerged and when it is easy to identify individual plants visually. A total of 14 plots, at least 10 m length and 2 m width, are therefore available over the 3 experiments showing contrasted conditions in terms of soil, climate, cultivars, sowing density and sowing machine.

2.2. Extracting plant coordinates from digital photos

The methods used to measure the plant distribution along the row are relatively tedious (Van der Heijden et al., 2007). Electromagnetic digitizer describes plant structure from a sample of coordinates of plant elements within the canopy volume (Ma et al., 2007). However, it is very low throughput and is not suitable for conducting intensive field measurements. Alternatively, algorithms have been developed to measure the inter-plant spacing along the row for maize crops from top-view RGB (Red Green Blue) images (Tang and Tian, 2008a,b). Improvements were then proposed by using 3D (Three dimensional) sensors (Jin and Tang, 2009; Nakarmi and Tang, 2012, 2014). However, these algorithms were only validated on maize crops that show relatively simple plant architecture with generally fixed inter-plant spacing.

In this work, plant coordinates along the row were measured using high resolution RGB images. A Sigma SD14 RGB camera with a resolution of 4608 by 3072 pixels was installed on a light moving platform (Fig. 1a). The camera was oriented at 45° inclination perpendicular to the row direction and was focused on the central row from a distance of around 1.5 m (Fig. 1a). The 50 mm focal length allowed sampling about 0.9 m of the row. Images were recorded along the row with more than 30% overlap (Brown and Lowe, 2006). For each plot, we collected at least 20 pictures corresponding to three to five rows over about 5 m length. Then the software AutoStitch (Brown and Lowe, 2006) was employed to stitch images. For each setup, one picture was taken over a chessboard panel placed on the soil surface to calibrate the image: the transformation matrix derived from the chessboard image was applied to all the images acquired within the same setup. It allows removing perspective effects and scaling the pixels projected on the soil surface. Hereafter coordinates of the plants correspond to the intersection between the bottom of the plant and the soil surface in the image. Firstly, they were manually marked from the photos displayed on the screen. Then a set of vectors was extracted representing the coordinates of targeting plants, which consists of at least 150 successive plants for each of the 14 plots. The precision of the coordinates' values was estimated as 1.5 mm by independent replicates of the process over the same images. Some slightly larger deviations may happen when there are occlusions by stones