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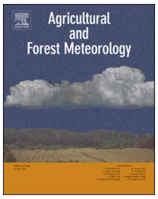

Research Paper

3D plant model assessed by terrestrial LiDAR and hemispherical photographs: A useful tool for comparing light interception among oil palm progenies

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ABSTRACT

The paradigm of functional-structural models (FSPM) assumes that studying the detailed organisation of plant structure allows a better understanding of functional processes; in particular the way plants capture light for performing photosynthesis. However, much attention must be paid toward the consistency between virtual plants and plants in the field in terms of size and geometry to accurately evaluate light interception. This paper thus aimed at i) assessing the capacity of a 3D architectural model based on oil palms (*Elaeis guineensis*) to accurately represent plants structural characteristics at both the scale of the individual plant and the cultivated plot and ii) employing the validated 3D mock-ups to investigate how light interception efficiency varies among progenies that exhibit different architectures. Innovative indicators related to plant geometry and topology were derived from terrestrial LiDAR scanners (TLS) and hemispherical photographs (HP) in order to assess a 3D plant model. Indicators such as plant height, width and volume, gap fractions and solid angle projections were established from field measurements and were compared to equivalent indicators that had been extracted from virtual TLS (VTLS) and virtual HP (VHP) simulated on 3D mock-ups. Indicators were then evaluated for their significance in terms of light interception. Progeny effect on light interception efficiency was finally evaluated for five progenies.

The structural indicators estimated from VTLS and VHP were significantly correlated with equivalent indicators estimated from TLS and HP, respectively, and with simulated outputs related to light interception. Light interception efficiencies estimated from validated 3D mock-ups differed significantly among the five progenies under study, most notably along plant development.

Our results highlight the relevance of combining TLS- and HP-derived indicators to evaluate the reliability of virtual 3D reconstruction of plants in relation to light capture, at both the plant and plot scales. The study paves the way for further investigations aiming at unravelling the relationships between oil palm architecture and the physiological processes driving its production.

1. Introduction

Functional-structural plant models (FSPM) are efficient tools for exploring plants performances (Vos et al., 2010). They are particularly suitable for investigating how plant architecture may alter light interception efficiency or carbon assimilation, either for perennial (Lamanda et al., 2008; Louarn et al., 2008; Da Silva et al., 2013) or annual species (Rey et al., 2008; Song et al., 2013; Barillot et al., 2014; Chen et al., 2014). With the development of structural models capable of generating genetics-dependent architectures (Kang et al., 2014; Migault et al., 2016; Xu et al., 2011), there is an increasing interest in using FSPM to compare plants derived from different genetic sources.

In this context, particular care must be taken for modelling plant geometry since this significantly influences the light captured by plants and the subsequent physiological processes such as carbon assimilation and plant transpiration. However, assessing 3D architectural characteristics of virtual plants in comparison with plants observed in the field is still methodologically complex. Overcoming the practical

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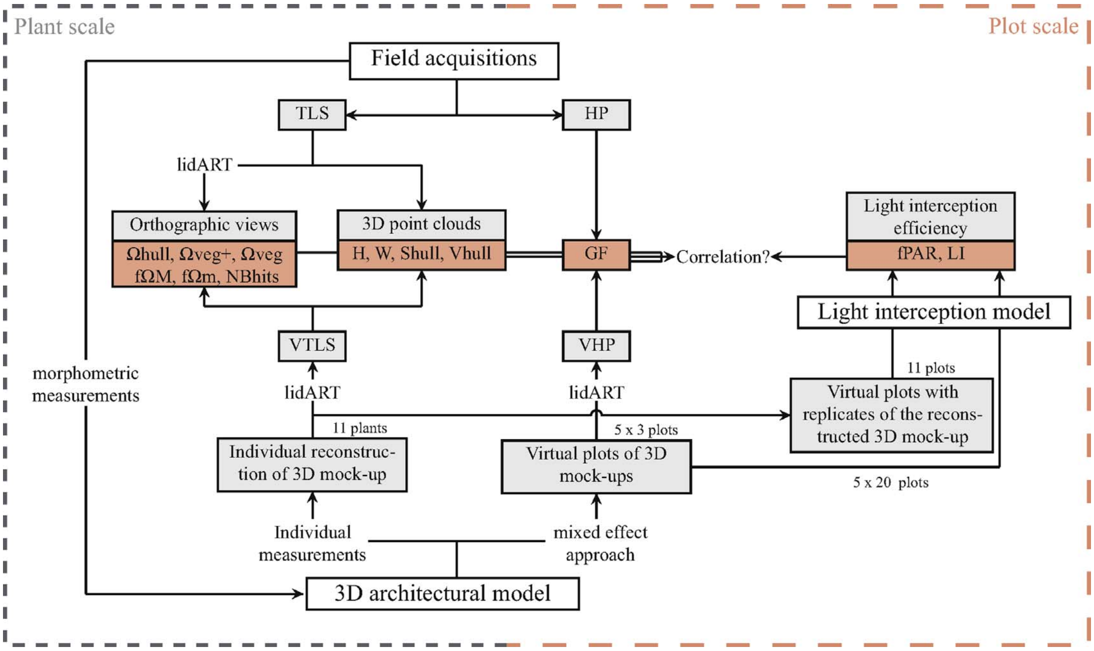

Fig. 1. Procedure to assess the quality of the 3D modeling approach in relation with light interception. The indicators and variables investigated are in red boxes (See Table 1 for abbreviations; TLS: terrestrial LiDAR scans; VTLS: virtual TLS; HP: hemispherical photographs; VHP: virtual HP; f_{PAR}: fraction of incident PAR intercepted; LI: Leaf irradiance). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

difficulties to assess 3D plant representations is thus a crucial factor to be considered for ensuring the capability of a FSPM to address plant performance.

Validations of FSPM with respect to light interception can be performed at the canopy scale accompanied by field measurements providing spatial information on either the leaf area distribution or the light interception. Spatial information on the light transmitted can be obtained from radiometric measurements using light sensors positioned within the plant itself (Sinoquet et al., 2001), under forest canopy (Onoda et al., 2014) or field crops (Maddonni et al., 2001; Xue et al., 2015). However such measurements can be quite time-consuming and complicated. First, only a small number of locations can be effectively sampled. Second, the installation of sensors on leaves can alter canopy structure and thus influence the exact way that light penetrates the canopy (Sonohat et al., 2002). Third, validations are hampered by the fact that simulations must be done under the same radiative conditions as in the field, both in terms of sun position as well as direct and diffuse components of incident radiation.

An alternative approach is to carry out measurements using a plant canopy analyzer (PCA; e.g. Licor LAI-2000/2200) or hemispherical photographs (HP) which can provide information that is independent of radiative conditions. HPs and PCA measurements have mostly been used for estimating leaf area index (LAI) at the plot scale (Bréda, 2003; Jonckheere et al., 2004; Roupsard et al., 2008). Both PCA and HP provide canopy "gap fractions" which are directly related to light interception since they represent the path for light rays to penetrate the canopy (Monsi and Saeki, 2005). PCA acquisitions nevertheless require a reference sensor, positioned either above the canopy or away from it in an open area, making it tedious to operate in case of tall canopies. Terrestrial Lidar scanners (TLS) have been used at the plot scale as an indirect ground-based method to estimate canopy gap fractions similarly to HPs (Danson et al., 2007; Ramirez et al., 2013; Seidel et al., 2015). LiDAR-based canopy gap fraction estimation revealed some benefits compared to HPs due to its insensitivity to sky illumination, although other sources of errors have been reported (Vaccari et al., 2013; Hancock et al., 2014). The major limitation of point-based gap fraction is the difficulty of analysing partial-returns when the laser beam hits the edge of plant components (e.g. leaves), leading to an underestimation of gap fractions (Vaccari et al., 2013; Woodgate et al., 2015). Alternatively, Van der Zande et al. (2011) have proposed a methodology to estimate light interception of heterogeneous forest canopy directly from TLS data ('Voxel-based Light Interception Model'), revealing another practical use of LiDAR for evaluating the radiative environment of plants.

Even if these methods are useful for getting valuable information at the plot scale and can be used to validate virtual scenes, the validation of 3D geometry at individual scale requires more detailed information. In this perspective, TLS opens up new prospects for characterizing single plant structure as it allows quick and effective *in situ* collection of 3D information at the plant scale, in either natural or planted stands.

Several recent studies have shown the usefulness of TLS to retrieve individual crown structure (Moorthy et al., 2011), LAI (Moorthy et al., 2008; Lin and West, 2016) or leaf area density (LAD; Hosoi and Omasa, 2007), or to rebuild 3D tree structure from TLS point clouds (Côté et al., 2009; Raumonen et al., 2013; Hackenberg et al., 2014). However rebuilding of fine structures such as twigs and shoots often remains problematic.

In a previous study (Perez et al., 2016), we developed an architectural model for oil palm (VPalm), able to reconstruct static 3D mock-ups of plants derived from field measurements. At the plant scale, a first assessment of Vpalm was achieved by comparing model predictions with field observations in respect to variables related to leaf and leaflet geometry (e.g. rachis and petiole length, leaflet length and shape, leaf and leaflet angle or leaf area). This was possible both in terms of progeny mean and inter-individual variance. The quality of 3D mock-ups was also partially evaluated at the plant scale considering the height of rachis tips. Nonetheless, the assessment of both the integrative structure and the intra-canopy structure of 3D plants, notably with respect to light interception remained to be carried out.

In the present study we propose an innovative way of using TLS to validate individual oil palm mock-ups that were independently reconstructed by the Vpalm model from a combination of direct morphometric measurements and allometric relationships. At the plant scale, integrative indicators of single plant architecture derived from TLS were compared to similar indicators extracted from virtual TLS performed on 3D mock-ups. At the plot scale, hemispherical