MODELLING SHADOW IN AGROFORESTRY SYSTEMS BASED ON 3D DATA

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Abstract

We describe an approach of a high-resolution model that allows for the quantification of tree shading on a daily, monthly, seasonal or annual time scale to generate realistic estimations of the shading dynamics in a given agroforestry system (AFS). We use 3D data of a tree derived from a terrestrial laser scanner and explain the steps undertaken to develop a vector-based model that quantifies and visualizes the shadow cast by single trees. It is able to compute the shadow of given tree models in time intervals of 10 min and above. The shadow model is flexible in its input of location (latitude, longitude), tree architecture and temporal resolution. The novel approach provides the possibility to feed this model with factual climate data such as cloud covers, enabling the user to retrospectively analyse the shadow regime below a given tree, and to quantify shadow-related developments in AFS.

Keywords: terrestrial laser scanning; light model; LiDAR; 3D tree model

Introduction

Plant growth depends on light interception. Hence, information about the availability of solar irradiance is of high importance for understanding and improving management practices of natural and agricultural ecosystems. Regarding the latter, estimations of solar irradiation availability are of particular interest for managing agroforestry systems (AFS). In these systems, woody perennials such as trees are deliberately grown together with agricultural crops and/or animals on the same land unit, resulting in a significant interaction of the AFS components with regard to the utilization of water, nutrients and light (Editors of Agroforestry systems 1982). On the one hand, a significant reduction of the light interception for the agricultural crops growing below trees can result in a drastic reduction of the crop productivity especially in case of light-demanding species, and on the other hand, more shade tolerant crop species may even react positively to shading.

Materials and methods

To develop the light model in question, we scanned a cherry tree (*Prunus avium* L.) growing on an experimental AFS site in SW-Germany close to the town of Breisach (48° 4’ 24’’ N; 7° 35’ 26’’ E, 182 m a.s.l.) with a terrestrial laser scanner (TLS). Scanning was performed in the dormant season to be able to generate a 3D tree model that comprises all branches without being occluded by leaves. The scans were performed with the phase shift scanner Z+F IMAGER 5010. At the time of scanning, the cherry tree was 19 years old, 11.0 m high and had a diameter at breast height of 16.8 cm. The field measurements were followed by a data processing step (Figure 1). The TLS data of the tree are first denoised and unnecessary surrounding was removed. The resulting point cloud was used as input for the open source Software SimpleTree (Hackenberg et al. 2015), which computes highly accurate cylinder models of trees.

Since we are not only interested in the shading effect of trees in Agroforestry systems in winter but also in summer, we had to model the leaves. For this purpose, we assumed that each twig with a diameter of 1 cm and less grows leaves. To simulate this situation, we adjoined computed ellipsoids around these twigs mimicking a set of leaves. The simulation process also included an increase of the minor axis radius of the ellipsoids of 1 cm per month from April to July, presuming a fully developed crown in July that stays at that level until September, and sheds its leaves in October. Subsequently, the position of the sun during the course of the day, month and year is calculated using the package insol in R (Corripio 2014). This information is merged with data about the solar irradiance that were obtained from the German Meteorological Service (Deutscher Wetterdienst, DWD). To quantify the loss of energy on the ground through shading, the information about solar irradiance in 10-minute intervals is calculated for a raster grid consisting of cells with a resolution of 10 cm x10 cm.

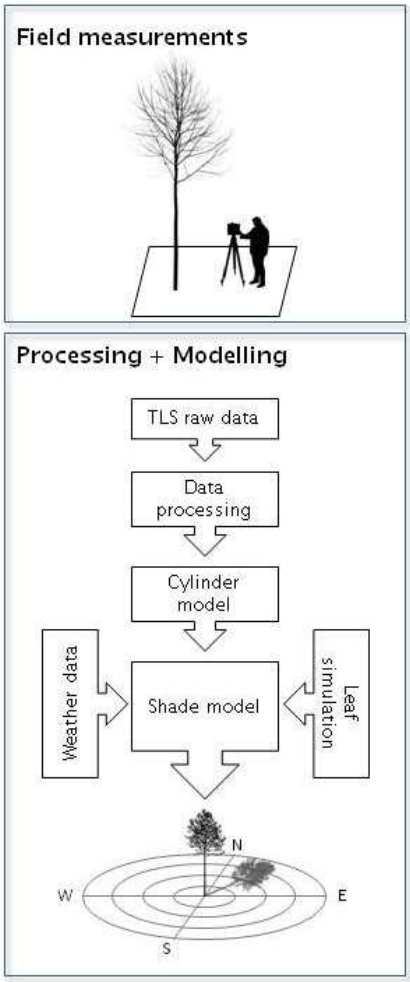


Figure 1: Data processing steps.

Results

Based on our approach, we modeled the monthly shadow for one entire year, covering the time from October 1, 2013, until September 31, 2014. The starting date was set to October since the tree was scanned at that time, and because October also represents the end of the vegetation period. Thus, the shadow projections of a full new growing season can be calculated. Figure 2 shows the shadow dynamics throughout this year in monthly sums.

From October to March, the shading effect of the leafless tree is comparably weak, but it reaches areas in a distance of more than 30 m northward from the tree's stem in a V-shape, especially in December. The shadow elongates until the time of the winter solstice, and widens after passing this time of the year. In spring, the shadow of the tree crown moves closer towards the tree due to the sun's shifting zenith positions, and it becomes increasingly intense due to the developing leaves. At the timings of the equinoxes, the shadow widens to a straight strip. In the period from June until September, the shadow is reaching the most intense and localized loss of solar energy on the ground, and spreads in a hyperbole shape around the tree. Figure 3a shows the annual solar radiation distribution below the model tree. The slightly asymmetrical shape of the cast shadow is due to the asymmetrical shape of the tree crown.

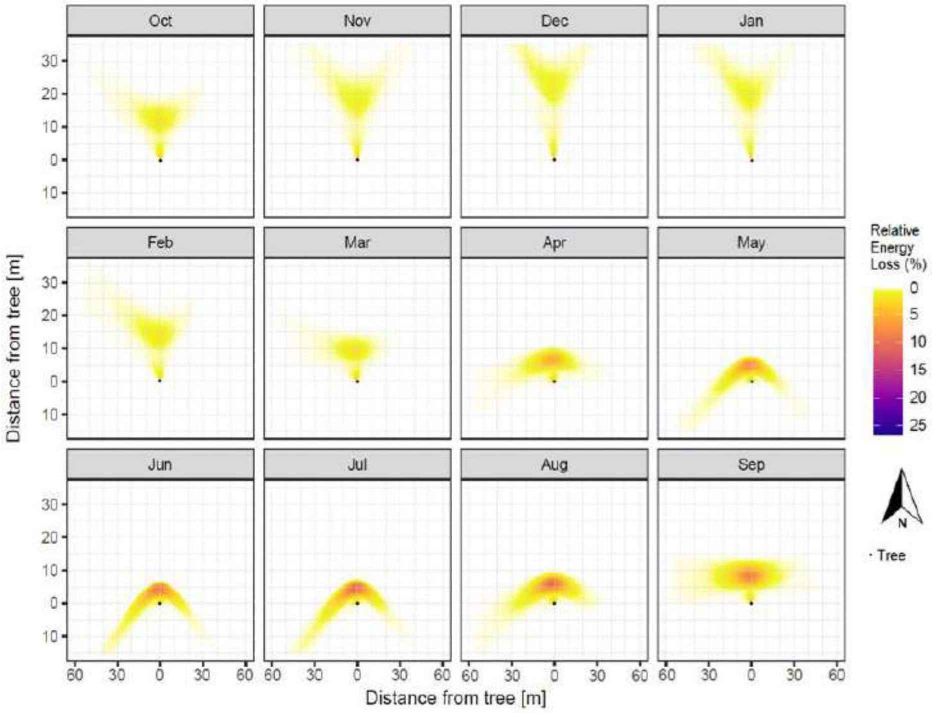
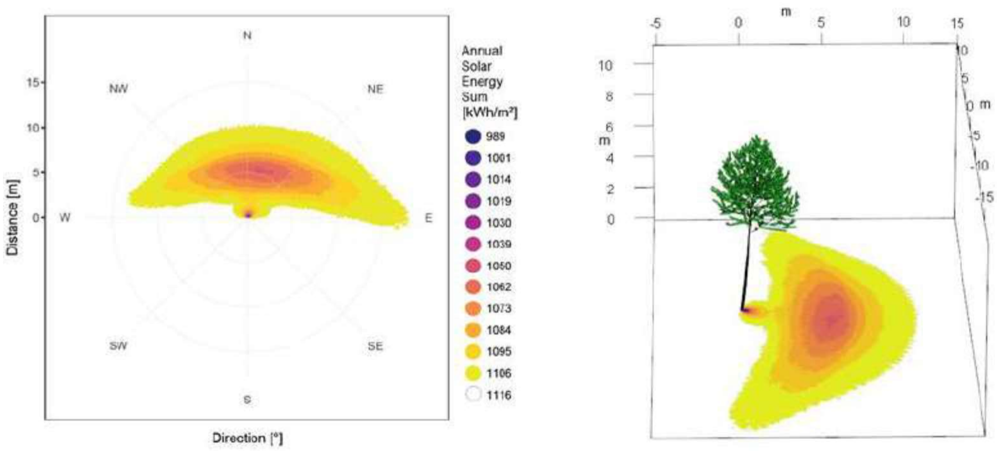


Figure 2: Monthly grids of solar energy losses from October 2013 until September 2014 in comparison to unshaded areas.

The maximum annual solar radiation without shadow amounts to 1116 kWh m-² (white area in Figure 3). The minimum annual solar radiation reaches 978 kWh m-² in the area under the tree crown (dark area in Figure 3). The tree crown shading is most intense in the area around five to seven meters northwards from the stem.



(**a**) (**b**)

Figure 3: (a) Annual solar radiation distribution below the model tree along the compass directions, the outer circle representing a radius of 15 m around the tree stem; (b) 3D visualization of the tree model with the annual solar radiation distribution.

Discussion and conclusion

Although the results displayed in former models from other research groups show similarities with our model outputs, (Dupraz and Liagre 2011; Talbot and Dupraz 2012; Artru et al. 2017), even the more advanced versions work with coarser resolutions of 1 m² grid cells (Talbot and Dupraz 2012; Artru et al. 2017) or 0.5 m x 0.5 m x 0.5 m voxels (Zhao et al. 2003; Sinoquet et al. 2005; Oshio and Asawa 2016; Grau et al. 2017). The high temporal resolution of 10-minute intervals and the options to compute hourly, daily, weekly, monthly, and seasonal dynamics of the light availability at any geographical location, but also the spatial resolution of a 10 cm x 10 cm grid on the ground surface provide new options for studying the interaction and the competition for light among trees and understorey crops with an unprecedented accuracy. The utilization of factual climate data enables a realistic retrospective modeling of the radiation regime of a given tree, and a quantification of future developments based on these data. The results can be adapted in management decisions in AFS or similar land use systems. With the obtained information, whole systems and their planting design can be planned and optimized to minimize light loss for light demanding crop species. Furthermore, our model can help to identify the best tree/crop combination, so that crops adjusted to the present or desired light regime can produce the maximal yield.

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