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Modelling of solar radiation influenced by topographic shading—evaluation and application for precision farming

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Abstract

Solar radiation is the major energy source on earth. Until now, little attention has been spent on how the spatially differencing solar radiation affects crop production and causes spatial crop yield differences in agricultural fields. For homogeneous soil conditions one would expect a similar crop yield all over the field. However yield variability is often observed even though management and soil conditions are relatively homogeneous. The objective of this study was to investigate, whether the distribution of solar radiation influenced by surface topography contributes to crop yield variability.

For a hummocky region in Luettewitz (State of Saxony, Germany) a Digital Elevation Model (DEM) was obtained by Laser-Altimetry with 1 m spatial resolution. In such a terrain, the amount of incoming solar radiation is affected by the topography. For a given point the amount of shading differs throughout a day and a year causing spatial differences of radiation and soil temperature. Using the GIS Arc/Info and the SRAD-Module from the TapesG-package the short wave incoming radiation was calculated based on a 6 m by 6 m grid cell size for a field site of 20 ha. The crop growth and nitrogen model "HERMES" was adapted to take into account site specific solar radiation in the calculation of biomass production and nitrogen and water dynamics. Model runs with and without topographic shading were performed for 225 points and compared against combine harvested grain yield for 1998 and 1999.

Good agreements were observed between simulated and measured shortwave solar radiation. A spatially related pattern (north or south exposed positions) could be observed for HERMES model runs including site specific solar radiation. Other factors like previous landuse or moisture distribution in flowlines could be identified additionally as influencing crop grain yield development.

Keywords: Topographic shading; Solar radiation modelling; Spatial distribution; Crop yield simulation

1. Introduction

Farmers currently look into yield variability to optimize their production under mainly economic consideration using the technology of precision farming. Researchers at the same time try to understand the within field variation of crop yield, and yield patterns for subsequent years (Stafford et al., 1996; Blackmore, 2000). As biomass production is a very complex process, crop growth models become valuable tools to understand differences in biomass production, because they integrate the effects of temporal and spatial parameters on yield development. However, the quality of predictions of observed grain yield variability is not satisfying (see Sadler et al., 2000).

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Nonlinear optimization techniques can help to overcome such problems. Basso et al. (2001) applied such techniques and still found 24% observed variability unexplained. This would lead to the assumption that (I) models do not consider certain processes at all, (II) their parameters are measured not precisely enough, or (III) certain processes are not precisely enough represented.

Solar radiation is one parameter used in crop growth models, being a driving force for biomass production. The impact of solar radiation on plant development has been investigated for a long time. Filzer (1939) observed lower dry grain yield with less light intensity. Hughes (1959) showed that duration and amount of grain development depended on light duration and intensity. For viticulture aspect is considered since a long time. However, little attention has been spent on how the spatial differentiation of solar radiation can alter crop production in agricultural fields. Until now, a constant solar radiation is assumed across a field site, even if under hummocky conditions the terrain affects the amount of incoming solar radiation.

A series of models exits to quantify the effect of shading on incoming solar radiation (Schaab, 2000). In general, incoming solar radiation models (ISRM) can be classified for:

(I) the spatial scale of the simulation (e.g. Dubsky et al. (1999) at a plant stand scale; Moore et al. (1993) at a landscape scale),
(II) complexity based on the number of input parameters (Digital Elevation Model, latitude, longitude, T_{max}, T_{min}, Cloudiness, Albedo, and other),
(III) the computed output parameters (potential solar radiation, diffuse solar radiation, direct solar radiation, duration of sunshine, temperature),
(IV) incorporation into a Geographical Information System (GIS) for data transfer via direct or indirect methods (GRASS, ArcInfo, Idrisi, None) and
(V) use of computing resources (fast/slow, precise).

Solar radiation modelling has been used in forested areas, where a combination of monthly values of the net-radiation budget and additional hydrologic information were used to characterize the small-scale heterogeneity of different forest types (Moore et al., 1993; Kumar and Skidmore, 2000). Other applications simulate photon transfer in spatially three-dimensional dynamic structures inside a plant canopy for plant breeding and nursing (Wernecke et al., 1999).

The effect of shading during different stages of crop development is rather complex. This was already found quite early by Schoder (1932) who investigated the parameters influencing assimilation. Therefore, solar radiation cannot simply be related to crop yield patterns, e.g. by empirical considerations. Instead modelling needs to be employed for this type of process description.

Therefore, the aim of this study was (I) to evaluate solar radiation computed with the SRAD model against measured solar radiation for different amounts of topographic shading in an agricultural landscape and (II) to evaluate the relevance of spatially variable solar radiation for crop growth modelling.

2. Material and methods

Weather conditions were monitored using weather stations from Lambrecht-company (REF1, 51°7′33″, 13°13′43″, 278 m above sea level) and Thiess-company (REF2, 51°08′30″, 13°13′16″, 256 m asl). Data were recorded for air temperature in °C, wind speed in m/s, global solar radiation in $\mathrm{J\,cm^{-2}}$, relative humidity in %, precipitation in mm and soil temperature at three depths (5, 10 and 20 cm) in °C. Data were monitored at intervals of 10 min. Additional global solar radiation (SR) was measured with two global solar radiation sensors (WS1, 51°7′37″, 13°14′8″, 271 m asl, WS2, 51°7′27″, 13°14′00″, 255 m asl, Thiess-company) for the field evaluation.

According to Adolf Thiess GmbH & CO.KG (1999) differences between daily solar radiation sums for calibrated sensor should be smaller than 10%. To further minimize these differences in daily SR sums, WS1 and WS2 were placed at the same location as REF2 for a period of 14 days. Results showed differences between WS1, WS2 (on average 2.48% with a standard deviation of 1.52%) and REF2 (on average 9.70% with a standard deviation of 1.57%).

A least square fit was performed on hourly radiation values to correct the hourly radiation values to the SR observed at REF2. For WS1 with $SR1_c = 1.0836 \times SR1 - 2.838$ ($R^2 = 0.9883$) and for WS2 with $SR2_c = 1.0788 \times SR2 + 4.4297$ ($R^2 = 0.9882$). WS1 as $SR1_c = 1.0836 \times SR1 - 2.838$ ($R^2 = 0.9883$) and values for WS2 with $SR2_c = 1.0788 \times SR2 + 4.4297$ ($R^2 = 0.9882$). Corrected values with negative solar radiation were excluded.

The distribution of solar radiation inside our agricultural landscape was calculated using the model SRAD. A short description of the model is given here, for an in-depth program description, the reader is refereed Wilson and Gallant (2001).

The potential solar radiation is computed based on latitude, slope, aspect, topographic shading and time during the year. It is corrected for monthly sunshine hours and cloudiness factors. Additionally, air temperature is calculated and corrected for elevation, slope/aspect and vegetation via the leaf area index.

The SRAD model input parameters can be divided into four groups: (I) elevation data, (II) atmospheric