Agricultural and Forest Meteorology 201 (2015) 196–208

Contents lists available at ScienceDirect

Agricultural and Forest Meteorology

journal homepage: www.elsevier.com/locate/agrformet

Shortwave radiation transfer through a plant canopy covered by single and double layers of plastic

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ARTICLE INFO

Article history:
Received 6 May 2014
Received in revised form 20 October 2014
Accepted 23 October 2014
Available online 28 November 2014

Keywords:
Plastic covers
Leaf area index
Radiation transfer
Clumping index
Transmittance
Soil albedo

ABSTRACT

A model that predicts radiation transfer through single and double layers of plastic covering over kohlrabi canopies is developed, parameterised and tested. This model will be the foundation of an energy balance and growth module for covered kohlrabi crops that can be used in cover management. Radiation transfer through covers is based on their laboratory-measured angular-resolved transmittances, which are upscaled to non-plane covers in the field. The upscaling procedure accounts for distributed facet slopes according to the Beckmann distribution and visibility, as well as interception preference according to the cosine of the facet-ray incidence angle. Additional measured and upscaled quantities include absorptance and the degree of haze at several angles. The effects of plastic ageing and wetting are measured and implemented into the model using simple empirical approaches. Radiation transfer through the canopy is described by a thoroughly tested 1D canopy model, which accounts effectively for multiple reflections between leaves and the soil. A reanalysis of combined gap fraction and leaf area data from a previous study revealed a tendency of kohlrabi canopies to overdisperse at early growth stages, when only minor leaf area overlapping occurs. Using hourly measurements of photosynthetic active radiation flux densities at the soil level over two growth seasons at one site, the overall model performed reasonably well for a non-woven fabric-based cover ($n = 1067$, $R^2 = 0.96$, RMSE = 6.62 W m^{-2}) and a combination of a low-density polyethylene perforated plastic on top of a non-woven fabric ($n = 1112$, $R^2 = 0.97$, RMSE = 5.11 W m^{-2}). Simulations showed rather low degree of model sensitivity to the specification of cover roughness, but a high level of sensitivity to a proper parameterisation of angular optical properties of covers and of canopy radiation transfer in the NIR spectral range.

1. Introduction

In spring, plastic covers enable field-grown vegetables to be harvested earlier by protecting them from late frosts and increasing the temperature under the cover markedly compared to uncovered crops. In Germany, one of the most important crops for this production system is kohlrabi (*Brassica oleracea var. gongylodes*). Non-woven fabric (NWF) and perforated film (PF) on top of NWF (NWF + PF) are mainly used. However, there is a serious risk of crop quality losses if the air temperature under the cover is excessively high. One reaction of kohlrabi plants to excess heat is to form upright tubers (instead of the more popular flat oval tubers). To avoid these risks, growers must decide when it is the right time to remove the cover, weighing up the risk of quality losses against the opportunity of yielding earlier harvests. There is a currently established temperature sum criterion based on a cumulated daily maximum temperature sum above the cover after planting. However, this empirical model is not precise enough for contemporary requirements in production safety.

Our long-term objective is therefore to develop a physically and physiologically based model of crop microclimates under plastic covers that interacts with plant growth and quality. In this study, we develop a radiation transfer model for PAR (photosynthetic active radiation, 400–700 nm) and NIR (near-infrared radiation, 701–3000 nm), which will be an essential part of the envisioned overall system model.

Previous studies on plastic covered plant–soil systems either assumed there was no interaction between the vegetation and shortwave radiation fluxes (Albright et al., 1989) or they do not consider the plant compartment (De Luca and Ruocco, 2000; Graefe, 2005; Ham and Kluitenberg, 1994; Wu et al., 1996). Other studies placed greater emphasis on the light transmission of greenhouse structures (Critten, 1983; Pieters and Deltour, 1999; Wang and Boulard, 2000).

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http://dx.doi.org/10.1016/j.agrformet.2014.10.011

Notation

I_0	direct part of incident shortwave radiation above the cover ($W\,m^{-2}$)
$I_{bc}(\theta)$	direct radiation intensity at the canopy top below the cover ($W\,m^{-2}$)
I_0^d	diffuse part of incident shortwave radiation above the cover ($W\,m^{-2}$)
$I_{bc}^{d'}$	diffuse sky radiation transmitted by the cover (W^{-2})
$I_{bc}^{d''}$	downward diffuse contribution from converting direct radiation while transmitting the cover ($W\,m^{-2}$)
$I_{bc}^{d'''}$	downward diffuse radiation generated by one interaction of the direct radiation flux with canopy, soil and cover ($W\,m^{-2}$)
I_s	incident radiation at the soil surface ($W\,m^{-2}$)
NIR	near-infrared radiation
NWF	non-woven fabric
PAR	photosynthetic active radiation
PF	perforated film
RMSE	root mean squared error
r_s	global radiation threshold sum for the drying cover (kWh)
X	parameter of the ellipsoidal leaf angle distribution

Greek symbols

$\alpha_{cv}(\theta)$	cover absorptance for direct radiation
α_{cv}^d	cover absorptance for diffuse radiation
β	surface slope (radiant)
δ	collimated light source zenith angle (radiant)
$\chi(\theta)$	cover haze function at incidence angle θ
ϕ	relative azimut between surface normal and light ray (radiant)
$\rho(\theta)$	directional–hemispherical reflectance at incidence angle θ
ρ^d	hemispherical-hemispherical reflectance
$\rho_s(\theta_s)$	soil albedo at soil water content θ_s
$\tau(\theta)$	directional–hemispherical transmittance at incidence angle θ
τ^d	hemispherical–hemispherical transmittance
$\tau_{DIR}(\delta)$	directional–directional transmittance at incidence angle δ
θ	sun or view zenith angle (radiant)
θ_s	volumetric soil water content ($m^3\,m^{-3}$)
$\Omega(\theta)$	leaf clumping index at zenith angle θ
Ω_{57}	leaf clumping index at 57°
Ω_0	leaf clumping index at nadir direction

Subscripts

bc	below cover
cv	cover
cy	canopy
l	leaf
0	above cover
s	soil

Superscripts

d	diffuse
′	previously defined quantity

Modelling radiation transfer in horizontal homogeneous plant canopies is well established, and is generally solved by using the one-dimensional radiation transport equation (Ross, 1981). However, for routine applications that provide net radiation fluxes in soil–vegetation–atmosphere models, for example, approximations to the full theory of multiple scattering of radiation are often applied (Goudriaan, 1977; Pinty et al., 2006; Verhoef, 1984). The objective of this study is to develop a combined model that describes the radiation transfer of plastic covered plant canopies. The model will be parameterised from comprehensive measurements of optical and structural properties of various covers used, soils and kohlrabi canopies.

2. Materials and methods

2.1. Site and experiment

Field trials were carried out at the site of Leibniz-Institute for Vegetable and Ornamental Crops in Großbeeren, Germany (52°21′ N, 13°19′ E) from 2011 to 2012. The site is characterised by silty sand with 5.5% clay (Rühlmann and Ruppel, 2005). In spring (March to June), kohlrabi (cv 'Lech') was grown in beds, with each bed comprising five rows with thirty plants each. A regular planting grid of 0.3 m × 0.3 m (distance between rows × within the row) was adopted, resulting in a planting density of about 111,000 plants/ha. There were two cover treatments: NWF and NWF + PF. NWF, consisting of polypropylene fibres, weighs 19 g/m^2; PF is 40 μm thick polyethylene plastic with 500 holes/m^2 (hole diameter is 1 cm). Covers were placed directly over the plants without any supporting structure. The plants were fertilised and irrigated in line with current practice; they did not constitute limiting factors for plant growth.

2.2. Field measurements

All measurements were taken at hourly or ten-minute intervals, and were aggregated to hourly means. Incident PAR at the soil surface, I_s, was recorded using one (2012) or two (2011) LI-191 line quantum sensors (LI-COR Biosciences Inc., Lincoln, NE, USA) per treatment placed diagonally towards the rows of kohlrabi in NWF and NWF + PF plots. All quantum flux outputs were converted to $W\,m^{-2}$ using a factor of 0.235 (Campbell and Norman, 1998). Incident PAR at the top of the canopy was also measured with a LI-191 line quantum sensor in order to improve angular and spectral consistency.

Global radiation data was obtained from a weather station located 200 m from the experimental site (CM11, Kipp & Zonen B.V., Delft, NL). The field soil moisture was measured using vertically inserted TDR sensors (CS625, Campbell Scientific Inc., Logan, UT, USA) at a 0–30 cm soil depth. The leaf area index (LAI) was determined directly in 2011 using an LI-3100 area metre (LI-COR Biosciences Inc., Lincoln, NE, USA) and indirectly in 2012 using an image-based gap fraction method (Sandmann et al., 2013). Additional LAI data was obtained using a plant canopy analyser (PCA) in 2011 (LI-2200, LI-COR Biosciences Inc., Lincoln, NE, USA). Weekly measured LAI were spline interpolated to hourly values using a continuously calculated thermal time since planting from the air temperature under the cover.

Furthermore, independent concurrent measurements of gap fraction (PCA, digital photography at nadir and 57° view angle) and LAI in uncovered kohlrabi crops (details given by Sandmann et al., 2013) were reanalysed. The leaf angle distribution parameter X from the ellipsoidal distribution (Campbell, 1986) was estimated using the software programme FV2200 (version 2.0, LI-COR Biosciences Inc., Lincoln, NE, USA). PCA-based gap fraction measurements from three different protocols (72 B readings altogether) were then linear averaged and analysed together with gap fraction estimates from segmented digital photographs for clumping index at different viewing zenith angles (0°, 7°, 22°, 38°, 53°, 57°).