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Energy balance and partitioning and vertical profiles of turbulence characteristics during initial growth of a banana plantation in a screenhouse

J. Tanny[a,b,*], V. Lukyanov[a], M. Neiman[a], S. Cohen[a], M. Teitel[c], I. Seginer[d]

[a] Institute of Soil, Water and Environmental Sciences, Agricultural Research Organization, Volcani Center, POB 15159, Rishon LeZion, 7528809, Israel
[b] HIT—Holon Institute of Technology, Holon, 58102, Israel
[c] Institute of Agricultural Engineering, Agricultural Research Organization, Volcani Center, POB 15159, Rishon LeZion, 7528809, Israel
[d] Faculty of Civil and Environmental Engineering, Technion—Israel Institute of Technology, Haifa, 3200003, Israel

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ABSTRACT

This study focused on boundary layer characteristics and evapotranspiration in a cultivated screenhouse. The temporal course of latent and sensible heat fluxes, as well as vertical profiles of turbulence characteristics, below and above the screen were determined as the crop developed. The study was in a young banana plantation screenhouse, 5.5 m high, from June 17 (DOY 169) to August 8, 2016 (221), i.e. 53 days. Two masts measured simultaneously. A manually operated lifting tower mast near the eastern down-wind edge of the screenhouse operated either continuously at a fixed height or measured vertical profiles between 2.5 and 10.2 m height during the same day. The second 'reference' mast was 20 m north of the tower. Continuous measurements included latent and sensible heat fluxes above the plants and below the screen. During the experiment plant height increased from 1.7 to 4.1 m, LAI increased from 0.3 to 1.6 and the Bowen ratio, defined as the ratio between sensible and latent heat fluxes measured below the screen, decreased from 1.9 to 0.3. Energy balance closure, expressed as the slope of the relationship between half-hourly consumed and available energy for this period was 76% ($R^2 = 0.92$); however, after summing up the fluxes over the whole period, the closure increased to 86%. Energy balance closure decreased with plant growth, presumably due to the more stable boundary layer associated with larger plants. During plant growth, ET per unit ground area increased linearly with LAI, but when calculated per unit leaf area it decreased, presumably due to increased mutual shading of leaves. Friction velocity below the screen was about 50% of that above the screen, illustrating the effect of the screen in absorbing momentum flux. Spectral energy slopes above the screen were close to the theoretical value typical of the inertial sub-range of steady state boundary layers, $-5/3$. Below the screen and within the canopy deviations from this theoretical value increased and the slope of spectra decay was higher than $-5/3$, indicating a higher rate of transfer of turbulent kinetic energy across scales. Integral length scale of turbulent vortices within and just above the canopy scaled with plant dimensions and between-plant distances, respectively; above the screen the integral length scale increased with height, as expected for fully developed turbulent flows over flat surfaces.

1. Introduction

The area of crop cultivation under screens and in screenhouses is constantly increasing worldwide. Screens are used for insect exclusion (Tanny et al., 2003; Moeller et al., 2004; Teitel et al., 2015), frost protection (Teitel et al., 1996), shading from supra-optimal solar radiation (Cohen et al., 1997, Cohen et al., 2005; Kittas et al., 2012), protection from wind and water saving (Dicken et al., 2013b; Kitta et al., 2014; Pirkner et al., 2014a;Pirkner et al., 2014b; Siqueira et al. 2012. Shading and water saving are mainly achieved by deploying light shading screens with relatively large holes, while insect exclusion is attained with insect-proof screens with tiny holes that prevent insects from entering the structure. A review of screenhouse microclimate and crop evapotranspiration is given by Tanny (2013).

Several studies have focused on turbulent fluxes of latent and sensible heat and on turbulence properties within the screenhouse. These demonstrated the applicability of the eddy covariance (EC) technique for direct latent (*LE*) and sensible heat flux (*H*) measurement in an insect proof screenhouse in which pepper was grown (Moeller et al., 2004), and for shading screenhouses used for banana and table grape production (Tanny et al., 2006, 2010; Dicken et al., 2013a; Pirkner et al., 2014a). For the insect-proof screenhouse, good agreement was

* Corresponding author at: Institute of Soil, Water and Environmental Sciences, Agricultural Research Organization, Volcani Center, POB 15159, Rishon LeZion, 7528809, Israel.
E-mail address: tanai@volcani.agri.gov.il (J. Tanny).

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obtained between diurnal curves of eddy covariance ET and sap flow measurements of plant transpiration. For the shading screenhouses, energy balance closure slopes were in the range 0.67–1.05, in agreement with previous reports for many canopies in the open (Wilson et al., 2002). Several of the previously mentioned studies analyzed turbulence characteristics of the flow in the air space between the canopy top and the screen and found spectral energy density slopes close to the theoretical −5/3 and flux-variance similarity ratios indicating marginal to fully developed turbulence.

Tanny et al. (2010) measured turbulent fluxes and turbulence characteristics at two heights within the air gap between the canopy top and the screen roof. They showed that friction velocity at the two heights was almost the same and the coefficient of surface drag decreased with height. The test of turbulence development using the flux-variance principle indicated that at the two levels turbulence was marginally fully developed. Eddy covariance flux measurements at 4.75 and 5.37 m height gave energy balance closure slopes of 1.02 and 0.87 respectively. The lower closure at the upper level was explained by the limited available fetch for the upper EC system. These results supported the validity of the constant-flux layer assumption within this air space.

Dicken et al. (2013a) measured turbulent fluxes in a banana screenhouse during 18 days. They divided the measurement campaign into two plant development stages, small plants, starting from 2.7 m height, and large plants, ending with 3.9 m height. Energy balance closure slope for the whole period was 0.75, however, when analyzed separately for the small and large plants the slopes were 0.67 and 0.86, respectively. They attributed the increased slope to the more homogeneous cover of the larger plants than the smaller ones. The measured evapotranspiration increased with plant growth and irrigation, as expected. For the two periods examined, the evapotranspiration per unit leaf area was almost unchanged. Based on the measured data, Dicken et al. (2013a) estimated soil evaporation to be between 4–10% of total ET.

Screenhouse banana plantations have become a standard cultivation system in Israel due to their improved yield and increased water use efficiency. Haijun et al. (2015) measured a reduction of 10% in banana transpiration in a screenhouse, and Siqueira et al. (2012) who modeled the screenhouse environment, simulated an expected increase of 25% in water use efficiency as compared to a banana plantation in the open. Consequently, investigations of turbulent latent heat flux have both scientific and practical significance.

This study further explores the plant-screen system by focusing on two aspects. The first is continuous eddy-covariance flux measurements at a single height to analyze the dynamics of partitioning between sensible and latent heat fluxes during plant growth, and energy balance closure. The second is vertical profiles of several turbulence characteristics for a range of heights, from within the plants, through the air layer between the crop and screen, and up to the boundary layer above the screen. The study was carried out in a banana plantation covered by a shading screen, deployed for improving yield and increasing the water use efficiency by reducing the irrigation demand.

2. Materials and methods

The experiments were carried out in a large, flat-roof banana screenhouse located on the Mediterranean coastal plain of Israel, near Kibbutz Nahsholim, west of the Carmel ridge, at 32°37′16.2″N 34°56′45.5″E and 10 m AMSL. Its width, roughly oriented E–W (azimuth of 275°), was 210 m, its length in the N–S direction was 610 m, and its height 5.5 m (see Fig. 5 below). The structure was completely enveloped (roof and sidewalls) with a white woven 17 mesh 'Crystal' screen with 9% nominal shading (Ginegar Plastic Products Ltd., Israel). Young banana plants were planted in March 2016 with 4.5 m between rows and 3.5 m within-row spacing. During the measurement period the height of the plants increased from 1.7 m to 4.1 m and the leaf area index (LAI) increased from 0.3 to 1.6 (Fig. 1).

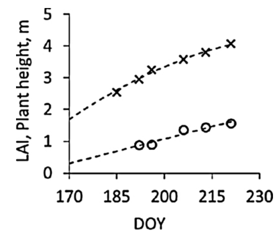

Fig. 1. Variation of plant height (X) and Leaf Area Index (LAI, O) during the measurement period. The dashed lines represent functions fitted to the data. The regression equation for LAI is LAI = 0.0258*DOY − 4.0835 (R^2 = 0.93) and for plant height, h_c = −0.0006*$(DOY)^2$ + 0.2837*DOY − 29.485 (R^2 = 0.99). Dashed lines are extrapolated back to DOY 170 to cover the measurement period during which direct measurements of LAI and h_c are missing.

Two masts were used. One was a standard mast, and the second was a lifting tower (model ULK 800, GUIL, Spain) with a platform that could be elevated by a manual crank to selected heights below and above the screen. The lifting tower was about 330 m north of the screenhouse's southern edge and 30 m west of its eastern edge. This position allowed a fetch of at least 170 m for the prevailing westerly wind. The standard mast, used for reference measurements, was positioned about 20 m north of the lifting tower. On each mast an array of sensors was mounted: a pyranometer (model CM5, Kipp & Zonen, The Netherlands), a net-radiometer (model Q7.1, REBS, WA, USA), temperature/relative-humidity (HMP45-C, Campbell Sci., Logan, UT, USA), and an eddy-covariance system consisting of a 3D ultrasonic anemometer (model 81000, R.M. Young, MI, USA) and a krypton hygrometer (model KH20, Campbell Sci., Logan, UT, USA).

The lifting tower was operated in two 'modes', referred to as 'continuous' mode when the tower was at a fixed height for a long period and 'profile' mode when the tower was cranked to different heights during a single day. Continuous measurements were made during a period of 52 days (DOY 169–220, 52 days, a total of 2496 half-hourly data points) to analyze turbulent fluxes of latent and sensible heat and additional energy balance components. For these measurements, the sensors were initially positioned at a height of 2.8 m above the ground (DOY 169-191) and when plant height increased, they were elevated to 4.3 m (DOY 192-220).

Profile mode measurements were made during 6 days (DOY 185, 192, 199, 206, 213 and 221) by elevating sensors to higher levels through an opening in the screened roof for about 3 h around noon. At each level, measurements lasted 15 min giving a vertical profile of several flow properties. Footprint data for the system are given in Section 4.3. Profile details are presented in Table 1.

Leaf area index (LAI) was determined from measurements of length and maximum width of all leaves on three typical plants. The product of these two measures was multiplied by 0.78, the area factor for this variety of banana (Bassette and Bussiere, 2005; Tanny et al., 2006).

3. Data analysis

3.1. Fluxes and profiles calculations

3.1.1. Continuous mode

Eddy covariance raw data sampled at 10Hz were processed using the EddyPro software package (Version 6; LI-COR, Inc.). The analysis included the effect of plant growth with time and corresponding changes in EC system height. Analysis was based on 30-min time intervals as is common for eddy covariance data analysis. Data collected during overlapping profile mode measurements (1.3% of all data points) were removed from the continuous data set. Instead, and for the purpose of continuity, data gaps were filled with averages of corresponding values from one preceding and one subsequent day at the same hours. The data analysis by EddyPro showed that the 90% flux footprint during daytime (09:00–18:00) continuous mode measurement