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BARD Project Number: IS-4374-11C

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Project Title:

Micrometeorological methods for inferring whole canopy evapotranspiration in large agricultural structures: measurements and modeling

Investigators

Principal Investigator (PI): Josef Tanny

Co-Principal Investigator (Co-PI): Gabriel Katul

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Keywords: Surface renewal, flux variance, Bowen ratio, half-order time derivative, eddy covariance, screenhouse, greenhouse, turbulent flux, energy balance, modeling.

Abbreviations commonly used in the report, in alphabetical order:

BR- Bowen ratio; EC – Eddy covariance; FV – Flux variance; HTD – Half-order time derivative; SR – Surface renewal;

Budget: IS: \$ 150,000

US: \$ 130,000

Total: \$ 280,000

Signature
Principal Investigator

Appendix G6a

Signature
Authorizing Official, Principal Institution

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Publication Summary (numbers)

	Joint IS/US authorship	US Authors only	Israeli Authors only	Total
Refereed (published, in press, accepted) BARD support acknowledged	2	28	6	36
Submitted, in review, in preparation	1		1	2
Invited review papers				
Book chapters				
Books				
Master theses			1	1
Ph.D. theses				
Abstracts		6	3	9
Not refereed (proceedings, reports, etc.)			1	1

Postdoctoral Training: List the names and social security/identity numbers of all postdocs who received more than 50% of their funding by the grant.

Tomer Duman, Post-doctoral researcher (currently at Duke University, USA)
SS number: 817281799

Cooperation Summary (numbers)

	From US to Israel	From Israel to US	Together, elsewhere	Total
Short Visits & Meetings	3		1 (BGU, Israel)	4
Longer Visits (Sabbaticals)				

Description of Cooperation:

The meetings were dedicated to mutual visits in the experimental sites in Israel, exchange of experimental data for use in the modelling tasks and discussions of possible field measurements, data analysis methods, and modeling approaches. Outlines of mutual papers were elaborated during the meetings.

Patent Summary (numbers)

	Israeli inventor only	US inventor only	Joint IS/US inventors	Total
Submitted				
Issued (allowed)				
Licensed

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Abstract

Original objectives and revisions

The original objectives as stated in the approved proposal were: (1) To establish guidelines for the use of micrometeorological techniques as accurate, reliable and low-cost tools for continuous monitoring of whole canopy ET of common crops grown in large agricultural structures. (2) To adapt existing methods for protected cultivation environments. (3) To combine previously derived theoretical models of air flow and scalar fluxes in large agricultural structures (an outcome of our previous BARD project) with ET data derived from application of turbulent transport techniques for different crops and structure types. All the objectives have been successfully addressed. The study was focused on both screenhouses and naturally ventilated greenhouses, and all proposed methods were examined.

Background to the topic

Our previous BARD project established that the eddy covariance (EC) technique is suitable for whole canopy evapotranspiration measurements in large agricultural screenhouses. Nevertheless, the eddy covariance technique remains difficult to apply in the farm due to costs, operational complexity, and post-processing of data – thereby inviting alternative techniques to be developed. The subject of this project was: 1) the evaluation of four turbulent transport (TT) techniques, namely, Surface Renewal (SR), Flux-Variance (FV), Half-order Time Derivative (HTD) and Bowen Ratio (BR), whose instrumentation needs and operational demands are not as elaborate as the EC, to estimate evapotranspiration within large agricultural structures; and 2) the development of mathematical models able to predict water savings and account for the external environmental conditions, physiological properties of the plant, and structure properties as well as to evaluate the necessary micrometeorological conditions for utilizing the above turbulent transfer methods in such protected environments.

Major conclusions and achievements

The major conclusions are: (i) the SR and FV techniques were suitable for reliable estimates of ET in shading and insect-proof screenhouses; (ii) The BR technique was reliable in shading screenhouses; (iii) HTD provided reasonable results in the shading and insect proof screenhouses; (iv) Quality control analysis of the EC method showed that conditions in the shading and insect proof screenhouses were reasonable for flux measurements. However, in the plastic covered greenhouse energy balance closure was poor. Therefore, the alternative methods could not be analyzed in the greenhouse; (v) A multi-layered flux footprint model was developed for a ‘generic’ crop canopy situated within a protected environment such as a large screenhouse. The new model accounts for the vertically distributed sources and sinks within the canopy volume as well as for modifications introduced by the screen on the flow field and micro-environment. The effect of the screen on fetch as a function of its relative height above the canopy is then studied for the first time and compared to the case where the screen is absent. The model calculations agreed with field experiments based on EC measurements from two screenhouse experiments.

Implications, both scientific and agricultural

The study established for the first time, both experimentally and theoretically, the use of four simple TT techniques for ET estimates within large agricultural screenhouses. Such measurements, along with reliable theoretical models, will enable the future development of low-cost ET monitoring systems which will be attainable for day-to-day use by growers in improving irrigation management.

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Achievements

Significance of main scientific achievements or innovation

The area of agricultural crops grown in screenhouses and greenhouses is constantly increasing. Reliable knowledge of evapotranspiration (ET) in such protected environments is becoming necessary for efficient water management by growers and for water supply management. Our previous BARD project established the use of the Eddy Covariance technique for ET measurements in the semi-open environment of protected crops, mainly large screenhouses. As noted earlier, the eddy covariance technique remains difficult to apply in the farm due to costs, operational complexity, and post-processing of the data – thereby inviting alternative techniques to be developed. The major innovation of this research is in examining four alternative techniques that are much cheaper to employ and simpler to operate than the EC.

The project examined four techniques, namely, the Surface Renewal, Flux Variance, Bowen Ratio (BR) and Half-order Time Derivative in three types of agricultural structures: (i) a banana plantation in a light shading (8%) screenhouse; (ii) a pepper crop in a dense insect-proof (50-mesh) screenhouse; and (iii) tomato crop in a naturally ventilated greenhouse with a plastic roof and 50-mesh screened sidewalls. The potential advantage of these four techniques is that ET can be estimated using low-cost temperature-humidity sensors and ancillary measurements of the energy balance components of net radiation and soil heat flux.

The above methods rely on calibration and validation against EC flux measurements. Hence, our initial task was to check the validity of the EC measurements in the three structures to be used in the investigation of the four aforementioned methods. Apart from the type of crop, the three structures differ in the cover properties and especially in its resistance to air penetration. The shading banana screenhouse imposed the lowest resistance while the plastic greenhouse the highest. Quality control analysis examined the validity of turbulence development, flow stationarity conditions and energy balance closure in the air gap between the canopy top and the horizontal screened roof. The study revealed that EC measurements were valid for flux measurements in the two screenhouses but not in the greenhouse. Although turbulent flow development and stationarity conditions were valid in the greenhouse, the energy balance closure was poor, presumably due to significant advective effects associated with the impermeable

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plastic roof of the greenhouse that lead to violations of the constant-flux layer assumption. Therefore, analysis of the four alternative methods was not pursued in the tomato greenhouse.

The scientific significance of the project lies in increased understanding of turbulence characteristics in protected agriculture related to the four turbulent transport (TT) methods. For the two screenhouses, two-point space time correlations demonstrated the larger obstruction applied by the insect-proof than the light shading screen. This was in agreement with the better performance of the SR and FV techniques in shading than in insect-proof screenhouses. A quadrant analysis identified in both screenhouses the existence of ejections and sweeps that are the major flow structures which enable the SR mechanism and hence the use of this approach in screenhouses. Analysis showed that in the shading screenhouse and during most hours of the day, turbulent transfer coefficients of heat and water vapor were nearly the same thereby hinting that the distributed sources of latent and sensible heat within the canopy are similar. This finding facilitated the use of the Bowen Ratio technique in such screenhouses.

A higher-order closure model, developed by our previous BARD that examined the effect of a screen on the mean flow field, turbulent stresses, radiative and energy fluxes, as well as scalar sources, sinks, fluxes, and mean concentrations within large screen houses was linked to a novel footprint model developed in this BARD project. Footprint models are routinely used to assess the spatial representativeness of TT estimated turbulent fluxes (e.g. ET) within or above canopies. Current interpretation of flux footprint in such protected environment is borrowed from open environments, where it is defined as a source weight function that describes contributions from all upwind surface emissions to a measured flux at some height above the surface. Footprint models commonly assume homogeneous surface sources positioned near ground-level or some effective displacement height and have been incorporated into commercial software packages. The novelty of the model developed here is its ability to represent the height variations of the main flow statistics in the confined space within such protected environments where TT estimates of ET must be conducted. The presence of a screen modifies the flow field and concomitant micro-environment (aerodynamic and radiative) in complex ways, which makes conventional footprint modeling a major challenge. The limited distance to the edge of the partially-enclosed structure also complicates the relation between the source and the measured flux, since fetch requirements are less likely to be fulfilled. The effects of all these factors on the

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interpretation of EC flux measurements or their TT estimates within screenhouses from field experiments are now resolved by this modeling framework.

Agricultural and/or economic impacts of the research findings

From the agricultural viewpoint, the project provided practical guidelines for application of the micrometeorological methods in screenhouses. The Bowen Ratio technique was shown to be valid in the banana shading screenhouse when temperature and humidity sensors were alternating in height thereby minimizing constant measurement errors; however, with fixed sensors the performance was relatively poor. The SR and FV techniques were both valid in the two screenhouses, with somewhat better performance in the shading than the insect-proof screenhouse. In both techniques, the optimal position of the miniature temperature sensor was just above the screen. In both FV and SR techniques, which are based on high frequency temperature measurements, it was shown that the frequency of data analysis could be reduced from its common value of 10Hz. For the SR and FV satisfactory results were obtained in frequencies as low as 2 Hz and 0.5 Hz (in the shading screenhouse), respectively. This satisfactory agreement hints that much of the temperature variance and turbulent heat transport within such systems is governed by large eddies. For both screenhouses, good correlations were obtained between extracted and directly measured values of ET using the two techniques. The HTD technique provided statistically significant coefficients of determination for the regressions between EC and HTD sensible heat fluxes in the two screenhouses.

The possibility of using a simple and low-cost technique for reliable ET estimates in screenhouses, along with the theoretical model which enables flux predictions under specific conditions will be most significant for improving the irrigation management and consequently the water use efficiency of screenhouse crops. The use of simple techniques would allow growers to directly and eminently implement such methods in their screenhouses to obtain actual values of whole canopy ET, information which is currently missing in the toolbox of the growers. The results of this project are intended to provide the first step towards the development of a commercial off-the-shelf system that will be economical for growers. This issue is of utmost significance mainly due to the expected water shortage in many regions of the world.

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Details of cooperation

The close cooperation between the two research teams, including mutual visits and meetings, significantly promoted the research objectives. This was evident throughout the project starting from the preparation of the original research proposal through the research work and finally in preparing this final report.

In particular, the setup of the measurement systems within the screenhouse, aimed at exploring the validity of the simple TT techniques, was mutually designed by the two teams. This proved to be a key parameter for the successes of the project in illustrating the fact that essentially, evapotranspiration in screenhouses can be estimated through simple TT techniques.

The PI (Tanny) and co-PI (Katul) met in person during the course of the project period complemented by several Skype based meetings. The in person meeting took place in an international workshop at Ben-Gurion University in Israel (May 2013) at the middle of the project. This allowed the two PIs to discuss some experimental results of screenhouse measurements, which were already completed by Tanny and to discuss further designs of the field study, measurements and modeling that shaped the effort of the post-doctoral fellow.

Three additional meetings within this project were the visits in Israel of the Duke post-doctoral fellow Dr. Tomer Duman, which took place on May 2013 (BARD financed), December 2013 and May 2014. Dr. Duman was in charge of executing the modeling tasks at Duke University under the guidance of Prof. Katul. During these visits, Dr. Duman was able to directly observe a field campaign that was just under operation in the Dead Sea region of Israel. This allowed him to closely realize the physical aspects of the screenhouse environment and certainly contributed significantly to the high coupling between the modeling and field measurements tasks. During these visits, Dr. Duman was also communicating with the Israeli students regarding exchange of data, data quality tests, and comparisons between the models developed by the US team and the field measurements.

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List of Publications

(Peer reviewed, BARD acknowledged)

Mutual papers:

Siqueira, M., Katul, G. and Tanny, J. (2012). The effect of the screen on the mass, momentum, and energy exchange rates of a uniform crop situated in an extensive screenhouse. *Boundary-Layer Meteorology*, 142 (3), 339-363.

Duman, T., Tanny, J., Dicken, U., Siqueira, M. B., Katul, G. (2015). Footprint estimation for multi-layered sources and sinks inside canopies in open and protected environments. *Boundary-Layer Meteorology*, 155 (2), 229-248.

Dicken, U., Duman, T., Cohen, S., Tanny, J. (2015). On the applicability of the eddy-covariance technique for continuous measurements of whole canopy fluxes in screenhouses. Submitted to *Agricultural and Forest Meteorology*.

Papers by the Israeli team:

Tanny, J. (2013). Microclimate and evapotranspiration of crops covered by agricultural screens: A review. *Biosystems Engineering*, 114(1), 26-43.

Rosa, R., Dicken, U., and Tanny, J. (2013). Estimating evapotranspiration from processing tomato using the surface renewal technique. *Biosystems Engineering*, 114(4), 406-413.

Dicken, U., Cohen, S., and Tanny, J. (2013). Examination of the Bowen ratio energy balance technique for evapotranspiration estimates in screenhouses. *Biosystems Engineering*, 114(4), 397-405.

Pirkner, M., Dicken, U. and Tanny, J. (2014). Penman-Monteith approaches for estimating crop evapotranspiration in screenhouses - a case study for table-grape. *International Journal of Biometeorology*, 58(5), 725-737.

Mekhmandarov, Y., Pirkner, M., Achiman, O., Tanny, J. (2015). Application of the surface-renewal technique in two types of screenhouses: sensible heat flux estimates and turbulence characteristics. *Agricultural and Forest Meteorology*, 203, 229-242.

Rosa, R., Tanny, J. (2015). Surface renewal and eddy covariance measurements of sensible and latent heat fluxes of cotton during two growing seasons. *Biosystems Engineering*, 136, 149-161.

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Papers by the US team:

Banarjee, T., G.G. Katul, S. Fontan, D. Poggi, and M. Kumar, 2013, Mean flow near edges and within cavities situated inside dense canopies, *Boundary-Layer Meteorology*, 149, 19-41.

Banarjee, T. and G.G. Katul, 2013, Logarithmic scaling in the longitudinal velocity variance explained by a spectral budget, *Physics of Fluids*, 25, 125106

Huang, J., G. Katul, and J.D. Albertson, 2013, The role of coherent turbulent structures in explaining scalar dissimilarity within the canopy sublayer, *Environmental Fluid Mechanics*, 13, 571-599

Katul, G.G., A. Porporato, C. Manes, and C. Meneveau, 2013, Co-spectrum and mean velocity in turbulent boundary layers, *Physics of Fluids*, 25, 091702

Palmroth, S., G.G. Katul, C. A. Maier, E. Ward, S. Manzoni, G. Vico, 2013, On the complementary relationship between marginal nitrogen and water-use efficiencies among *Pinus taeda* leaves grown under ambient and CO₂-enriched environments, *Annals of Botany*, 111, 467-477

Salesky, S.T., G. Katul and M. Chamecky, 2013, Buoyancy effects on the integral lengthscales and mean velocity profile in atmospheric surface layer flows, *Physics of Fluids*, 25, 105101

Thompson, S. and G.G. Katul, 2013, Implications of non-random seed abscission and global stilling for migration of wind-dispersed plant species, *Global Change Biology*, 19, 1720-1735

Vico, G., S. Manzoni, S. Palmroth, M. Weih, and G.G. Katul, 2013, A perspective on optimal leaf stomatal conductance under CO₂ and light co-limitations, *Agricultural and Forest Meteorology*, 182-183, 191-199.

Volpe, V., M. Marani, J.D. Albertson, G.G. Katul, 2013, Root controls on water redistribution and carbon uptake in the soil-plant system under current and future climate, *Advances in Water Resources*, 60, 110-120.

Banerjee, T., G.G. Katul, S. Salesky, and M. Chamecki, 2014, Revisiting the formulations for the longitudinal velocity variance in the unstable atmospheric surface layer, *Quarterly Journal of the Royal Meteorological Society*, doi: 10.1002/qj.2472

Duman, T., G.G. Katul, M.B. Siqueira, and M. Cassiani, 2014, A velocity-dissipation Lagrangian stochastic model for turbulent dispersion in atmospheric boundary-layer and canopy flows, *Boundary-Layer Meteorology*, 152, 1-18, DOI 10.1007/s10546-014-9914-6

Gleicher, S.C., M. Chamecki, S.A. Isard, Y. Pan, and G. Katul, 2014, Interpreting three-dimensional spore concentration measurements and escape fraction in a crop canopy using a

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coupled Eulerian-Lagrangian stochastic model, *Agricultural and Forest Meteorology*, 194, 118-131

Huang, C., S. Launianen, T. Gronholm, and G.G. Katul, 2014, Particle deposition to forests: An alternative to K-theory, *Atmospheric Environment*, 94, 593-605

Katul, G.G., A. Porporato, S. Shah, and E. Bou-Zeid, 2014, Two phenomenological constants explain similarity laws in stably stratified turbulence, *Physical Review E*, 89, 023007

Katul, G.G. and C. Manes, 2014, Cospectral budget of turbulence explains the bulk properties of smooth pipe flow, *Physical Review E*, 90, 063008

Lin, M.Y., A. Khlystov, and G.G. Katul, 2014, Vegetation collection efficiency of ultrafine particles: From single fiber to porous media, *Journal of Geophysical Research: Atmospheres*, 119, 222-229

Manoli, G., S. Bonetti, J.C. Domec, M. Putti, G. Katul, and M. Marani, 2014, Tree root systems competing for soil moisture in a 3D soil-plant model, *Advances in Water Resources*, 66, 32-42

Manzoni, S., G. Katul, and A. Porporato, 2014, A dynamical system perspective on plant hydraulic failure, *Water Resources Research*, 50, DOI: 10.1002/2013WR015236

Manzoni, S., G. Vico, G. Katul, S. Palmroth, and A. Porporato, 2014, Optimal plant water-use strategies under stochastic rainfall, *Water Resources Research*, 50, DOI: 10.1002/2014WR015375

Oldroyd, H., G. Katul, E. Pardyjak, and M. B. Parlange, 2014, Momentum balance of katabatic flow on steep slopes covered with short vegetation, *Geophysical Research Letters*, 41, DOI: 10.1002/2014GL060313

Thompson, S.E., S. Assouline, L. Chen, A. Trahtenbrot, T. Svoray, and G. G. Katul, 2014, Secondary dispersal driven by overland flow in drylands: Review and mechanistic model development, *Movement Ecology*, 2:7, doi:10.1186/2051-3933-2-7.

Trahtenbrot, A., G.G. Katul, and R. Nathan, 2014, Mechanistic modeling of seed dispersal by wind over hilly terrain, *Ecological Modelling*, 274, 29-40

Way, D.A., G.G. Katul, S. Manzoni, and G. Vico, 2014, Increasing water use efficiency along the C3 to C4 evolutionary pathway: a stomatal optimization perspective, *Journal of Experimental Botany*, 65, 3683-3693, doi: 10.1093/jxb/eru205

Zhang, Q., S. Manzoni, G. Katul, A. Porporato, and D. Yang, 2014, The hysteretic evapotranspiration-vapor pressure deficit relation, *Journal of Geophysical Research: Biogeosciences*, 119, 125-140

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Banerjee, T., M. Muste, G. Katul, 2015, Flume experiments on wind induced flow in static water bodies in the presence of protruding vegetation, *Advances in Water Resources*, 76, 11-28

Bonetti, S., G. Manoli, J.C. Domec, M. Putti, M. Marani, and G.G. Katul, 2015, The influence of water table depth and the free atmospheric state on convective rainfall predisposition, *Water Resources Research*, 51, 2283-2297

Fatichi, S., G. G. Katul, V.Y. Ivanov, C. Pappas, A. Paschalis, A. Consolo, J. Kim, and P. Burlando, 2015, Abiotic and biotic controls of soil moisture spatio-temporal variability and the occurrence of hysteresis, *Water Resources Research*, 51, 3505-3524, 10.1002/2014WR016102

Li, D., G. Katul, and S. Zilitinkevich, 2015, Revisiting the turbulent Prandtl number in an idealized atmospheric surface layer, *Journal of the Atmospheric Sciences*, 72, 2394-2410, doi:10.1175/JAS-D-14-0335.1

In Press

Duman, T., A. Tracktenbrot, D. Poggi, M. Cassiani, and G. Katul, 2015, Dissipation intermittency increases long-distance dispersal of heavy particles in the canopy sublayer, conditionally accepted, *Boundary-Layer Meteorology*

Banerjee, T., D. Li, J.Y. Juang and G. Katul, 2015, A spectral budget model for the longitudinal turbulent velocity in the stable atmospheric surface layer, to appear *Journal of the Atmospheric Sciences*