Final Scientific Report

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Project Title: Separating Components of Evapotranspiration to Improve Efficiency in Vineyard Water Management

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Keywords *not* appearing in the title and in order of importance. Avoid abbreviations.
evaporation, evapotranspiration partitioning, transpiration, irrigation, cover crops

Abbreviations commonly used in the report, in alphabetical order:
evaporation (E), evapotranspiration (ET), micro Bowen ratio (MBR), North Carolina (NC), transpiration (T)

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US: \$178,480

Total: \$325,000

Signature
Principal Investigator

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	0	0	2
Submitted, in review, in preparation	3	0	0	3
Invited review papers	0	0	0	0
Book chapters	0	0	0	0
Books	0	0	0	0
Master theses	1	0	0	1
Ph.D. theses	1	0	0	1
Abstracts	8	2	2	12
Not refereed (proceedings, reports, etc.)	6	0	0	6

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

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Cooperation Summary (numbers)

	From US to Israel	From Israel to US	Together, elsewhere	Total
Short Visits & Meetings	2	4	3	9
Longer Visits (Sabbaticals)	0	0	0	0

Description Cooperation:

Cooperation between the group members was extremely successful. In addition to several face-to-face meetings, both in Israel and in the USA, bi-monthly conference calls were initiated between all project members, including all involved students. Discussions during these conference calls, exploiting the multidisciplinary nature of the group, significantly advanced the group understanding in the various aspects of the research. This synergistic collaboration is reflected by joint authorship on all manuscripts resulting from the project.

Patent Summary (numbers)

	Israeli inventor only	US inventor only	Joint IS/US inventors	Total
Submitted	0	0	0	0
Issued	0	0	0	0
Licensed	0	0	0	0

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Abstract

Vineyards are found on six of seven continents, producing a crop of high economic value with much historic and cultural significance. Because of the wide range of conditions under which grapes are grown, management approaches are highly varied and must be adapted to local climatic constraints. Research has been conducted in the traditionally prominent grape growing regions of Europe, Australia, and the western USA, but far less information is available to guide production under more extreme growing conditions. The overarching goal of this project was to improve understanding of vineyard water management related to the critical inter-row zone. Experiments were conducted in moist temperate (North Carolina, USA) and arid (Negev, Israel) regions in order to address inter-row water use under high and low water availability conditions. Specific objectives were to: i) calibrate and verify a modeling technique to identify components of evapotranspiration (ET) in temperate and semi-arid vineyard systems, ii) evaluate and refine strategies for excess water removal in vineyards for moist temperate regions of the Southeastern USA, and iii) evaluate and refine strategies for water conservation in vineyards for semi-arid regions of Israel. Several new measurement and modeling techniques were adapted and assessed in order to partition ET between favorable transpiration by the grapes and potentially detrimental water use within the vineyard inter-row. A micro Bowen ratio measurement system was developed to quantify ET from inter-rows. The approach was successful at the NC site, providing strong correlation with standard measurement approaches and adding capability for continuous, non-destructive measurement within a relatively small footprint. The environmental conditions in the Negev site were found to limit the applicability of the technique. Technical issues are yet to be solved to make this technique sufficiently robust. The HYDRUS 2D/3D modeling package was also adapted using data obtained in a series of intense field campaigns at the Negev site. The adapted model was able to account for spatial variation in surface boundary conditions, created by diurnal canopy shading, in order to accurately calculate the contribution of inter-row evaporation (E) as a component of system ET. Experiments evaluated common practices in the southeastern USA: inter-row cover crops purported to reduce water availability and thereby favorably reduce grapevine vegetative growth; and southern Israel: drip irrigation applied to produce a high value crop with maximum water use efficiency. Results from the NC site indicated that water use by the cover crop contributed a significant portion of vineyard ET (up to 93% in May), but that with ample rainfall typical to the region, cover crop water use did little to limit water availability for the grape vines. A potential consequence, however, was elevated below canopy humidity owing to the increased inter-row evapotranspiration associated with the cover crops. This creates increased potential for fungal disease occurrence, which is a common problem in the region. Analysis from the Negev site reveals that, on average, E accounts for about 10% of the total vineyard ET in an isolated drip-irrigated vineyard. The proportion of ET contributed by E increased from May until just before harvest in July, which could be explained primarily by changes in weather conditions. While non-productive water loss as E is relatively small, experiments indicate that further improvements in irrigation efficiency may be possible by considering diurnal shading effects on below canopy potential ET. Overall, research provided both scientific and practical outcomes including new measurement and modeling techniques, and new insights for humid and arid vineyard systems. Research techniques developed through the project will be useful for other agricultural systems, and the successful synergistic cooperation amongst the research team offers opportunity for future collaboration.

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Achievements

A common approach to understanding water use in agricultural systems worldwide is to assess system-level evapotranspiration (ET), either through measurements, modeling, or some combination of the two. Sparse canopy systems such as vineyards are comprised of multiple components (e.g., vines, inter-row soil and/or groundcover) that each contribute to system ET. Quantifying component water and energy fluxes is critical for distinguishing between beneficial (crop transpiration) and potentially detrimental (non-crop transpiration and/or evaporation) water use, thereby informing management decisions aimed at improving productivity and water use efficiency. The overarching goal of this project was to improve understanding of vineyard water use and management related to the critical inter-row zone. Experiments were conducted in both moist temperate (North Carolina, USA) and arid (Negev, Israel) regions in order to address inter-row water use under high and low water availability conditions. Technical achievements of the project included developing improved measurement and modeling techniques for vineyard inter-rows. Practical achievements included quantifying inter-row ET and interpreting associated implications for arid and humid vineyard conditions.

Technical Achievements: A literature review examining the state of technology for ET partitioning (Kool et al., 2014), pursued for this project, clearly indicates a growing interest in quantifying how system components independently contribute to system-level ET. It also highlights several shortcomings, including a lack of studies where multiple system components have been independently measured and few available methods for making these independent measurements. Thus an important scientific goal for our project was to develop techniques for measuring and modeling components of ET, which can ultimately be used to gather information for guiding practical decisions on water management.

Several measurement and modeling techniques were examined and improved in order to determine component ET within vineyards. This included development of micro Bowen ratio (MBR) measurement systems for continuous measurement of inter-row ET (Holland et al., 2013) and modification of the HYDRUS 2D/3D modeling package to accommodate spatially variable boundary conditions associated with diurnal shading (Kool et al., under review).

MBR energy balance methodology utilized air temperature and water vapor concentration measurements within inter-rows. Measured ET rates at the NC site were well correlated between MBR systems and microlysimeters for both fescue and bare surface inter-row

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conditions. MBR daily ET estimates, determined by compositing measurements from fescue interrows and bare soil under vines, were also well correlated to and of similar magnitude as vineyard eddy covariance ET measurements during periods when the vines were dormant. Overall, MBR systems provided a reasonable approach to determine ET for the inter-row component within the temperate NC vineyard. At the Negev site, MBR measurements of ET were not well-correlated with those from microlysimeters. Analysis revealed that the high temperatures of the soil surface adversely affected MBR measurements in the Negev; a modified MBR design is currently being tested for future work.

The HYDRUS 2D/3D model was calibrated and tested using a combination of continuous above canopy measurements, and short-term intensive measurements below the canopy, including actual and potential E, and solar radiation along transects between adjacent vine rows at the Negev site. Potential and actual E below the canopy were highly variable, both diurnally and with distance from the vine-row, as a result of shading and distinct wetted areas typical to drip-irrigation. While the magnitude of actual E was mostly determined by water content, diurnal patterns depended strongly on position relative to the vine-row due to variable shading patterns. The HYDRUS 2D/3D model was modified to permit the use of spatially variable surface boundary conditions and was thus able to successfully simulate the magnitude, diurnal patterns and spatial distribution of E, including expected deviations as a result of variability in soil saturated hydraulic conductivity. Results suggest that similar methodology may be useful to better understand components' contributions to water and energy fluxes in other complex or sparse canopy systems.

Practical Achievements: The primary practical goal of the project was to understand the contribution of water loss via ET from inter-rows under typical management systems in the Negev (drip-irrigated) and NC (rainfed with inter-row cover crops) to system water use.

Analysis of three 24-h campaigns conducted throughout the 2012 growing season in the Negev site reveal that, on average, E accounts for ~10% of the total vineyard ET (the inter-row E plus the vine canopy T) in an isolated drip-irrigated vineyard in a desert, with daily values as high as 17%. The fraction E/ET increased from May until just before harvest in July. During this period, the training system and the unique architecture of the vineyard, apparently keep the fractions of vegetation cover and exposed soil relatively constant. The seasonal changes were therefore explained by changes in weather conditions. From May to July, potential evapotranspiration increased, driving higher rates of soil water evaporation as

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summer approached. To validate these trends, daily estimates of the E/ET fraction throughout the season are required and will be pursued through work proposed as a project continuation.

The NC site represents the extreme case of substantial inter-row water use within the vineyard. Based on analysis presented in Holland et al. (under review) and preliminary eddy covariance data analysis, vine T accounts for only 7-55% of ET in this vineyard, characterized by conditions of excess availability of water. The inter-row fescue cover crop was responsible for up to 93% of total ET at the start of growing season (May). Fescue water use was fairly constant throughout the season, but represented a much smaller fraction of total ET during peak vine water use in July and August. Despite fescue inter-row ET, soil water depletion was insufficient to limit water availability or produce stress in the vines. Fescue inter-row vapor pressure increased compared to the bare soil inter-rows by an average of 2% during the growing season. Data suggest that fescue ET may increase inter-row humidity and fungal disease potential in warm, humid environments, while providing only modest influence on water availability which is desired to limit vegetative vine growth.

Project Impacts: Vineyards are found on six of seven continents, producing a crop of high economic value with much cultural significance. The project undertaken here quantified ET and provided improved measurement and modeling technologies applicable across the full spectrum of production conditions from arid, drip irrigated to humid, rain-fed vineyards. Approaches developed herein should also be applicable to other sparse-canopy agricultural systems such as agroforestry and high-value production in orchards.

Though the specific economic value of this project cannot be quantified, it is noted that viticulture is estimated to have economic impacts >\$1.28B and >\$100M in North Carolina and Israel, respectively. Work undertaken as part of this project provides a means to improve management including possible reduction of fungicide application, following considerations on inter-row cover crops so as to moderate inter-row ET and humidity. Conservative use of irrigation water is paramount for vineyards in Israel. Project results confirm that evaporation amounts are relatively small but also suggest that the timing of irrigation within the day may further reduce water losses to evaporation by making use of diurnal shading patterns.

Beyond research impacts, work also supported BARD's emphasis on training and collaboration. Impacts included training for several early career scientists: a post-doctoral scientist, a Ph.D. student, and a M.S. student; and collaboration amongst project personal as well as many additional collaborating scientists in both Israel and the USA.

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Details of Cooperation

The project was made possible by a synergistic collaboration amongst team members, with each team member providing a unique contribution. Co-PIs Heitman and Ben-Gal, with expertise in rain-fed and irrigated vineyard practices, respectively, served as directors for respective sites in North Carolina and Israel. Collaborator Agam provided expertise in energy balance modeling and measurements, and collaborator Sauer provided expertise in eddy covariance and Bowen ratio measurement systems. Additional contributions from collaborators Havlin and Lazarovitch (unnamed on original project team) facilitated the participation and training of two graduate students, one each in the USA (S. Holland) and Israel (D. Kool).

Cooperation between the group members was extremely successful. In addition to several face-to-face meetings, both in Israel and in the U.S. (partly supported by the BARD funds and partly funded by external sources to the project), bi-monthly conference calls were initiated between all project members, including all involved students. Discussions during these conference calls, exploiting the multidisciplinary nature of the group, significantly advanced the group understanding in the various aspects of the research. This synergistic collaboration is reflected by joint authorship on all manuscripts resulting from the project. Success of the cooperation and collaboration has led the group to work together to pursue opportunities to extend the project's successful outcomes through a proposed continuation.

Face-to-Face Meetings

- Nov. 2009: Heitman, Sauer, and Agam met at ASA-CSSA-SSSA Meeting, Pittsburg, PA, to discussion project initiation.
- Jan. 2010: Agam and Sauer hosted by Heitman and Havlin in Raleigh, NC, to prepare equipment exchange and measurement protocols.
- May 2011: Heitman and Howard (M.S. student) hosted by Agam and Ben-Gal at Gilat Research Station and Blaustein Institute for Desert Research for discussion of mid-term results and Negev site visit.
- Oct. 2011: Heitman and Ben-Gal met at ASA-CSSA-SSSA Meeting, San Antonio, TX, for project discussion and planning.
- May 2012: Ben-Gal and Sauer hosted by Heitman and Havlin in Raleigh, NC, for mid-term project discussion and North Carolina site visit.

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- Nov. 2012: Sauer hosted by Agam and Ben-Gal at Gilat Research Station and Blaustein Institute for Desert Research for discussion of mid-term results.
- Nov. 2012: Kool (Ph.D. student) hosted by Heitman in Raleigh, NC, to discuss project results and analysis.
- Nov. 2013: Agam, Ben-Gal, Heitman, and Sauer met at ASA-CSSA-SSSA Meeting, Tampa, FL, to discuss project progress and manuscript preparation.
- Nov. 2013: Kool (Ph.D. student) hosted by Heitman in Raleigh, NC, to discuss project results, analysis and manuscript preparation.

Publications

Journal Articles

- [1] Holland S., Heitman J.L., Howard A., Sauer T.J., Giese W., Ben-Gal A., Agam N., Kool D., and Havlin J. 2013. Micro-Bowen Ratio System for Measuring Evapotranspiration in a Vineyard Interrow. *Agricultural and Forest Meteorology*, 177, 93-100.
- [2] Holland S., Howard A., Heitman J., Giese W., Sutton T., Agam N., Ben-Gal A., Havlin J.L., and Sauer T.J. Implications of Fescue for Water Dynamics in a Vineyard. *Agronomy Journal*, under review.
- [3] Kool D., Agam N., Lazarovitch N., Heitman J.L., Sauer T.J., and Ben-Gal A. A Review of Approaches for Evaporation Partitioning. *Agricultural and Forest Meteorology*, 184, 56-70.
- [4] Kool D., Ben-Gal A., Agam N., Šimůnek J., Heitman J., Sauer T.J., and Lazarovitch N. Spatial and Diurnal Below Canopy Evaporation in a Desert Vineyard: Measurements and Modeling. *Water Resources Research*, under review.
- [5] Kool D., Heitman J., Agam N., Sauer T.J. Ben-Gal A. and Lazarovitch N. Detection of soil evaporation from a vineyard using soil heat pulse sensors. In preparation.

Master/Ph.D. Theses

- [1] Holland S. 2012. *Below-Canopy Water and Energy Transfer in a North Carolina Vineyard*. M.S. Thesis. NC State University, Raleigh, NC.
- [2] Kool, D. *Soil evaporation in a drip-irrigated wine vineyard in a desert area*. Ph.D. Dissertation. Ben-Gurion University of the Negev, Israel. In preparation.

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Abstracts

- [1] Agam N., Kool D., Lazarovitch N., Heitman J.L., Sauer T.J., Ben-Gal A. Soil evaporation in a drip-irrigated vineyard in a desert area. International Conference on Drylands, Deserts and Desertification. Sede-Boker campus, Israel.
- [2] Heitman J.L., Agam N., Ben-Gal A., Havlin J., Howard A., Holland S., Kool D., and Sauer T.J. 2012. Inter-row Evapotranspiration in Arid and Humid Wine-Grape Vineyards. AMS Conf. Ag. For. Meteorol. Boston, MA, USA.
- [3] Heitman, J.L., Howard A., Holland S., Agam N., Ben-Gal A., Sauer T.J., Havlin J., and Giese G. 2012. Below Canopy Evapotranspiration in a Rain-fed Southeastern U.S. Vineyard. ASA-CSSA-SSSA Meeting, Cincinnati, OH, USA.
- [4] Holland S., Heitman J.L., Howard A., Havlin J., Sauer T.J., and Giese G.. 2011. Measuring the Influence of an Inter-Row Fescue Crop on the Below Canopy Humidity in a North Carolina Vineyard. ASA-CSSA-SSSA International Meeting, San Antonio, TX, USA.
- [5] Howard A., Heitman J.L., Havlin J., Giese G., and Sauer T.J. 2010. Water Dynamics for North Carolina V. Vinifera. ASA-CSSA-SSSA Meeting, Long Beach, CA, USA.
- [6] Kool D., Agam N., Lazarovitch N., Heitman J.L., Sauer T.J., and Ben-Gal A. 2012. Below Canopy Evaporation in a Drip-Irrigated Vineyard in Southern Israel. ASA-CSSA-SSSA Meeting, Cincinnati, OH, USA.
- [7] Kool D., Agam N., Lazarovitch N., Heitman J.L., Sauer T.J., and Ben-Gal A. 2013. Below canopy evaporation dynamics: Implementing variable boundary conditions in HYDRUS 2D/3D. International Workshop on Eco-hydrology of Semiarid Environments: Confronting Mathematical Models with Ecosystem Complexity. Beer-Sheva, Israel.
- [8] Kool, D., Agam N., Lazarovitch N., Heitman J.L., Sauer T.J., Ben-Gal A., and Šimůnek J. 2013. Below Canopy Evaporation Dynamics: Implementing Variable Boundary Conditions in HYDRUS 2D/3D. ASA-CSSA-SSSA International Meeting, Tampa, FL, USA.
- [9] Kool, D., Agam, N., Lazarovitch, N., Šimůnek, J., Heitman, J.L., Sauer, T., and Ben-Gal, A. 2013. Below canopy evaporation dynamics: Implementing variable boundary conditions in HYDRUS 2D/3D. Automated methods for continuous measurements in agriculture and forestry. Sede Boqer Campus, Israel.

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- [10] Kool, D., Agam, N., Lazarovitch, N., and Ben-Gal, A. 2012. The importance of evaporation from the soil to the water budget of an irrigated wine vineyard in the Negev. – Kennes haNegev, (כנס הנגב למחקר ופיתוח הקלאי). Ramat Negev, Israel.
- [11] Kool, D., Agam, N., Lazarovitch, N., and Ben-Gal, A. 2011. ET components investigated individually - testing the Two Source Model in an arid vineyard – International Symposium on Sensing in Agriculture, in memory of Dahlia Greidinger. Haifa, Israel.
- [12] Sauer, T., Kool D., Holland S., Agam A., Ben-Gal A., Heitman J.L., and Howard A. 2012. New Technique for Measuring Surface Energy Balance and Soil Water Evaporation beneath Sparse Plant Canopies. International Conference on Drylands, Deserts and Desertification. Sede-Boker campus, Israel.