Three Dimensional Modeling of Water Use and Photosynthesis in Almond Orchards

Project No.: PREC1.Bailey

Project Leader:

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Grantee(s) of the Almond Board are REQUIRED to address sections A through G. These should be **sumitted in PDF**, using Arial font size 12 for the main text, and be five to seven pages in length.

A. Summary *(In laymen's terms – emphasize key findings and recommendations)*

This project seeks to develop a 3D simulation platform that can be used to perform virtual experiments in almond orchards in order to better understand the effects of various orchard designs and management decisions. For example, if spacing between trees in an orchard is reduced, how will this affect light interception, photosynthesis, and water use?

We have completed initial model development and are now in the stage of validating model simulations against measurements. We identified several possible sources of bias between model results and lysimeter measurements of evapotranspiration, including the amount leaf area re-constructed from LiDAR data, the model averaging scale, and input environmental conditions. We are in the process of evaluating and addressing each possible source of bias to improve robustness in modeled transpiration.

The final stage of this project will involve simulating orchards with varying canopy architectures (tree and row spacings, within-crown densities, etc.) to determine how orchard structure affects orchard level photosynthesis and water-use.

B. Objectives *(300 words max.)*

1. Specify the goal(s) and specific objectives of the proposal – if a collaborative effort, identify who is the lead for each objective
2. Identify annual outputs or milestones for each of the objectives

The overall goal of this project is to develop a simulation platform that serves as a tool to perform virtual experiments in almond orchards in order to better understand the effects of various orchard designs and management decisions. Specific objectives are given in Table 1 below:

Table 1. Key objectives, timelines and milestones

Objective(s)	Date to be accomplished	Milestones and deliverables associated to the objective
1. Adapt the Helios simulation system to almond orchards in order to develop an efficient, three-dimensional modeling system that can accurately predict water transport, microclimate, radiation interception, and photosynthesis.	April 2018	Objective 1 will be considered complete when we are able to produce simulations of the leaf-level radiative flux, water flux, and photosynthetic fluxes for an actual almond orchard. The deliverable is a working modeling system. Note that this milestone was successfully achieved in year 1.
2. Perform model calibration, verification, and validation.	April 2020	This objective will be considered complete when we are able to simulate tree- or canopy-level fluxes of water vapor at hourly intervals with an agreement index between model and experimental data that is greater than 80%. We will specifically compare against data from the Kearney lysimeter and possibly other datasets. The deliverable will be data comparisons between the model and experimental data.
3. Use the model to examine a wide range of canopy architectures and quantify trade-offs between water usage and photosynthesis	March 2021	Milestones for Objective 3 and the project as a whole will be recommendations on canopy designs and irrigation practices that optimize water use efficiency.

C. Annual Results and Discussion *(This is the core function of this report)*

1. Describe activities and outputs for each objective
2. Discuss significance of these in terms of progress toward goals, change in approach, next steps or other conclusions based on this year's results

The main work performed this past year contributed to the model calibration, verification, and validation objective. We conducted preliminary comparisons between modeled evapotranspiration and lysimeter measurements collected by Ken Shackel for a Nonpareil tree at the Kearney Agricultural Research and Extension Center. We found that the model overestimated the peak in diurnal ET and that the peak was lagged in comparison with the measurements. This lead us to consider several possible sources of bias within the model, including the averaging scale at which calculations were carried out in the model, the representativeness of the canopy microclimate data used as input to the model, and the overall leaf area reconstructed using LiDAR data used as input to the model.

Initial modeling was conducted at the leaf scale (e.g., light interception was averaged over each individual leaf and this value was used to model the energy budget, stomatal conductance, and transpiration for each leaf). Although this method was computationally efficient, it was not clear that it was necessarily the most accurate method since there can be considerable heterogeneity in the light environment across any given leaf dependent on shading by other leaves. Model averaging scale is relevant because the processes we are interested in (e.g., stomatal conductance, photosynthesis, transpiration) have non-linear responses to light so that using an average light condition does not necessarily result in the correct total photosynthesis, for example. We tested a range of smaller model averaging scales by dividing individual leaves up into smaller sub-patches in the model and performing model calculations at this scale. We found that using our initial leaf-level averaging scale could substantially overestimate canopy level fluxes compared with the finer scale sub-leaf averaging we tested. This was especially true for the denser canopies tested, while simulations with less dense canopies showed less bias. We also found that bias is substantially reduced by using even a relatively small number of sub-patches per leaf, with diminishing returns on accuracy as greater and greater numbers of smaller sub-patches are used. We selected an intermediate sub-leaf averaging scale to achieve greater accuracy without increasing computation expense drastically.

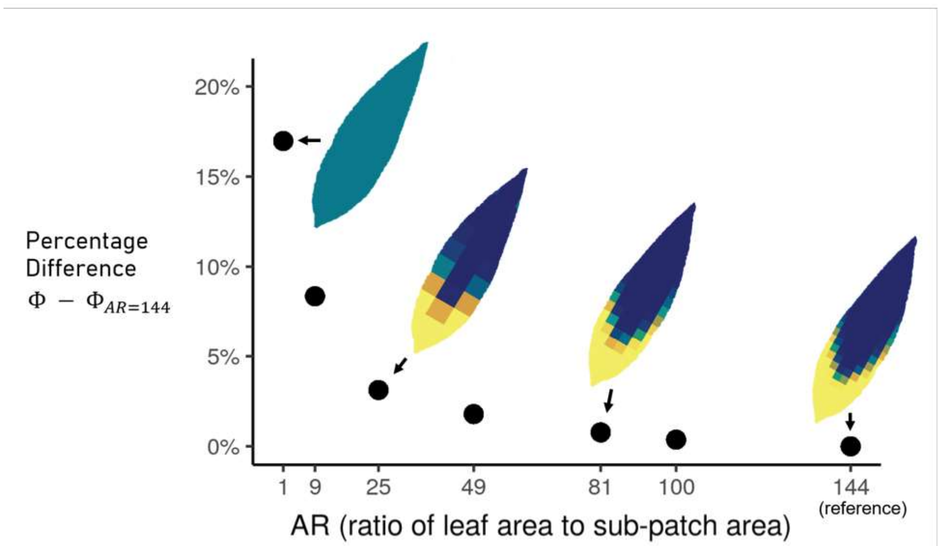

Figure 1. Percentage difference (error) in generic radiation saturating process between simulations of an almond orchard using finest averaging scale tested (AR = 144) and larger averaging scales (AR = 1-100). On the x-axis, AR is the ratio of individual leaf area to individual sub-patch area. Images of leaf sub-patch divisions are given for select values of AR for illustration purposes.

Second, we hypothesized that including more accurate environmental conditions in our model as input could help improve simulation results. We initially applied a constant air temperature, humidity, and wind speed for the entire simulation domain based on measurements above the canopy or from a nearby CIMIS station (located over grass). To test if more accurate microclimate input could improve results of the ET simulation, we collected a vertical profile of meteorological measurements on two days in summer 2019. We are currently implementing the ability to add this type of profile measurement input to the model so that we can evaluate the impact on modeled orchard transpiration.

Lastly, we hypothesized there might be a possible bias in the overall leaf area reconstructed using LiDAR data due to the LiDAR beam hitting multiple leaves at a time. This issue may be more important in almond canopies which have smaller leaves compared with vineyard canopies where initial development of this methodology was conducted (Bailey and Mahaffee 2017a,b). This prior work in vineyard canopies utilized a discrete-return type LiDAR which implicitly averages multiple hits per beam. The current measurements taken in almond orchards are utilizing the full-waveform type LiDAR instrument which returns multiple hits per beam separately. The question is if and how to incorporate this information in accurately estimating leaf area density from LiDAR data. To determine the degree to which our current LiDAR processing method might introduce bias into the estimates of almond orchard leaf area density, we are conducting tests in which the LiDAR scans are simulated for virtual canopies where the exact geometries (e.g., leaf area density, leaf size) are known. If such tests on known canopies produces bias in leaf area density estimates, we will test multiple methods of averaging or filtering multiple hits per scan to try to improve results.

As we test each of these possible sources of bias we expect to validate simulations against the lysimeter measurements. Once model validation is complete, we will use it to study how various orchard architectural features affect water usage and photosynthesis. For example, different pruning practices are sometimes used to maximize sunlight penetration into the canopy in order to maximize photosynthesis and yield. However, too much sunlight causes saturation of photosynthesis, leading to increased heat and water stress with negligible gains in photosynthesis. Furthermore, these architectural differences between canopies result in different water usage characteristics, which are not reflected in simple crop coefficients. The model will also be used to determine architectural corrections for crop coefficients that are better tailored to a specific field. For example, instead of using a single crop coefficient that is assumed to be generally applicable to all almond orchards across an entire region, corrections could be developed based on the models that account for different orchard designs, cultivar combinations, and pruning practices.

D. Outreach Activities

1. Please describe outreach activities including the event description (date, location, topic of the presentation, aprox number of participants and type of audience)

- A poster describing this project was presented at the Almond Board of California Conference on 2019-12-10 in Sacramento. The audience included interested growers and researchers.
- An oral presentation based on work conducted for this project was given at the American Geophysical Union Fall Meeting on 2019-12-12 in San Francisco. The presentation was part of the session, “Trends in Digital Agriculture: Crop Sensing Technologies Toward Climate-Resilient Agricultural Systems” and the audience consisted of approximately 50-100 researchers. Citation: Kent, E. R. and Bailey, B. N.

American Geophysical Union Fall Meeting (2019). San Francisco, CA. “The Role of Averaging Scale in Modeling Non-linear Leaf Level Processes for Canopies using a Three-dimensional Leaf-resolving Model” (oral presentation).

E. **Materials and Methods** *(500 word max.)*:
   1. Outline materials used and methods to conduct experiment(s)
   2. Note any challenges or unforeseen developments that were encountered resulting in change of methodogy, timeline, or scope of project

Helios 3D Modeling Framework

The primary material used for this project is the Helios 3D modeling framework, a C++ API developed by Bailey (2019). Helios includes plugins for 3D tree geometry construction, LiDAR data processing, radiation transfer, surface energy balance, stomatal conductance, and photosynthesis.

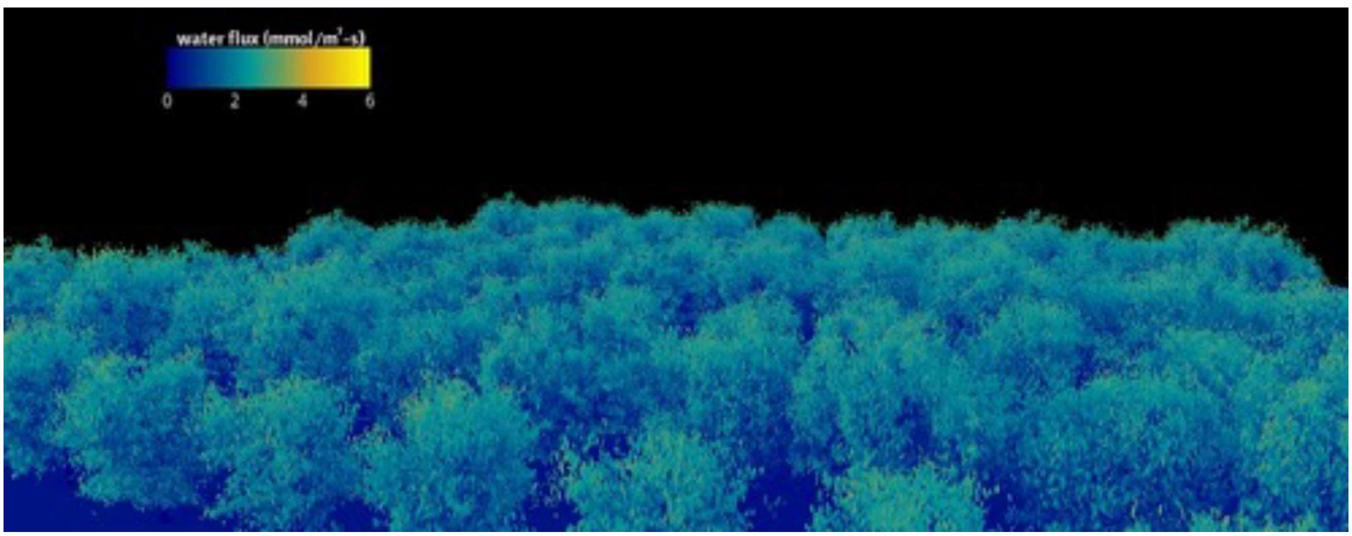

Figure 2. Example three-dimensional virtual orchard construction generated as part of our experimental campaigns at the Kearney lysimeter almond orchard.

Calibration and Validation Measurements

A large weighing lysimeter at the Kearney Agricultural Research and Extension Center is being used to measure the evapotranspiration from a Nonpareil almond tree and this will be compared with model results for model validation. Lysimeter weight is recorded every 10 minutes. Differences in weight between subsequent measurements represents loss or gain of water from the lysimeter system, corresponding with evapotranspiration by the tree or irrigation respectively.

In order to accurately represent the lysimeter tree in the model, additional measurements were taken during several days throughout the previous growing seasons. LiDAR scans of parts of the orchard were collected in order to reconstruct the orchard geometry within the model. A ground-based full-wave-form LiDAR system was mounted on a wagon and was pulled up and down several rows in the Kearney orchard surrounding the lysimeter. Four scans per tree were used to reconstruct leaf surfaces from the point-cloud data following the method of Bailey and Ochoa (2018). Manual leaf size measurements were also collected in the orchard to help validate LiDAR reconstructions. Application of these methods to some of the data collected in the almond orchard resulted in leaf area densities that were likely too high, with some voxels showing unrealistically high values. We hypothesize this is due to the LiDAR beam hitting multiple leaves at a time and are investigating this possibility with synthetic LiDAR data with the Helios modeling framework where the exact leaf areas of a canopy are known.

Leaf gas exchange and stem water potential data were collected in the orchard to provide input parameters for the stomatal conductance and photosynthesis models. Reflectivity and transmissivity of leaves and reflectivity of the orchard floor were collected as model input. Profiles of air temperature, humidity, and wind speed measurements were also collected for use as model input.

F. Publications that emerged from this work

1. List peer review publications in preparation, accepted or published
2. Other publications (e.g. outreach materials)
3. Please provide copies of publications

Kent, E. R. and Bailey, B. N. (In preparation). "The role of averaging scale in modeling non-linear leaf level processes for heterogeneous canopies".

Kent, E. R. and Bailey, B. N. (In preparation). "The role of averaging scale in modeling non-linear leaf level processes for homogeneous canopies". (In preparation).

Bailey, B.N. (2019). Helios: a scalable 3D plant and environmental biophysical modelling framework. Frontiers in Plant Science 10:1185

Bailey, B.N. and Ochoa, M.H. (2018). Semi-direct tree reconstruction using terrestrial LiDAR point cloud data. Remote Sensing of Environment 208:133-144.

References Cited:

Bailey, B.N. (2019). Helios: a scalable 3D plant and environmental biophysical modelling framework. Frontiers in Plant Science 10:1185

Bailey, B.N. (2018). A reverse ray-tracing method for modelling the net radiative flux in leaf-resolving plant canopy simulations. Ecological Modelling 368:233-245.

Bailey, B.N. and Ochoa, M.H. (2018). Semi-direct tree reconstruction using terrestrial LiDAR point cloud data. Remote Sensing of Environment 208:133-144.

Bailey, B.N. and Mahaffee, W.F. (2017b). Rapid, high-resolution measurement of leaf area and leaf orientation using terrestrial LiDAR scanning data. Meas. Sci. Technol. 28:

Bailey, B.N. and Mahaffee, W.F. (2017a). Rapid measurement of the three-dimensional distribution of leaf orientation and the leaf angle probability density function using terrestrial LiDAR scanning. Remote Sens. Env. 193:63-76.