Three-Dimensional Modeling Water Use and Photosynthesis in Almond Orchards

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Objectives:

The overall objective 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 on water use and productivity. Specific objectives are listed below:

1. Adapt the Cronus 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.
2. Perform model calibration, verification, and validation.
3. Use the model to examine a wide range of canopy architectures and quantify trade-offs between water usage and photosynthesis.

Interpretive Summary:

Field experimentation, along with intuition, has been the traditional approach used by agronomists and growers to better understand crops, and ultimately improve efficiency in production. Making robust conclusions that lead to adoption of new practices is typically slow, as very large data sets are required in order to separate physiological effects from the high natural variability in the system. Inability to rapidly vary environmental, geographical, and architectural conditions also limits the utility of field experimentation. These challenges can potentially lead to widely used management practices that are primarily based on anecdotal rather than sound observational evidence.

The purpose of this project is to develop the next generation of almond simulation tools based on highly accurate and efficient three-dimensional crop models that can be used to rapidly evaluate proposed orchard design or management strategies in a simulated environment. It is

not expected that the tool will entirely replace field trials, but rather will provide a tool for rapidly evaluating many proposed designs or practices in a simulated environment before investing in a field experiment. The modeling system used is based on the Cronus crop modeling framework developed by the PI (baileylab.ucdavis.edu/cronus). Cronus is unique from any other crop modeling system in that it uses detailed, physically based models that can represent individual leaves through whole-canopy-scales. This project focuses on extending the system for use in almond crop systems and using the tool to examine interactions between canopy architecture and trade-offs between water use and photosynthetic production.

The first stage of this project, model development, has been completed. Models for virtual tree construction (Weber and Penn 1995), radiative transfer (Bailey 2018), microclimate (Bailey et al. 2016), photosynthesis, and water transport (Buckley, Turnbull, and Adams 2012) have been implemented in the Cronus modeling framework, allowing simulations of orchard water use and photosynthesis to be performed.

To start testing the integrated framework for almond orchards, we have been working in collaboration with Dr. Ken Shackel to utilize his lysimeter measurements of tree water use at Kearney Agricultural Research and Extension Center. Last season, we performed initial terrestrial laser scanning (LiDAR) measurements of a portion of the orchard to obtain the three-dimensional geometry of the trees (**Figure 1**) and collected leaf-level gas exchange data needed to parameterize the model. We performed simulations of evapotranspiration for the portion of the orchard that was examined (**Figure 3**), and also compared results against the lysimeter data (**Figure 4**), which overall showed very good agreement between the model and measurements. We were able to approximate LiDAR-derived orchard architecture using a model for virtual tree generation (**Figure 2, Figure 5**). This initial work has demonstrated the feasibility of our approach. Future work in the second stage of this project will first focus on calibration and rigorous testing, and validation of the model using additional field data.

The third stage of this project will use the model to study how orchard architectural features including pruning and tree and row spacing affect orchard water use and photosynthesis. The model will 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 will be developed based on the models that account for different orchard designs, cultivar combinations, and pruning practices.

Additional development of the system is anticipated beyond the scope of this project. Further model improvements are anticipated to add functionality such as sub-models for growth, yield, and disease spread. This would allow the simulation system to be used to address a wide range of questions to support decision-making in almond orchards, ranging from spray application to placement of pollinators. Thus, although the results of this project will provide an immediate benefit to growers, it will also be a starting point for many years' worth of further model development that will have a wide range of future benefits to growers.

Materials and Methods:

Objective 1. Model Development

Overall Strategy: Much work to date has focused on understanding physical and physiological processes in plants at the leaf level (e.g., energy transfer, photosynthesis, water potential). This is often because leaf-level measurements are easier to collect and lend themselves to laboratory experimentation. Despite this understanding of processes at the leaf level, a fundamental challenge in the field of plant physiology has been scaling these processes from leaves to whole canopies (Ehleringer and Field 1993). This often requires the use of questionable and inaccurate scaling assumptions. The models used in this work utilize a “brute force” approach to perform this scaling. Microclimate (and other quantities of interest) are modeled at the leaf scale and simply aggregated to form plants and whole canopies, which is the most accurate and straightforward means of up-scaling. This means that plant-to-plant interactions and competition are directly represented. Past modelers have used this approach, but because of computational limitations, have only been able to feasibly scale up to the plant scale (Sarlikioti, de Visser, and Marcelis 2011; Garin et al. 2014).

In this work, unique high-performance computing capabilities are used to overcome these limitations. For decades, computer scientists have used graphics processing units (GPUs) as a means for accelerating complex “models” associated with rendering computer-generated images for display. GPUs are standard hardware on all desktop and laptop computers and can be considered miniature supercomputers that were designed to rapidly perform graphics computations in parallel. In this work, we leverage the efficiency afforded by GPUs to accelerate model calculations, allowing for physical simulations of unprecedented size and detail.

The Cronus crop modeling framework was originally developed by the PI as a modeling and decision support platform in grapevine canopies, which can simultaneously predict growth, yield, microclimate, and disease spread. This work adapts the Cronus simulation system to almond orchards. Cronus integrates state-of-the-art models for radiation, microclimate, evapotranspiration, and photosynthesis to represent transport processes of interest at scales ranging from leaves to canopies. By explicitly representing every leaf in the canopy using mechanistic physics-based models, the modeling system is robust to changes in architecture and can represent tree-to-tree competition effects.

Canopy Radiation and Microclimate: Canopy microclimate plays a critical role in nearly any physiological process in plants. It is also typically very costly to model and represents the majority of model run time. Local microclimate couples all components in the crop system and is a primary means by which neighboring plants interact with each other. This makes modeling microclimate particularly challenging because it means we are modeling a fully coupled system, rather than isolated elements. Radiation transport is by far the most computationally expensive component of microclimate modeling. The NVIDIA® OptiX™ engine (developer.nvidia.com/optix) is a highly optimized ray-tracing engine, which was be used as a basis for radiation transport modeling as described in Bailey (2018). Using this engine to accelerate model calculations, Bailey (2018) demonstrated model scaling up to whole-canopy-scales without compromising physical realism and accuracy.

The leaf energy balance equation (Jones 2014) is the primary basis for modeling canopy microclimate. The energy balance equation partitions net radiative energy into sensible and evaporative heating/cooling, and also allows for the determination of surface temperature. The models were accelerated by implementing them in the NVIDIA® CUDA framework ('Compute Unified Device Architecture (CUDA) Programming Guide' 2007), which utilizes the GPU to perform calculations in parallel. The overall modeling approach has been validated by Bailey et al. (2016) for different plant types and is typically able to reproduce measurements to within estimated instrument error.

Water Transport and Photosynthesis: Evapotranspiration at the leaf surfaces is modeled using the evaporative cooling term in the leaf energy balance, which includes a sub-model for stomatal conductance. Stomatal conductance, along with boundary-layer conductance, are primary regulators of water transport through the plant. The model of Buckley, Turnbull, and Adams (2012) will be used to predict stomatal conductance, which includes feedback mechanisms to account for soil water potential, solar irradiance, and vapor pressure deficit. The model will be applied at the leaf-level and driven by coupling it to the radiation and microclimate calculations. An empirical photosynthesis model was implemented that calculates net photosynthesis as a function of irradiance, temperature, and intercellular CO_2 concentration. The latter is dependent on the stomatal conductance so that the photosynthesis and conductance models are evaluated iteratively.

Objective 2. Model Calibration, Verification, and Validation

As model detail increases, there is also a corresponding need for increasingly detailed data to perform model validation. The models to be used in this project have many unique built-in verification checks that are performed before every simulation. These act as sanity checks to ensure that models are at least physically consistent. Although these verification checks are a valuable tool, formal field validation is also necessary to ensure that model predictions are consistent with reality and to calibrate the models.

To begin testing the models for almond orchards, we have been working in collaboration with Dr. Ken Shackel to utilize his almond lysimeter data at Kearney Ag. Research and Extension Center. The lysimeter orchard is located near Parlier, California, with rows spaced 21 ft and trees spaced at 13 ft. Rows alternate between Nonpareil and two pollinizer varieties (Monterey and Wood Colony). A single Nonpareil tree is grown in a weighing lysimeter, which is a large scale that measures change of weight associated with water loss by the tree.

Initial LiDAR scanning for determining three-dimensional geometry of the canopy (**Figure 1**) and leaf-level gas exchange measurements needed to parameterize the stomatal conductance and photosynthesis components of the model were collected in October 2017. LiDAR data was collected on six trees of each variety in the orchard for initial testing.

Figure 1. Three-dimensional laser scanning data (LiDAR) of the Kearney Agricultural Research and Extension Center almond orchard.

Reconstruction of canopy geometry was carried out using the initial LiDAR data and the method of Bailey and Ochoa (2018). This reconstructed geometry was used in an initial test simulation of the orchard (**Figure 3**). Modeled evapotranspiration for the lysimeter tree was compared with corresponding lysimeter data (**Figure 4**), which showed good agreement.

While the LiDAR data is useful for reconstructing actual orchards and will be used for model validation in this work at specific orchards, the third stage of this project will involve modeling many different canopy architectures. It is not feasible to perform LiDAR scans for every possible orchard configuration within the scope of this project, and one of the advantages of using a model is that we can explore potential canopy architectures that may not currently be in use. Using the implemented model for the construction of virtual trees (Weber and Penn 1995) we can create virtual orchards without LiDAR data (**Figure 2**). We are performing initial testing and calibration of this model against LiDAR data by dividing the orchard into a grid of cells and calculating plant area density (PAD, plant/leaf surface area per unit volume) for each cell (Bailey and Mahaffee 2017a,b). We examined vertical and horizontal distributions of PAD for each of the three varieties planted in the Kearney Ag. Research and Extension Center almond orchard and adjusted tree geometry model parameters to approximate the LiDAR measured PAD (**Figure 5**).

In late June 2018 we collected additional field data over the course of two days at the Kearney Ag. Research and Extension Center. LiDAR scans were taken of 90 trees in the orchard, including full rows of each variety. Additional leaf-level gas exchange data was collected for parameterizing stomatal conductance and photosynthesis models. Spectral radiation data was collected to determine leaf reflectivity and transmissivity needed by the radiative transfer model. This recently collected data is currently being processed and will be used to improve the next round of model simulations. Another round of data collection at the Kearney orchard is anticipated for August 2018.

Figure 2. Example three-dimensional virtual orchard construction generated by the implemented tree geometry model.

Objective 3. Model Usage

Initially, the model will be used 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 (or even declines) in photosynthetic production. 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.

Results and Discussion:

Using data from initial field measurements in October 2017 we performed simulations of evapotranspiration for the portion of the Kearney almond orchard (**Figure 3**). We compared results against the lysimeter data (**Figure 4**), which overall showed very good agreement between the model and lysimeter data. We were able to approximate mean vertical and horizontal distributions of PAD measured by the LiDAR scans of the Kearney orchard with the tree geometry model (**Figure 5**). This initial work has demonstrated the feasibility of our approach. We will do a more detailed and rigorous testing and validation of the model using recently collected field data in June 2018 and using future data to be collected late 2018.

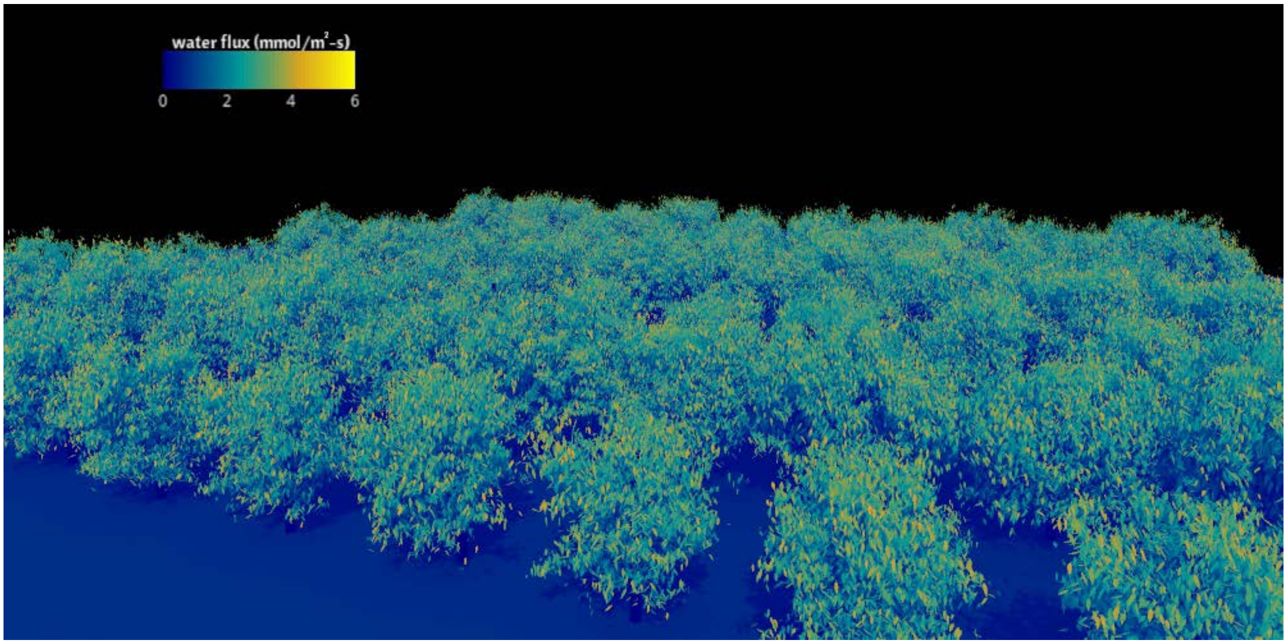

Figure 3. Three-dimensional simulation of leaf water use (transpiration) for Kearney Agricultural Research and Extension Center almond orchard. The leaves and ground surface are colored according to their rate of water loss.

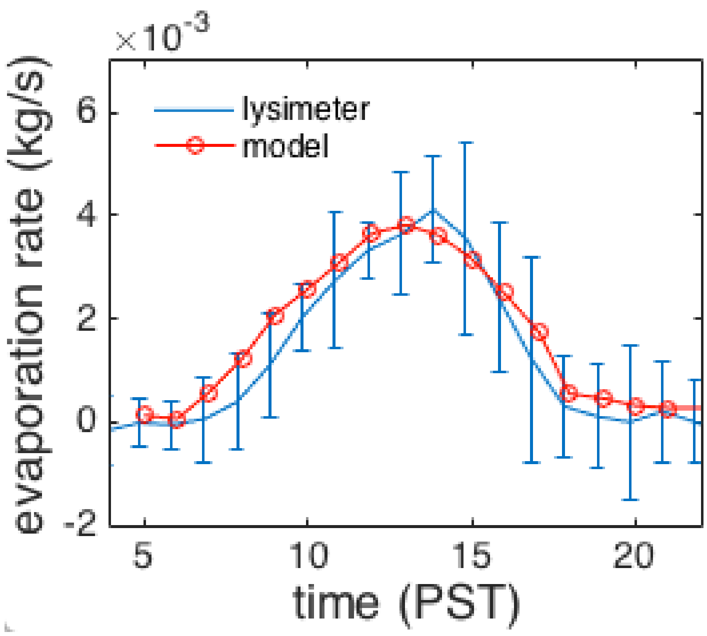

Figure 4. Comparison of modeled whole-tree ET (red circles) against lysimeter measurement (blue line) at Kearney Agricultural Research Experiment Station.

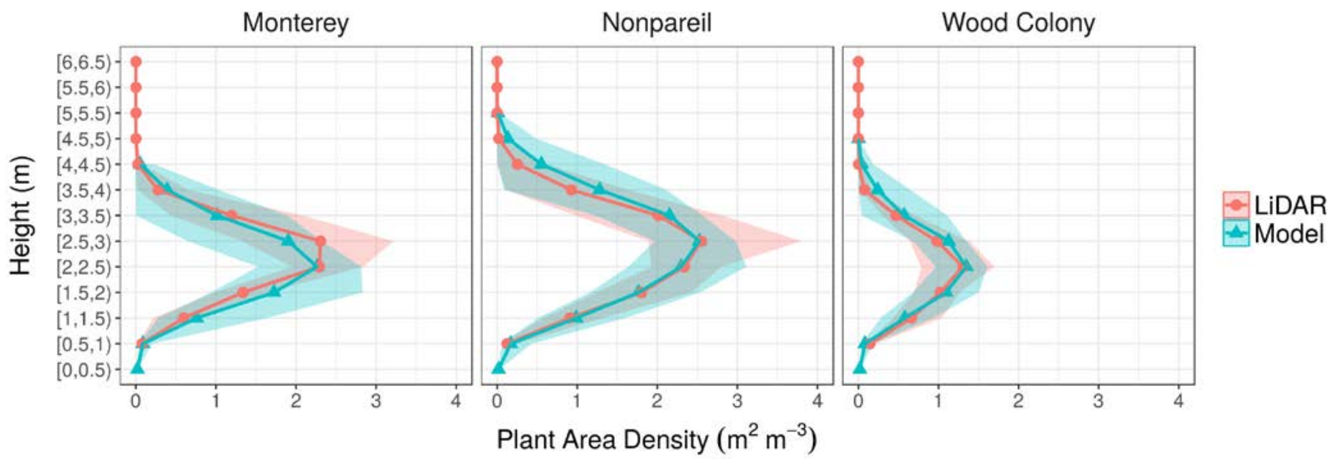

Figure 5. Comparison of vertical distribution of plant area density (PAD) calculated from LiDAR data (red) and using the virtual tree construction model (blue). Each variety is shown in a separate panel. Lines represent the average PAD value and shaded area shows the range of values across six trees.

Research Effort Recent Publications:

Bailey, B.N., and Ochoa, M. 33rd Conference on Agricultural and Forest Meteorology (2018). Boise, ID ``Direct scaling of biophysical models from leaves to canopies.'' (oral presentation).

Bailey, B.N.. Phenome (2018). Tucson, AZ ``Coupling terrestrial LiDAR measurements of tree architecture with high-resolution biophysical models to provide insights into plant-environment interactions.'' (oral presentation).

Bailey, B.N., Mahaffee, W., and Ochoa, M. American Geophysical Union Fall Meeting (2017). New Orleans, LA ``Direct scaling of leaf-resolving biophysical models from leaves to canopies.'' (oral presentation).

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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 Mahaffee, W.F. (2017b). Rapid, high-resolution measurement of leaf area and leaf orientation using terrestrial LiDAR scanning data. Meas. Sci. Technol. 28:064006

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