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Continuous, long-term, high-frequency thermal imaging of vegetation: Uncertainties and recommended best practices

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ABSTRACT

Leaf temperature is an elementary driver of plant physiology, ecology and ecosystem productivity. Individual leaf temperature may deviate strongly from air temperature, and may vary throughout the canopy. Measurements of leaf temperature, conducted at a high spatial and temporal resolution, can improve our understanding of leaf water loss, stomatal conductance, photosynthetic rates, phenology, and atmosphere-ecosystem exchanges. However, continuous high-resolution measurement of leaf temperature outside of a controlled environment is difficult and rarely done. Here, thermal infrared cameras are used to measure leaf temperatures. We describe two long-term field measurement sites: one in a temperature deciduous forest, and the other in a subalpine conifer forest. The considerations and constraints for deploying such cameras are discussed and the temperature errors are typically +/−1 °C or smaller ($\sigma = 0.60\,^{\circ}$C, $2\sigma = 1.20\,^{\circ}$C). Lastly, we compare leaf temperature by species and height at hourly to multi-seasonal timescales and show that on average, leaf temperature is warmer than air temperature in a temperate forest. Leaf temperature can be uniform or heterogeneous across a scene, depending on canopy structure, leaf habit, and meteorology. With this data, we verify that leaf temperature follows classic expectations, yet exhibits noteworthy departures that require additional study and theoretical consideration.

1. Introduction

The effect of temperature on photosynthesis and transpiration by plant canopies is of fundamental importance to plant evolution, productivity, and distribution (Long and Woodward, 1988; Schimper, 1903; von Humboldt and Bonpland, 1807; Walter et al., 1975). Variations in canopy temperature directly affect leaf-water loss and photosynthetic rates, impacting tree budgets and ecosystem-scale exchanges of water, carbon, and energy. Leaf temperature affects photosynthesis by changing cell membrane fluidity, enzyme reaction kinetics, diffusion constants and dissolution of CO_2 and O_2, which control the ratio of photorespiration to photosynthesis (Lambers et al., 1998). Though we have general understanding of the factors that influence leaf temperature (Gates, 1980, 1968, 1964), we lack high quality, high frequency, long-term data with which to validate and improve leaf temperature simulation models. This lack of data has largely been due to the logistical constraints on recording leaf temperatures in a natural, uncontrolled environment.

Previously, measuring leaf temperature in the field has been accomplished by two techniques: (1) affixing fine-wire thermocouples to vegetation, or (2) using thermal infrared (TIR) thermometers. Thermocouple measurements require vigilance to ensure the thermocouples remain attached to the vegetation and necessitate a Herculean effort to obtain statistically significant measures of total canopy temperature and how leaf temperature varies throughout the canopy (Miller, 1972, 1971). Therefore, thermocouples limit data to small sample numbers over relatively short time periods. Likewise, TIR thermometer measurements suffer

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from a lack of spatial and/or temporal resolution. Field mountable thermometers (also known as infrared radiometers) offer a "blind" approach, which integrates thermal signals from target and non-target objects (e.g. branches and soil) into a single value for the field-of-view. Point-and-shoot, portable TIR thermometers (such as the TG165 spot camera, FLIR Systems, Inc.) lack temporal resolution, giving sparse data on a rapidly varying quantity. It is not feasible to record accurate and long-term, continuous measurements of leaf and canopy temperature with either the thermocouple or infrared thermometer approach.

Within the past two decades, thermal infrared cameras have been developed with the robustness, power specifications, pixel resolution, and sensitivity to enable continuous monitoring of canopy temperatures across an entire growing season (Kruse and Skatrud, 1997; Vollmer and Möllmann, 2010). These sensors are also small and affordable enough to deploy to field sites. Recent work with thermal cameras has demonstrated the power to measure species-specific responses to leaf energy balance, but did not capitalize on the continuous monitoring capability of these instruments, nor did the work assess measurement error (Leuzinger and Körner, 2007; Leuzinger et al., 2010; Reinert et al., 2012; Scherrer et al., 2011). Additional work has utilized thermal cameras for characterization of stomatal conductance and closure, irrigation schedules, and plant stress, but focused exclusively on laboratory or crop field environments where some external factors can be controlled, and also did not take advantage of the continuous monitoring capabilities of the technology (Ballester et al., 2013; Berger et al., 2010; Grant et al., 2006; Jones, 2004, 1999; Jones et al., 2009).

There are three goals for this work. First, we quantify the accuracy of continuous thermal infrared imaging in natural, forested settings. We characterize the errors in image-derived temperatures, describe the accuracy with which environmental and vegetation parameters must be known, and show that sensor noise has a minimal impact on the temporal and spatial variation of pixels in an image. Secondly, we suggest best practices for acquiring TIR image data, and create software for correcting interferences in large datasets of images. Finally, we use these new data and tools to explore the thermal signatures of deciduous and evergreen vegetation on timescales ranging from seconds to multiple seasons.

2. Materials and methods

2.1. Site descriptions

Our primary field site is the 40 m tall "Barn Tower" (42.5353°N 72.1899°W) at the Harvard Forest, 110 km west of Boston, MA. The tower is surround by mixed forest stands dominated by red oak (*Quercus rubra* L.), red maple (*Acer rubrum* L.), and white pine (*Pinus strobus* L.). We have mounted two thermal infrared cameras atop the tower: a model A655sc (FLIR Systems, Inc., 640 × 480 pixel resolution, 45° FOV), and a model A325sc (FLIR Systems, Inc., 320 × 240 pixel resolution, 6° FOV). The cameras point north, are inclined 20–30° below the horizon, and are arranged such that the FOV of the A325 is a zoomed-in region of the A655 FOV. Images are acquired continuously every 15 min by FLIR's ExaminIR software running on fanless industrial computers (Neousys POC-100, Logic Supply, Inc.) at the base of the tower and connected to the cameras via Ethernet. We have also recorded several days of images at one-second intervals.

Mounted atop the same tower, observing the same canopy are: two VIS-NIR networked digital cameras (StarDot NetCam SC), one VIS-NIR hyperspectral camera (Surface Optics Corporation SOC710), a 4-channel net radiometer (Kipp & Zonen CNR4), a dual temperature/relative humidity probe (Vaisala HMP35c), a sunshine sensor (Delta-T Devices BF5), and an eddy-covariance flux system (LI-COR LI-7200, LI-7550 controller, 7200-101 flow module). These instruments provide measurements necessary for correcting interferences in the images recorded by the FLIR cameras and for interpreting differences between canopy and air temperature.

A matte black painted copper plate (6″ × 6″ × 0.075″, emissivity = 0.985) is mounted in the canopy with a copper-constantan thermocouple affixed to its back. The plate is visible in the FOV of both thermal cameras, and the thermocouple is logged continuously at rates of 0.1–5 Hz, depending on season. In addition, 12 fine-wire thermocouples were affixed to the abaxial surface of leaves in an oak canopy within the FOV of the cameras (approximately 33 m from the cameras) for 25–27 June 2013. The thermocouples were recorded as 30 s mean values.

We have deployed a similar instrument package to the 26 m tall Ameriflux tower (40.0329°N 105.5464°W) at the University of Colorado's Mountain Research Station on Niwot Ridge, 40 km west of Boulder, CO. The tower is surround by mix of evergreen needleleaf species: lodgepole pine (*Pinus contorta* Douglas ex Loudon), Engelmann spruce (*Picea engelmannii* Parry ex Engelm.), and subalpine fir (*Abies lasiocarpa* (Hook.) Nutt.). We have mounted an A655sc camera (FLIR Systems, Inc., 640 × 480 pixel resolution, 45° FOV) near the top of the tower, pointed east and inclined about 30° below the horizon. Supporting measurements are made similar to the Harvard Forest instrumentation, and image acquisition is performed by FLIR's ResearchIR software running on a fanless industrial computer mounted on the tower. Visible images of the canopy at Harvard Forest and Niwot Ridge are provided in Supplementary Fig. S1.

2.2. Camera-canopy distance

Accurate temperature measurements with thermal cameras require knowing the distance between camera and target object so that atmospheric attenuation of the thermal signal can be calculated. For the A325 camera with the 6° lens, this is straightforward, since the narrow angle lens means that the entire field-of-view is approximately the same distance from the camera. As deployed, this distance is 33 m, measured by laser range finder, and objects within the FOV vary in distance to the camera by less than 2 m.

Determining camera-canopy distance is more challenging for the A655 cameras, since the FOV encompasses much more. As deployed, the A655 FOV include tree crowns as close as 10 m and as far as 200 m. While a rudimentary distance map for each sensor array could be generated by hand, we developed an optimized approach using digital photographs and structure from motion software to generate a 3D pointcloud of each study area and then re-render the camera scene to create a distance map for the sensor.

Briefly, low-altitude, high-resolution digital images of the Harvard Forest site were taken with 25–50% overlap between images. These images, along with coordinates and elevations of known ground control points were loaded into PhotoScan (Agisoft LLC) to calculate an accurate, 3D pointcloud of the canopy (Dandois, 2014). A similar pointcloud was generated in PhotoScan for Niwot Ridge using images taken from multiple heights and look angles on the tower. Then, each pointcloud was analyzed by a custom script to re-render each thermal camera scene. The script projects the camera pixel array onto the 3D pointcloud from the vantage point of the camera, using the camera orientation, sensor pixel dimensions, and lens FOV, and finds the pointcloud point in each pixel's solid angle projection that is closest to the camera. This point is assumed to be the one each pixel "sees", and its color is assigned to that pixel in the array. In this way, a color rendering of the visible scene is produced and can be compared to the physical locations of the tree crowns in the thermal FOV. Once the rendered scene is verified by visual assessment, a distance is assigned to each pixel, according to the coordinates of point in the pointcloud used for that pixel. Empty pixels in the distance map are filled using values