Remote Sensing Tree Physiology: Comparing ECOSTRESS to sap-flux transpiration rates

Joshua Frear
MEM ‘21

Advisors Jennifer Swenson, Sari Palmroth, & Jean-Christophe Domec
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Executive Summary

Transpiration, or plant water loss, is a critical component of water balance and flux for terrestrial systems worldwide, yet uncertainty in large-scale estimates create significant challenges for water resource forecasting (Jasechko 2013, Coenders-Gerrits 2014). Effectively measuring changes in transpiration over time can provide insight into water availability issues facing a tree, a stand, or a landscape. As temperature and precipitation patterns change in the next century and cause shifts in water availability, forest health around the world is likely to change, too, and should be monitored. Currently, transpiration is often monitored at research sites with specialized eddy covariance flux towers, or sap-flux sensors installed in trees that measure the transpiration of individual trees or stands. To measure transpiration frequently across the Earth, a different approach is required. One possible tool for this is ECOSTRESS (Ecosystem Spaceborne Thermal Radiometer Experiment on Space Station).

ECOSTRESS is an experiment run by NASA's Jet Propulsion Laboratory that measures elements of plant transpiration worldwide (Fischer 2020). Attached to the International Space Station, the ECOSTRESS radiometer measures latent heat flux and estimates plant water loss occurring around the world every day. The objective of this project is to investigate and compare ECOSTRESS to more traditional methods of measuring transpiration at three temperate forest research sites in the US and France. Comparing transpiration and evapotranspiration data at each site since the inception of ECOSTRESS in 2018 reveal significant but weak correlations between the two measurements (all $r^2 < 0.4$). ECOSTRESS generally measured much higher transpiration for the days of overpass compared to sap-flux measurements. Time of day of overpass had a significant relationship with the difference

between the two measurements, but sub-setting the data to exclude times of day with low transpiration or winter months generally did not improve the correlations, except for excluding morning observations. Based on these observations, ECOSTRESS should be used with caution for non-spatial time-series-type studies. Additionally, there remains a significant spatial difference between the two approaches, as one ECOSTRESS pixel covers about half a hectare.

1. Introduction

1.1 Transpiration

Transpiration, or plant water loss, is a critical component of water balance and flux for terrestrial systems worldwide, yet uncertainty in large-scale estimates create significant challenges for water resource forecasting (Jasechko 2013, Coenders-Gerrits 2014). Plants respond to variation in soil water availability and atmospheric fluxes by adjusting physiologically and structurally to regulate their transpiration (Poyatos et al. 2016). Effectively measuring changes in transpiration over time can thus provide insight into the water stress faced by a tree, a stand, or a landscape. These stresses are expected to increase as temperature and precipitation patterns change in the next century. One of the challenges is reliably measuring transpiration at coarse scales.

1.2 Sap-flux measurements

One method of reliably measuring transpiration for an individual tree is the sap-flux method, developed by Granier from thermometric methods first experimented with in the 1930s by Huber (1987, see Fernandez 2008). At the tree scale, transpiration can be measured through xylem sap flow. All water passing through the xylem can be expected to drive E_T, so if the volume of sap can be measured, E_T can be derived from that volume (Domec et al. 2012). The Granier method involves inserting two probes into the trunk of the tree, with thermometers and a heating element to measure sap flow in the tree, which is labor-intensive. This is scaled up to an estimation at the stand level by separating trees into crown classes and calculating the proportion of sapwood that each class size contributes to the stand (Granier 1987, Rafael Poyatos et al. 2020).

Sap-flow measurements are a classic bottom-up approach to estimating E_T, starting with field data that provide a high degree of confidence at the tree level, and inferring the stand-level transpiration from that. These measurements have a wide range of applications, and have been used to assess environmental sensitivity to factors like nutrients, water, vapor pressure deficit, and photosynthetically active radiation, or abiotic disturbances like hurricanes (Ewers et al. 1999, Oren et al. 1999). They have been also used in conjunction with other methods to quantify aspects of competition for water resources and niches in communities (Silvertown et al, 2015).

1.3 ECOSTRESS

ECOSTRESS (Ecosystem Spaceborne Thermal Radiometer Experiment on Space Station) is a NASA Jet Propulsion Laboratory experiment that uses a radiometer mounted to the International Space Station (ISS) to measure plant temperatures worldwide (Fischer 2020). The ECOSTRESS team have developed higher-level products from this thermal data, including evapotranspiration (E_T, which corresponds to the sum of plant transpiration, soil evaporation and plant water interception following rain events), water use efficiency (how much water a plant uses for metabolism compared to the water lost in transpiration), and Evaporative Stress Index (ESI), a relative measure of temporal increases and decreases in evapotranspiration. These measurements could contribute significantly to our ability to measure and analyze changes in water fluxes.

The ECOSTRESS approach models the level of E_T occurring at the stand scale through calibration of plant temperature measurements. The ECOSTRESS radiometer contains five bands in the TIR (thermal infrared) range, centered at 8.28, 8.63, 9.07, 10.6, and 12.05 µm respectively, with band widths ranging from 0.34 to 0.54 µm (ECOSTRESS L2 documentation). This aspect of ECOSTRESS builds on ASTER, NASA's Advanced Spaceborne Thermal Emission and Reflection Radiometer, and these bands have been demonstrated to be sensitive to changes in surface temperature and relative humidity, allowing the measurement of both land surface temperature and spectral emissivity.

Heat flux can be divided into two types: sensible and latent. Sensible heat flux is easily measurable, as it is when the heat leads to a rise in temperature. Latent heat flux is the heat flux that does not change temperature but causes a state change – from liquid to gas, for instance. Measuring the latent heat flux of vaporization is key to measuring the amount of water evaporation occurring. ECOSTRESS calculates evapotranspiration through two algorithms: PT-JPL, which is used in this paper, and ALEXI, which is suited for agricultural applications. ECOSTRESS stands out among current and planned remote sensing instruments because of its combination of spectral, temporal, and spatial resolution, with a mid-sized pixel, multiple TIR bands, and frequent revisit time (ECOSTRESS L2 documentation).

ECOSTRESS may have applications outside of measuring transpiration, as it has been used to measure thermal anomalies over volcanoes and geothermally active areas (Silvestri et al. 2020) and diurnal surface temperature in urban environments (Chang et al. 2021).

2. Study Rationale and Aims

The objective of this project is to investigate and compare two independent approaches to estimating transpiration: remotely-sensed coarse scale (70-m pixel) ECOSTRESS radiometer measurements from ISS, and fine scale sap-flow measurements of individual trees (a well-established and reliable method of estimating), scaled up to stands. This study aims to examine how ECOSTRESS measurements correlate with scaled measures from individual trees at three long-term study sites that have many measurements available from both approaches. Any divergences in results between the two approaches will be investigated as well, with an attempt to identify the underlying causes of differences between the two measures. ECOSTRESS has spatial coverage that covers far more area than what is possible with field measurement and is a potentially powerful tool in assessing transpiration rates worldwide. By comparing it to specific study sites over a period of multiple years, we can give a general indication of the confidence that users of ECOSTRESS data can have in its accuracy.

3. Materials and Methods

Sap-flux measurements are taken from three research sites with available data: one in Duke Forest in North Carolina, and two in France.

Site	Latitude	Longitude
Duke Forest, Durham, USA	36° 1'36.05" N	78°59'48.95" W
ICOS, Salles, France	44° 29' 37.21" N	0° 57' 21.9" W
Lascaux, Montignac, France	45° 3'13.20" N	1°10'16.32"E

The sites represent two young (9 - 10 year-old) pine plantations (longleaf pines and maritime pines at the Duke and ICOS Salles sites, respectively) and one mature (75-year-old) natural regeneration (pubescent oak mixed with Scots pine) site at Lascaux. At the French sites, the stands exceed the ECOSTRESS pixel size, so tree sapflow data can be used as a good proxy for stand transpiration at the ECOSTRESS scale. The Duke Forest site is smaller than the other sites, with both a fast-growing understory and surrounding fields that are not pine stands, so field transpiration measurements, when scaled up to the ECOSTRESS pixel size should be considered estimates. Sap-flow sensors installed on 8-12 trees per species at these sites follow the method developed by Granier (1987), which consists of a pair of vertically-aligned cylindrical probes that are inserted into the sapwood 10 cm apart, with the upper probe containing a heating element. Dispersion of heat through sap flow is translated into speed of sap flow and volume over time. Recorded temperatures can be used to derive sap flux because the velocity of sap passing through a given surface of sapwood within a given time, or sap flux density, drives differences in temperature measurements between the two probes (Granier 1987; Oishi et al. 2016). The volume of sap directly corresponds to water lost in transpiration, as water uptake starts in the roots. Water that is intercepted by the crown and evaporates from there is treated separately. Evapotranspiration at ICOS Salles was measured directly using eddy covariance. At Lascaux, leaf-level transpiration was measured on 5-7 different understory species and scaled up to the site using their respective biomass, and combined with climatic data to find ET.

Given that the tree is in a stable state, the measure of sap flux is also a measure of water entering the tree and a measure of water consumed by transpiration. Transpiration measurements can then be scaled up using stand composition measurements to infer transpiration of the entire stand (Granier 1987, Ward et al. 2017).

ECOSTRESS data has been collected since 2018 across the world and may be downloaded from the APPEARS portal for any point location. ECOSTRESS data has a somewhat irregular recurrence pattern, corresponding to the flight path of the International Space Station; and cloudy days are not usable. For each site, there were between 26 and 44 dates that provided Level 3 data from ECOSTRESS from program inception in July 2018 and December 31, 2020. Level 3 data includes evapotranspiration values for both instantaneous values and full-day estimates, as well as three percentages for canopy, soil, and intercepted water that sum to 100 percent. Transpiration is indirectly given as the canopy percentage multiplied by the evapotranspiration value.

The ECOSTRESS measurements are recorded in W/m2, while the field transpiration is measured in mm/day. To convert this, W/m^2 is converted into $MJ/m^2/day$ and then to mm/day, with ratio of 1:0.0352512 for full-day transpiration estimates, and similarly in reverse to convert field values to W/m^2. For instantaneous transpiration estimates, the ECOSTRESS instantaneous transpiration estimate was compared to sap-flux transpiration for a short time period (between 15 and 60 minutes) that corresponded to the time of day for the ECOSTRESS observation.

4. Results

4.1 Full-day transpiration

Correlations were generally weak between full day field-measured transpiration and ECOSTRESS transpiration estimates across the three sites (Figures 1-3).

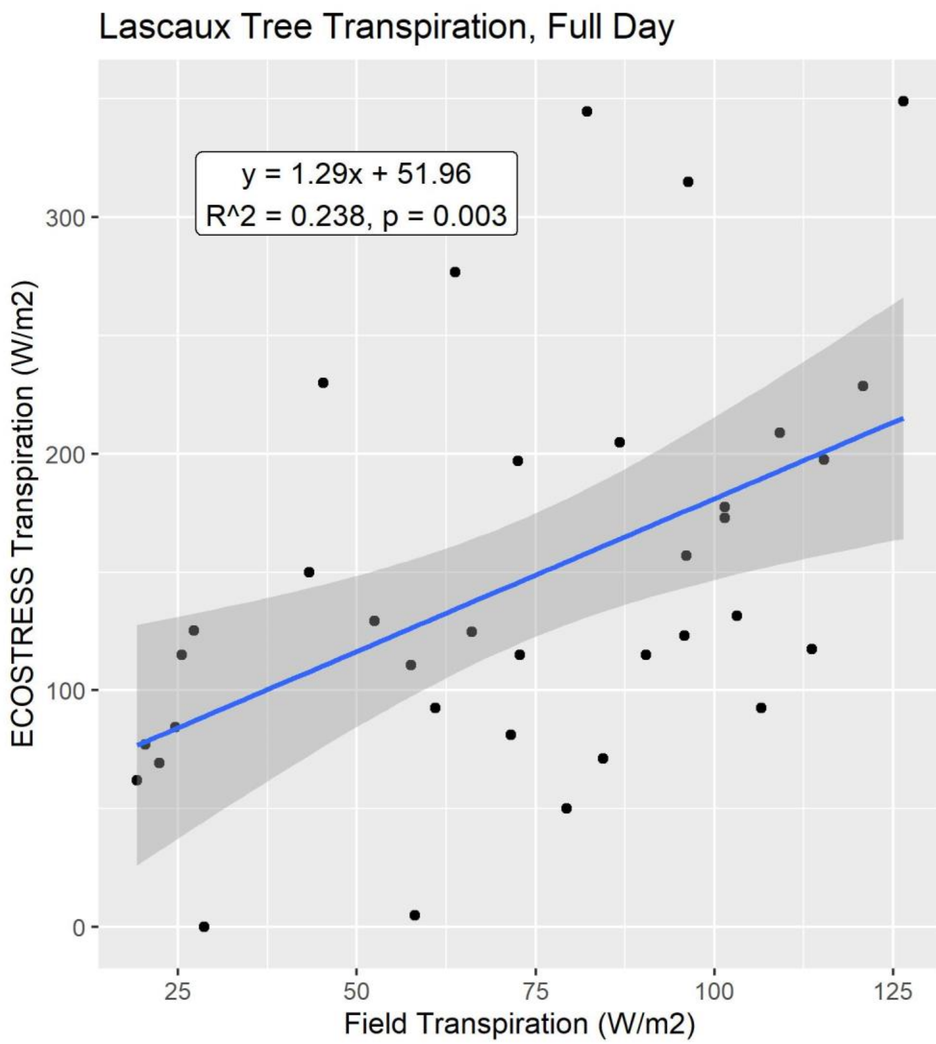

Figure 1. Full-day transpiration at the Lascaux, compared with ECOSTRESS transpiration estimates for days when both datasets were available, July 1, 2018 to December 31, 2020. (r^2 = 0.238, p = 0.003, n = 35).

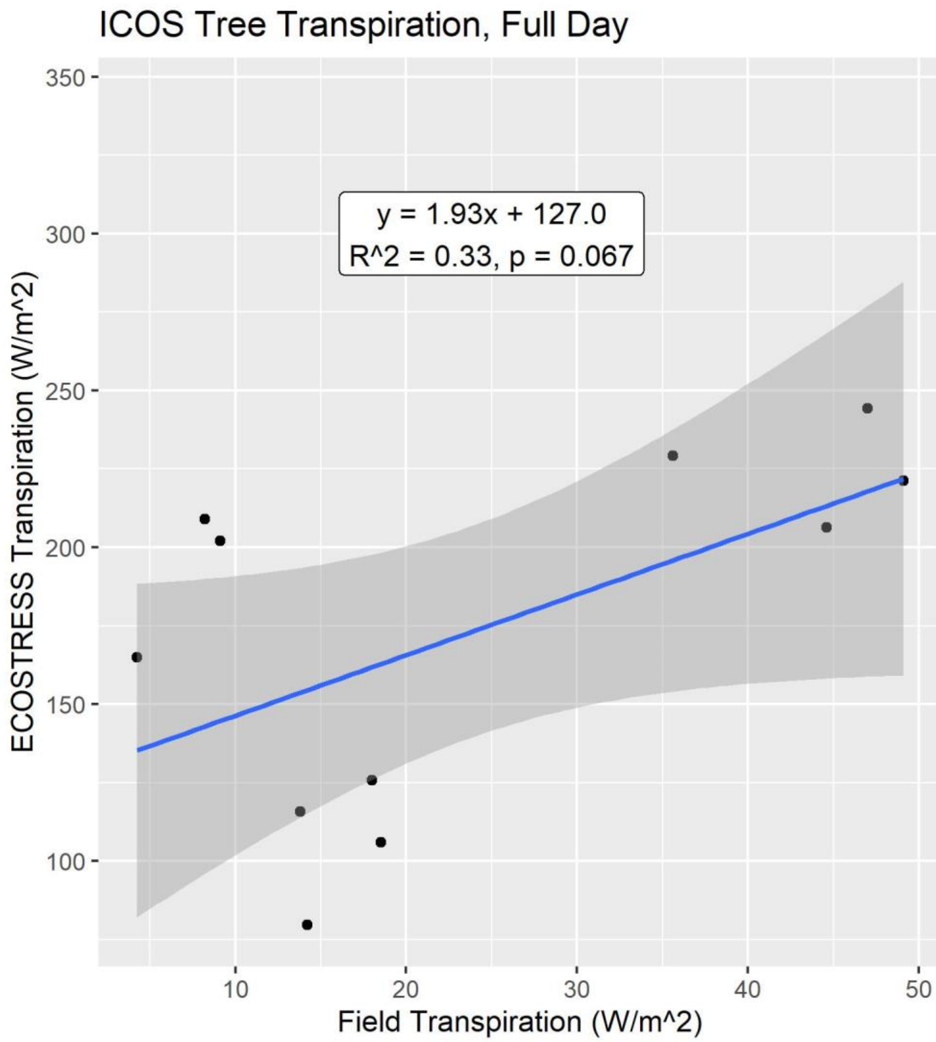

Figure 2. Full-day transpiration at ICOS Salles compared with ECOSTRESS transpiration estimates for days when both datasets were available, July 1, 2018 to December 31, 2020. (r^2 = 0.33, p = 0.067, n = 11).

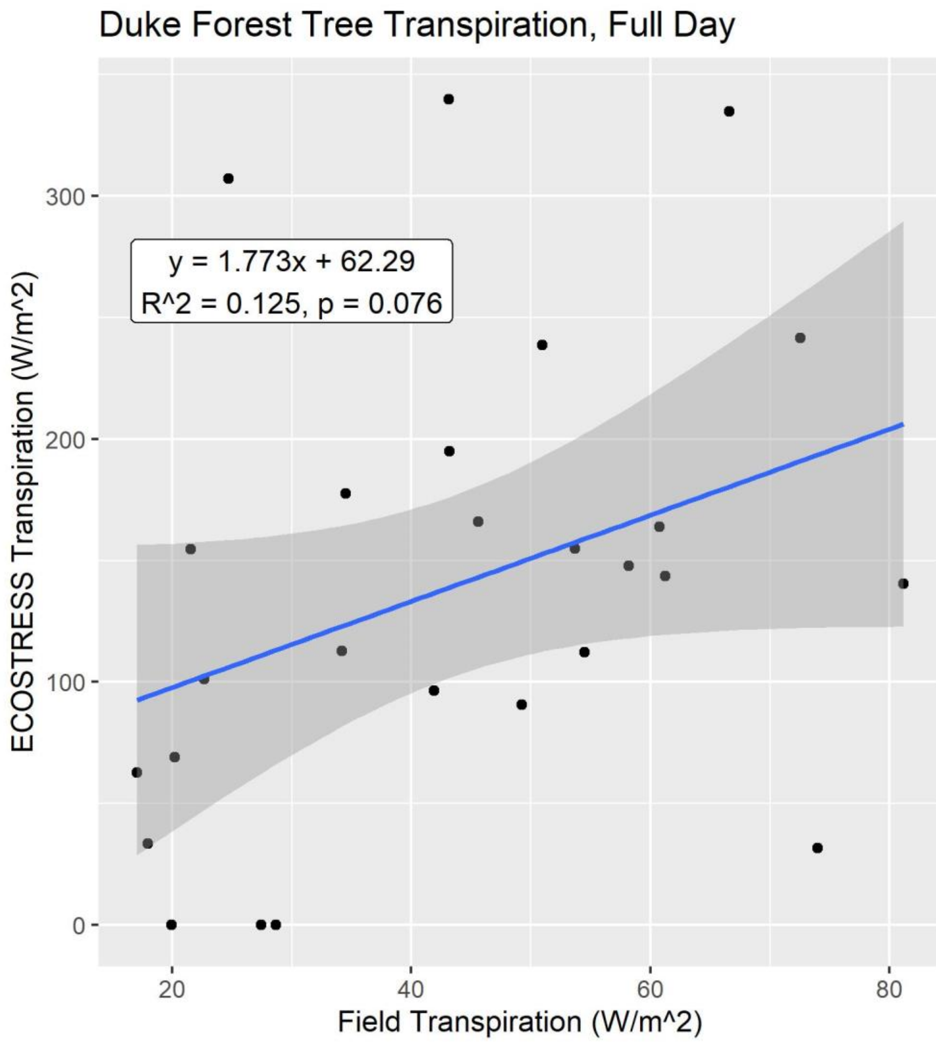

Figure 3. Full-day transpiration at the Duke Forest site compared with ECOSTRESS transpiration estimates for days when both datasets were available, July 1, 2018 to December 31, 2020. (r^2 = 0.125, p = 0.076, n = 26).

4.2 Instantaneous transpiration

The ECOSTRESS instantaneous transpiration estimates were also compared to the sap-flux transpiration occurring at the time of ECOSTRESS observation. These comparisons yielded weak correlations as well in two of the sites (Figures 4 - 5), while ICOS Salles showed no significant relationship between the two (Figure 6).

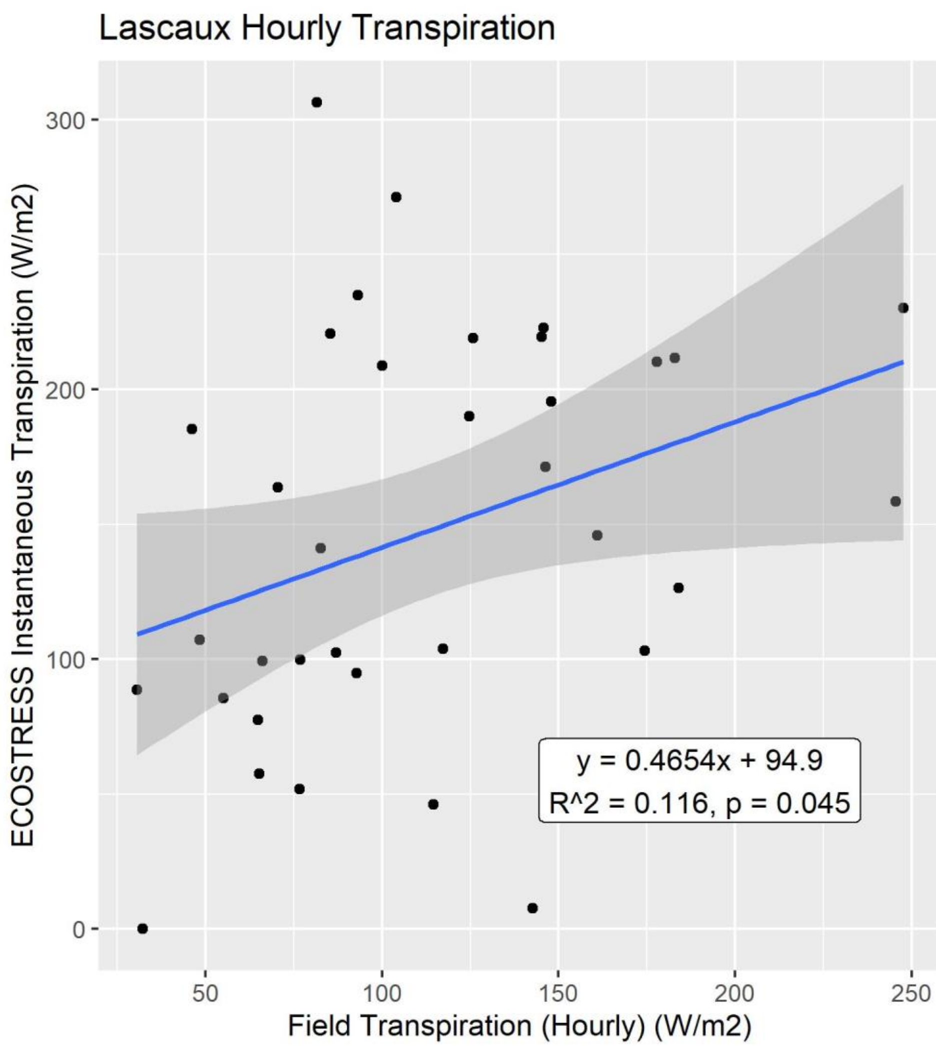

Figure 4. Instantaneous measure of transpiration from ECOSTRESS at Lascaux compared to the field measurement of sap-flux transpiration from the same hour. (r^2 = 0.116, p = 0.045, n = 35).

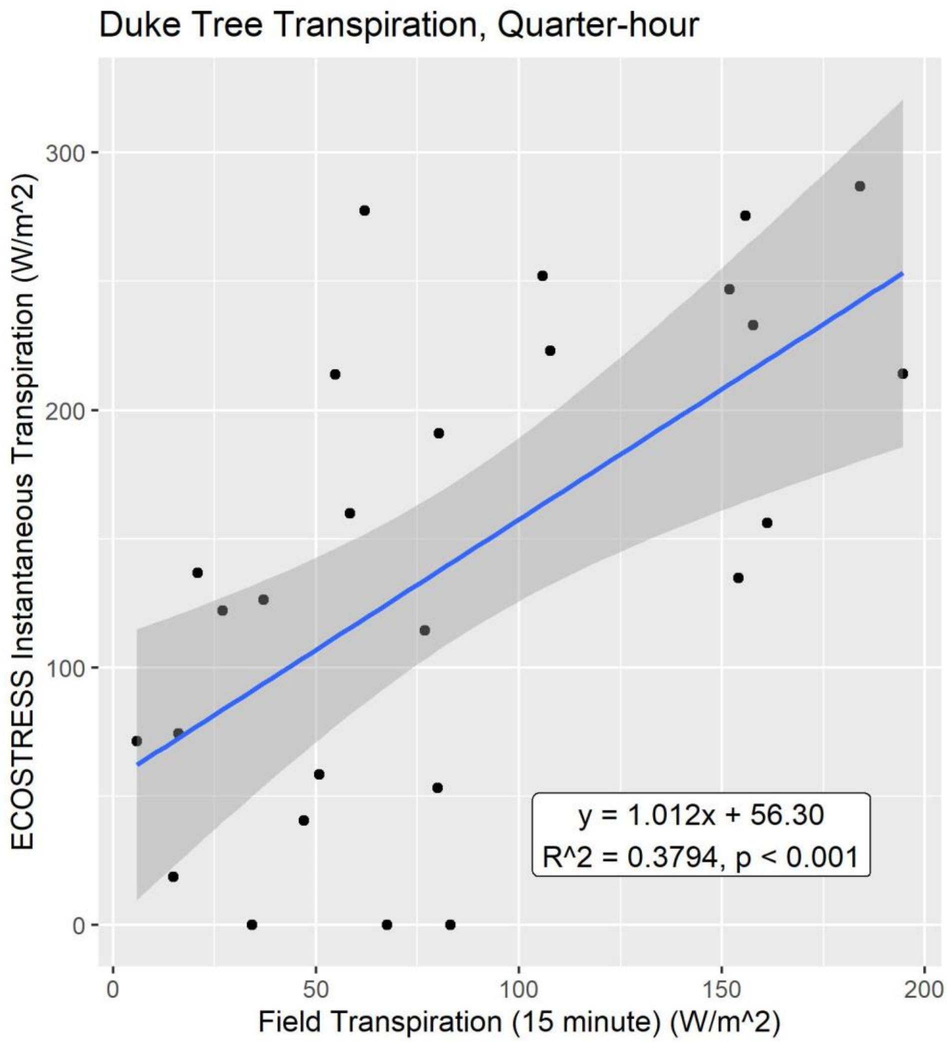

Figure 5. Instantaneous measure of transpiration from ECOSTRESS at Duke Forest compared to the field measurement of sap-flux transpiration from the same hour. ($r^2 = 0.3794$, $p = 0.00081$, $n = 26$).

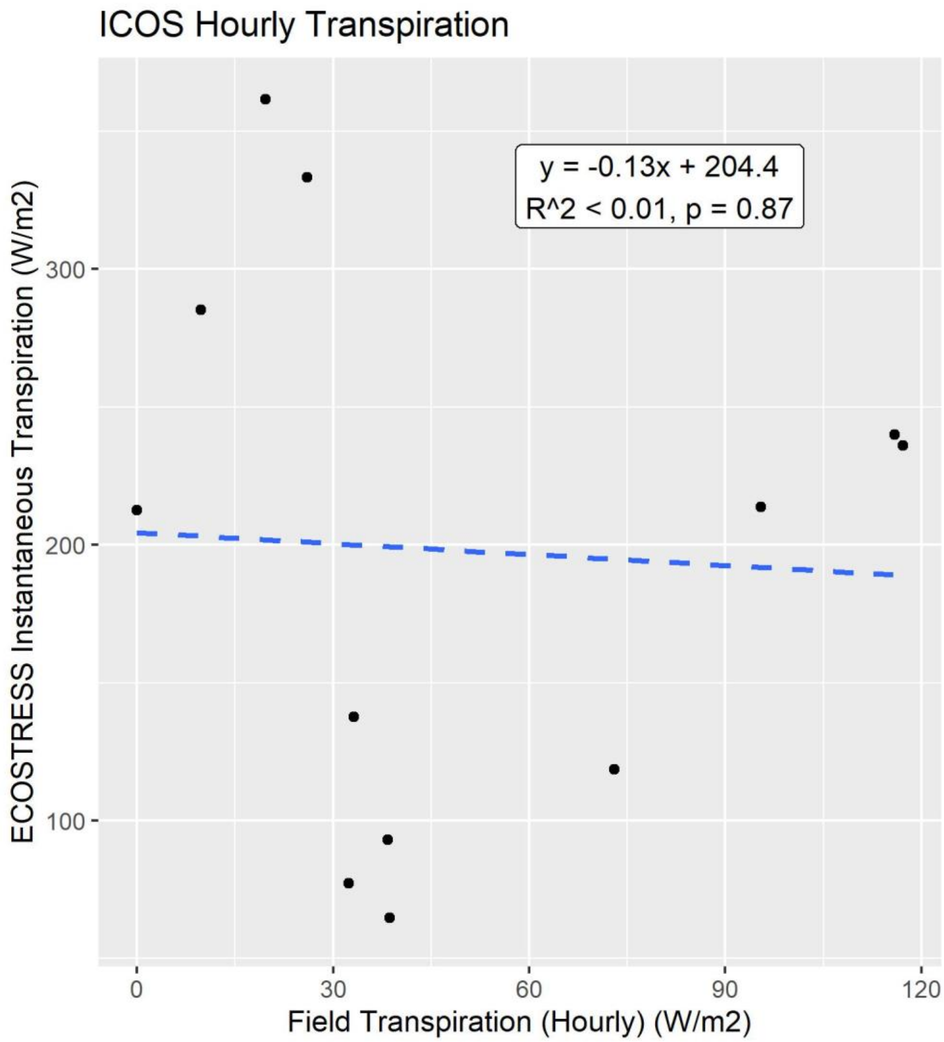

Figure 6. Instantaneous measure of transpiration from ECOSTRESS compared to a short interval of sap-flux transpiration from the same time. ($r^2 < 0.01$, p = 86, n =12).

4.3 Evapotranspiration

The Lascaux and ICOS Salles sites also had measures of evapotranspiration in addition to transpiration. Those were compared to the measure of evapotranspiration in ECOSTRESS. The two measures had significant correlation at Lascaux (Figure 7), but no significant relationship at ICOS (p = 0.68, 0.70 respectively).

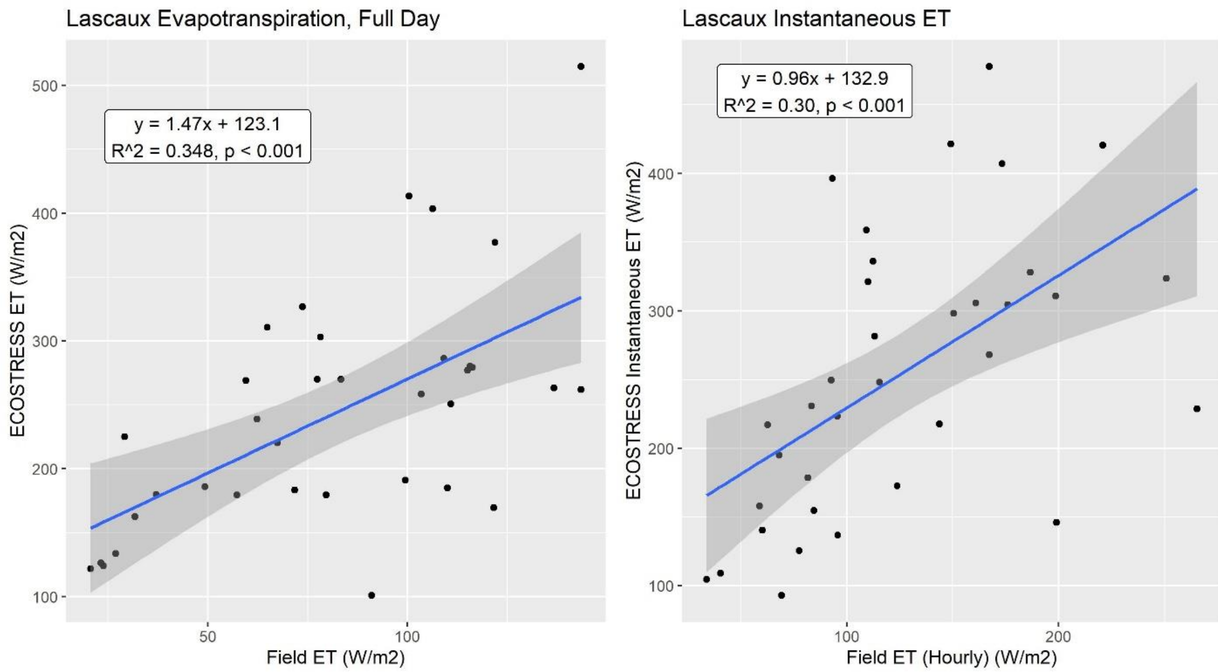

Figure 7. Comparison of Evapotranspiration measures at Lascaux (Full Day $r^2 = 0.348$, $p < 0.001$, 30-minute $r^2 = 0.30$, $p < 0.001$, $n = 35$).

4.4 Data Subsets and Time of Day

One potential explanation for the difference between ECOSTRESS and sap-flux data is that ECOSTRESS is taking an observation at the time of satellite overpass and extrapolating full-day transpiration from that. It might be expected observations in the morning or evening would have more uncertainty and more error, given that most transpiration is occurring in the middle of the day (see Venkatraman 2016).

One approach to examining the effect of time of day on ECOSTRESS measurements is to subset the data by time of day. Excluding both morning (before 10 AM) and evening observations (after 4 PM) from the data did not improve the correlations at the three sites for either of the full-day measurements (T and ET), but excluding morning-only observations improved the correlations at Lascaux for full-day transpiration (from $r^2 = 0.238$, $p = 0.003$, $n = 35$ to $r^2 = 0.295$, $p = 0.003$, $n = 28$).

While many of the correlations did not improve with a data subset, the time of day of the ECOSTRESS overpass at a given research site did appear to explain some of the variability in the data and the weakness of correlations. To examine this, the time of satellite overpass, expressed as hours from noon on that day, was compared with the absolute difference between the two methods of measuring of full-day evapotranspiration. A significant positive relationship exists at Lascaux ($r^2 = 0.26$, $p < 0.001$) and ICOS ($r^2 = 0.34$, $p < 0.001$). This relationship also holds for full-day transpiration measurements as well for all three sites. (Lascaux: $r^2 = 0.20$, $p < 0.01$; ICOS: $r^2 = 0.17$, $p = 0.09$; Duke: $r^2 = 0.392$, $p < 0.001$).

5. Discussion

ECOSTRESS generally correlates with on-the-ground sap-flux measurements. However, the relationship between the two was weak at each research site, with multiple days that had differences in measurement that were substantial. ECOSTRESS numbers appear to be overestimating transpiration and evapotranspiration.

The correlations found here are similar to those found in other papers, but a bit lower. Most literature uses eddy-covariance towers to measure field evapotranspiration, instead of Granier sap-flux. For example, Michel et al. 2016 found r^2 values of 0.67 for tower measurements and 0.58 for remote-sensed ET measurements over 20 sites spread across a variety of climates. Those authors observed that correlations were higher in wet climates and consistently lower in dry ones. Additionally, the PT-JPL algorithm (which is used by ECOSTRESS) was neither better nor worse than the other three algorithms examined. Zheng et al. compared remote-sensed ET values to eddy-covariance values in Northeastern Thailand and obtained a range of r^2 values from 0.53 to 0.06 with RMSE values between 1 and 2 mm d^{-1} (Zheng et al. 2019). The authors observed higher correlations in crop sites and lower correlations in forest sites.

In the ECOSTRESS observations, we found some observations that underestimated transpiration, to the point of days being assigned canopy transpiration values of zero (and all evapotranspiration assigned to soil evaporation and intercepted water), even when the sap-flux data was showing transpiration. However, the general trend for the sites we examined was that ECOSTRESS overestimated transpiration and evapotranspiration. These results are interesting in light of Shi and Hu (2021), who found that the thermal data underestimated estuary surface temperature by 1-2 degrees Celsius.

The correlations found between the difference of the two methods and time of day as hours from noon were significant and positive at all three sites. This trend indicates that further the ECOSTRESS overpass is from solar noon, the more its full-day measurement will vary from the field measurements for that day. Removing early-morning measurements from the datasets improved the correlation between the two.

This project could be expanded by using field data from more field sites and by experimenting with generating different algorithms than the ECOSTRESS JPL algorithm.

6. Conclusion

ECOSTRESS is a potentially powerful tool that is effective for spatial comparisons at a given time, but caution is advised for using ECOSTRESS higher-level products for time-based comparisons in one location. Our results indicate examining ECOSTRESS measurements over time at one location is not a replacement for field study using sap-flux measurements.

The usefulness of ECOSTRESS for time-series-type projects is limited by the heavy use of MODIS data to supplement the ISS radiometer. Adding remote sensing bands to the project would remove dependence on MODIS and help accuracy but would significantly change the cost and feasibility of the ECOSTRESS mission. One example of this is microwave sensing for soil evaporation (Zhang et al. 2019).

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