Evapotranspiration in a Subtropical wetland savanna using low-cost Lysimeter, Eddy Covariance and Modeling approaches

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**Abstract**

*Evapotranspiration (ET) constitutes the largest loss of water from subtropical grassland and wetland ecosystems, yet data in much of the world have high uncertainty at the landscape scale as there is little information on plant water use. Additionally, anthropogenic alterations to grasslands are a major threat globally and alter ecosystem water use, but the impact of these changes is often unquantified. A major reason for this is the complexity and expense of field-based ET quantification methods such as agricultural lysimeters and eddy covariance systems. Accurate measurements of ET are critical for sustainable water management. This study developed two different low-cost lysimeters – weighing-type and water level based, to measure ET under controlled conditions for single species as well as mixed grassland and wetland communities. Lysimeters were placed in an open sided shadehouse with a transparent roof to exclude rainfall. ET values were then compared with (i) Actual ET measurements from an eddy covariance tower onsite, (ii) vapor transport-based ET models – FAO Penman-, Modified Turc and Abtew Simple Radiation models, and (iii) ET data from the Florida Automated Weather Network. Both weighing-type and water level lysimeters showed seasonal patterns and annual magnitudes similar to the other ET methods. Annual ET measurements from weighing-type lysimeters (881-1278 mm for four plant species, n=5 per species, 20 in total) and water level lysimeters (1085 mm, plant community average, n = 31) were similar to model estimates (1000-1200mm). Actual ET from eddy covariance was 722 mm for ten months (missing data for February and March), while lysimeter measurements for the dominant grass Paspalum notatum was 885mm for the same 10 months. Low-cost lysimeters can inform regional ET models/remote sensing data lacking field validation and thus are potentially useful for water resources and ecosystem management in data-poor regions of the world.*

**Keywords**

*Plant water use, grasslands, wetlands, lysimeters, evapotranspiration, low-cost instrumentation, water resources management*

1. **Introduction**

Evapotranspiration (ET) – the sum of soil water evaporation and plant transpiration, typically constitutes the largest loss of water from tropical and subtropical regions of the world (Thornthwaite, 1951; Fisher *et al.*, 2009; Peters, 2016). The magnitude and seasonality of this water loss is significantly influenced by vegetation type and thus greatly differs with land cover such as forests, grasslands, wetlands, rainfed agriculture, irrigated agriculture and urban areas. Changes in land use alters soil-plant-atmosphere moisture feedbacks, thereby strongly affecting regional water balances with important implications for sustainable water resources management (Fisher *et al.*, 2017) and the maintenance of natural flow regimes and water availability for aquatic and riparian ecosystems (Allan & Johnson, 1997). Accurate quantification of ET at the landscape level is thus essential for water resources planning and management at the river basin scale for both present and future land cover and climate scenarios (eg. Rose & Sharma, 1984, Fisher *et al.*, 2017) as well as for wetland/river floodplain restoration and compensatory mitigation projects (Lott & Hunt 2001).

Grasslands cover about 20% of the land area in the tropics (Parr *et al.* 2014, Bond 2016), including both old-growth grasslands (Veldman *et al.* 2015, and human-modified grasslands (Veldman *et al.* 2016). Natural grasslands are under serious pressure for conversion to intensive pasture systems and these anthropogenic alterations can dramatically alter ecosystem water balance. Additionally, most current studies of water balance are on temperate grasslands and there are knowledge gaps from subtropical and tropical grasslands. In subtropical Florida, grasslands and wetlands make up ~30% and 15-25% of the land area. These grasslands and wetlands contain diverse plant species adding another layer of complexity to quantifying ET (Cai *et al.*, 2019). Additionally, the defined wet and dry season affect both soil water availability and phenology adding other sources of ET variation (Fisher *et al.*, 2017, Drexler et al 2004).

Due to financial, technical and logistical challenges in measuring ET, with the exception of irrigated agriculture, there remains considerable uncertainty in quantifying ET across most of the world, let alone the understudied subtropics and tropics (Holmes, 1984; Nouri *et al.*, 2013, Baffaut *et al.*, 2020). Methods have either a hydrological or micrometeorological perspective and differ in their assumptions and requirements, with some that measure ET while others estimate ET (Ochoa-Sanchez *et al.*, 2019). Methods that measure ET - weighing precision lysimeters (for irrigated agriculture) and eddy covariance (agriculture, ecosystems) - are prohibitively expensive and complex to maintain (Allen *et al.*, 1990, Ruiz-Penalver *et al.*, 2015) and thus are absent from much of the world. Furthermore, eddy covariance has at times been associated with uncertainty from energy balance closure issues (Foken, 2008, Leuning *et al.*, 2012) and assumptions on vegetation/topographic homogeneity (Wohlfahrt *et al.*, 2010; Baldocci and Ryu, 2011; Miranda *et al.*, 2016, Moorhead et al 2019, Denager *et al.*, 2020). Weighing precision lysimeters can also be utilized to measure water loss from grassland and wetland plants (Koerselman & Beltman, 1988), as it is feasible to grow these plants in lysimeters (unlike trees). However, commercial weighing lysimeters are prohibitively expensive (Allen *et al.*, 1990, Ruiz-Penalver *et al.*, 2015), ranging from US$5,000-$30,000 and also require periodic calibration (Mariano *et al.*, 2015). Other methods estimate rather than measure ET – such as vapor transport models, water balance methods, diurnal groundwater level fluctuation and remote sensing and are often accompanied by high uncertainty (Rose & Sharma 1984, Rana & Katerji., 2000; Mueller *et al.*, 2013). As a response to this, Lu *et al.* (2018) compared ET from potted wheat and maize against weighing precision lysimeters and found that after after correcting for differences in soil moisture, biomass and crop density between the two methods, pot lysimeters yielded similar results, and hence were recommended as inexpensive research tools in areas lacking instrumentation.

The goals of this study were threefold. First, we set out to fill a knowledge gap from subtropical grasslands and wetlands and provide estimates of ET. Data was collected in south-central Florida and results of this study can be applicable to similar grasslands in South America, Northern Australia, subtropical Africa and Asia. Second, we designed low-cost weighing type and water level lysimeters that would be useful in data-poor and resource-limited parts of the world with similar vegetation characteristics. These low-cost lysimeters were planted with multiple plant species and communities allowing us to assess variation in ET. Third, we compared ET estimates form low-cost lysimeters to an on-site eddy covariance tower at the same study location as well as with a suite of widely-used ET models and regional ET data.

We expected both types of low-cost lysimeters to track the seasonal variation that is typically seen in ET data from other methods for the region (higher values in the summer growing season), because meteorological variables are the primary driver of ET. In terms of magnitude, we expected the low-cost lysimeters to indicate higher ET than eddy covariance because of the potentially higher water availability to plants in the lysimeters arising from manual watering. At the same time, we expected the models to predict even higher ET values than both lysimeters and eddy covariance, because models yield Potential ET (ie. ET under conditions of no water limitation), while the lysimeter plants would see periods of water limitation. In terms of species ET differences, we expected wetland species to have higher ET than upland species on account of adaptation to an environment with greater water availability.

If low-cost lysimeters yield ET data that resembles other independent estimates in both magnitude and seasonality, they could constitute a simple yet useful method to obtain location-specific ET for landscapes that have rainfed farms, grasslands and/or wetlands and thereby provide a local vegetation component to customize ET models and datasets.

1. **Methods**

*2.1 Study site*

The 4200 ha Buck Island Ranch (BIR), a division of Archbold Biological Station, is located in the headwaters of the Everglades in southcentral Florida (27° 09’ N, 81° 12’ W – Fig. 1). BIR is a part of the Archbold-University of FL LTAR site, one of 18 LTAR sites across the US that is generating data, technologies, and models to inform the sustainable intensification of agriculture at the national scale (Kleinman *et al.*, 2018). The climate is subtropical with average rainfall of 1360 mm and minimum and maximum temperatures of 15.9 and 29.0 °C (average of 30 years). Evapotranspiration is typically almost as high as rainfall (Saha *et al.*, 2012, Baffaut *et al.*, 2020).

Soils are sandy with an organic layer horizon on top, dominated by Alfisols and Spodosols. The region, originally a seasonally inundated wetland–savanna mosaic has been drained by an extensive ditch-canal network constructed since the mid-20th century. Currently, wetlands, grasslands and woodlands (Fig. 1) occur across hydrological gradients and the wide variety of plant communities likely differ widely in water uptake and transpiration. This study measured ET at the species level (for some common species across grass, forb and sedge habits) as well as at the community level for a variety of mixed-species plant communities from grasslands and seasonal wetlands typical of the subtropical Everglades headwaters region.

*2.2 Meteorological station and vapor-transport based meteorological ET models*

The weather station at BIR provided rainfall (Texas Electronics TE25 Raingage), net solar radiation (Kipp and Zonen pyranometers and pyrgeometers for incoming and reflected short and longwave radiation), air temperature, relative humidity (Rotronic Hygroclip2 Temperature/RH Probe) and windspeed (RM Young wind monitor) for this study. Radiation data was obtained because net solar radiation is the main driver for ET, accounting for about 72% of ET in South Florida (Abtew, 1996).

Two globally used reference ET models and one regionally developed ET model were selected. The first model was the combination version of the FAO-Penman-Monteith Model (Shuttleworth, 1992). The Penman-Monteith equation has been found to be applicable for humid regions (de Bruin, 1983) including Florida (Mitchell, 2004). The combination version adds modelled vegetation influences on ET by incorporating leaf area index (LAI) and vegetation height to the FAO-Penman- model (Allen et al 1998), apart from net radiation, air temperature, windspeed and relative humidity. In the case of both grasslands, and wetlands, LAI is taken to be 2 meters and vegetation height 1 meter (obtained from long-term productivity studies at BIR) . The second model was the Modified Turc method (Turc, 1961) which has been found to agree with the combination FAO-PM in South Florida (Saha et al, 2012) and requires fewer meteorological parameters (ie net solar radiation and air temperature). The third model was Abtew’s simple radiation model (Abtew, 1996) that was developed and calibrated specifically for South Florida and requires just net solar radiation as an input. The models were run on a daily time step using a Microsoft FoxPro program with meteorological data from the weather station at BIR. As mentioned earlier in the introduction, all three models calculate Potential ET, ie the maximum amount of water loss via ET assuming no water shortage or limiting conditions for plants.

* 1. *Regional data for ET and solar radiation*

Published daily ET and net solar radiation data for the region (Okeechobee station, 35 km. away from BIR) was downloaded from the Florida Automated Weather Network (FAWN) website (https://fawn.ifas.ufl.edu/tools/et/) for 2014-2018. FAWN was set up with the purpose of supporting decision making and resource management. FAWN ET data is calculated by customizing FAO-PM output with crop coefficients (Mitchell, 2004).

*2.4 Eddy covariance ET*An existing eddy covariance tower was located at the center of an improved pasture that consisted primarily of *P. notatum* along with irrigation ditches having wetland vegetation dominated by *Juncus effusus* subsp. *solutus*. The eddy covariance tower consisted of a three-dimensional sonic anemometer Young 81000 V (R.M. Young Company, Traverse City, MI, USA) for measuring wind speed, direction, and virtual temperature, an enclosed-path CO2/H2O infrared gas analyzer LI-7200 (LI-COR Biosciences, Lincoln, NE, USA) and an open-path CH4 LI-7700 gas analyzer (LI-COR Biosciences, Lincoln, NE, USA). Raw data were acquired at 10 Hz. Instruments were always kept at a height 1.34 times the average plant height to minimize occasions when the flux footprint extended beyond the plot’s edge (Raupach, 1994). Data were processed using EddyPro (LI-COR Biosciences, Lincoln, NE, USA), and data corrections included cross-wind correction of sonic temperature by the firmware (81000 V, R.M. Young Company, Traverse City, MI, USA), lagged covariances between vertical wind velocity and each flux scalar, corrections for air density fluctuations (Webb *et al.* 1980) and for spectroscopic effects for CH4 fluxes ( Moncrieff *et al.*, 1997; Moncrieff *et al.*, 2004). Low quality, non-representative fluxes as well as fluxes below the u\*- threshold (Chamberlain *et al.*, 2017; Gomez-Casanovas *et al.*, 2018) were discarded. Gaps in the half-hour H2O flux record were filled using a linear interpolation (Falge *et al.* 2001). The flux tower footprint was 389 meters radius on average. Auxiliary measurements including air temperature, relative humidity, net radiation, photosynthetically active radiation, soil heat flux, soil temperature, moisture, and precipitation were compiled at 30-min intervals and logged to a CR3000 datalogger (Campbell Scientific, Logan, UT, USA) synchronized to the LI-7200 as described in (Gomez-Casanovas *et al.*, 2018).

Evapotranspiration was calculated as follows:

ET = latent heat flux (W/m^2)/ latent heat of vaporization (2.264705 MJ/kg), followed by appropriate unit conversions to obtain ET values in mm/day. Negative values of latent heat flux were excluded from the analysis, because those values refer to condensation - the reverse process of evapotranspiration fluxes. ET values thus calculated were then compared with ET values yielded by the flux data processing software EddyPro (LiCor, USA) which is also based upon latent heat flux data, but in addition accounts for the change in the latent heat of vaporization of water with temperature.

*2.5 Weighing-type low-cost lysimeters*

Weighing-type lysimeters were used to measure ET at the species level. This type of lysimeter (Fig. 2) consisted of a plastic pot (top diameter 15 m, height 15 cm) with a single plant and was kept in a shadehouse. The shadehouse had open sides to permit cross breezes and avoid building up humidity that can otherwise suppress ET. The shadehouse roof was made of 2mm thick transparent greenhouse-grade plastic to exclude rainfall. Initial PAR (Photosynthetically Active Radiation) measurements indicated a reduction of 2-5% inside the shadehouse as compared to outside the shadehouse; the roof was also cleaned off algae that accumulated in folks during the wet season. This study utilized four species as described below, with five replicate lysimeters per species for a total of twenty lysimeters. Pots were shuffled inside the shadehouse to equalize east-west exposure to sunshine. The lysimeters were watered to saturation, left to drain for 10 minutes until field capacity and then weighed on a balance to 0.01 gram precision. The time period of 10 minutes was selected after observing how long it took with these sandy + organic mix soils to fully drain after saturation, ie no more drops leaving the pot. Pots were placed on a large tray to detect any additional drainage of water from the pots within an hour of weighing. The pots were weighed again at the same time of day after 2-3 days (Mondays, Wednesdays and Fridays), after which they were watered to saturation, weighed after draining to field capacity and the cycle repeated.

*Calculation of ET for weighing-type lysimeters:*

The difference in pot weights between consecutive measurements yields the water loss in grams over that measurement period; this water loss is then expressed as a volume (1 gm = 1 cm3). This volume of water is then converted to a height of water column after dividing it by the area of the top of the pot, thereby yielding a measure of evapotranspiration in millimeters. The only way water can leave the lysimeter is via soil evaporation and plant transpiration.

Species included for the weighing-type lysimeters were: 1) *Paspalum notatum* (Bahia grass) - one of the most widely planted forage grasses in South Florida ranchlands, a perennial grass with strong, shallow, horizontal rhizomes and a native to South and Central America (Quarin, Burson, & Burton, 1984); 2) *Axonopus fissifolius (*Common Carpet grass), a perennial grass with creeping stolons, native to Florida and primarily distributed in subtropical areas; 3) *Phyla nodiflora* (Turkey Tangle Frogfruit), a stoloniferous forb with decumbent stems and scanty roots (root depth c. 15 cm), native to Florida, and 4) *Rhynchospora colorata (*Starrush whitetop - Cyperaceae)*,* a native sedge commonly found in wet prairies and edges of wetlands, in moist soils that can be inundated for part of the year, and consequently this plant has a low drought tolerance (regionalconservation.org). Plants were obtained in the field (around 20 individuals per species) and planted in the lysimeter pots. The study commenced when the plants were fully established. The five replicates of each species were chosen out of the 20 such that they were similar in age and height, with no visible differences in biomass or number of leaves and branches.

Measurements began in Feb 2018 and were conducted three times a week until January 2019 at the end of the study. Note that the above difference in weight includes both water loss via ET as well as biomass gain from plant growth over the few days; however the latter was held to be relatively miniscule. Productivity studies in both improved and semi-native pastures at BIR (Boughton, submitted) suggest an average daily graminoid biomass gain of 1.02 g/m2, which works out to 0.00785 g/day for a pot of 10 cm diameter, that is four orders of magnitude less than the differences in weight observed in course of lysimeter trials.

*2.6 Water level low-cost lysimeters*

Water level-based lysimeters were used to measure ET at the plant community level for a variety of plant communities as described below. Thirty water level lysimeters were deployed in total.

The water level lysimeter consisted of a large hard plastic mesocosm (70 cm diameter, 55 cm height, Fig. 2) with an impermeable bottom in which were placed three 4-litre pots or four 3-litre pots with plants. Water was filled up to a certain mark inside the mesocosm wall, and the drop in water level was measured after one week. The decrease in water volume is attributed to the sum of evapotranspiration from the pots and open water evaporation from the mesocosm. These are the only pathways of water loss because rainfall is excluded by keeping these mesocosms inside the shadehouse similar to the weighing-type lysimeters. The mark on the mesocosm wall is made at a level corresponding to around 10 cm below the soil surface in the pots; this is in order to prevent root inundation (and thereby plant stress). The pots had drainage holes at the bottom that enabled access to the water in the mesocosm. Controls for calculating open water evaporation from mesocosms were made by placing similar pots inside that were filled with soil to avoid floating up and covered with Aluminum foil to prevent any evaporation or plant growth. Open water evaporation was then subtracted from total water loss to obtain ET from the pots within the mesocosms.

*Calculation of ET for water level lysimeters:*

Weekly ET = (weekly water loss from mesocosm - weekly water loss from controls) /Area of pots. Measurements began in Feb 2018 and were conducted weekly until January 2019 at the end of the study. Some of the water level lysimeters employed a variety of mixed plant communities (comprised of grasses, sedges, forbs and shrubs) that arose from the seedbank in soil collected from semi-native grasslands and wetlands. Other water level lysimeters were planted with either forage grass species (*Hemarthria altissima, Paspalum notatum)* or dominant wetland grasses (West Indian Marsh Grass *Hymenachne amplexicaulus* and *Urochloa mutica*). However, weeding was not regular in course of the experiment, and the dominant species lysimeters ended up with other species from the seedbank or aerial dispersal. Hence the precise species or composition was not kept track of throughout, and thus in this study we are not able to identify species-differences in the water level lysimeters. Lysimeters were shuffled periodically to minimize location bias; this was done when water level was low, for relative ease of movement.

2.7 *Data Analysis*

*Comparison of ET methods:* ET measurements for weighing-type lysimeters (3 times a week) and water level lysimeters (once per week) were summed up to obtain monthly values, as monthly ET facilitates visualizing seasonality and comparison across methods. Monthly ET data from the weighing-type lysimeters and water level lysimeters were correlated with ET from eddy covariance, the three models and FAWN using R version 4.0.0. Out of the four species used for weighing-type lysimeters, *P. notatum* was chosen for the correlation analysis with the eddy covariance ET given that it is the dominant plant species in the pasture where the eddy flux tower was located.

*Comparison of species level ET –* a one-way ANOVAwas conducted to examine species differences in monthly ET over the entire year (weighing-type lysimeters, n=5 per species, for 4 species). In addition, a correlational analysis was carried out between the monthly ET datasets of the individual species to examine similarity of the seasonal trend exhibited by each species.

1. **Results**

*3.1 Meteorological and Growing Conditions*

In 2018, rainfall had the usual seasonal distribution (Fig. 3) but was lower (1170 mm) than the average rainfall over 2014-2019 (1327 mm +/- 109 mm SD). Monthly average air temperature followed the seasonal pattern with highs in summer (Fig. 4). May 2018 was unusually cloudy with very few periods of clear sunshine, as corroborated by incoming radiation measurements, both at the weather station situated 30 m. away from the lysimeters as well as FAWN data for Okeechobee (35 km away), with a decrease noted in May, contrary to the usual bell-shaped radiation profile over summer (both shown in Figure 1 included in Supplemental Data).

*3.2 ET models and data*

All three models (FAO-PM, Modified Turc and Abtew’s net radiation model) showed a similar seasonal pattern (Fig.3) with increasing reference ET in early summer (March), peaking in June/July and declining thereafter. They also exhibited an uncharacteristic seasonal dip in ET in May, corresponding to the decrease in net solar radiation mentioned above. Annual ET estimates for each model were similar: FAO-PM (1370 mm) was very close to Abtew’s model (1366 mm) while Modified Turc had a slightly lower annual ET of 1317 mm. ET data from the FAWN station at Okeechobee also had a seasonal trend similar to the ET models (Fig. 3) but was lower in magnitude coming in at 1061 mm.

*3.3 Eddy covariance ET*

The uncharacteristic dip in May that was noted in all the models was also seen in the eddy covariance ET data (Fig. 3). Data was not available for February and March owing to tower operational issues. Hence the monthly data (Fig. 3) excludes data from those two months, and the 10-month total ET was ~ 722 mm. Calculated ET values were almost perfectly correlated with those from EddyPro (r2 = 0.99) but were slightly higher. Because the latter adjusts the latent heat of vaporization for ambient air temperature, we use the latter here.

*3.4 Weighing-type lysimeters*

All four species showed a similar seasonal pattern, of higher ET in the summer months (growing season –April to September) as compared to winter (Oct-March) (Fig. 4). In addition, all the lysimeters recorded an uncharacteristic decrease in May, when usually ET rates are the highest in South Florida. *Rhyncospora colorata* was observed to have the highest ET (both monthly and annual – 1278 ± 117 mm), followed by intermediate values for *Paspalum notatum* (1060 ± 92 mm) *& Phyla nodiflora* (991 ± 91 mm)*,* with *Axonopus fissifolius* (881 ± 104mm) showing the lowest ET values (Fig. 4). Monthly ET (averaged over 5 lysimeters per species) were significantly different at the p < 0.05 level for the four species [ F(3,44) = 3.49, p = 0.023 ] (Table 2). The 2-3 day ET data are included in Supplementary Material (online).

*3.5 Water level lysimeters:*

The seasonal pattern of ET detected by weighing-type lysimeters was also exhibited by water level lysimeters (blue bars – Fig. 4), including the uncharacteristic drop in ET in May. The annual ET recorded by the water level lysimeters (average ± st.dev. for 31 lysimeters = 1085 ± 306 mm) was similar in magnitude to the weighing-type lysimeters. Water level lysimeters were also sensitive to ET/water use differences between plant species or communities, as seen from the range of measurements obtained on any given week (standard deviation, Fig. 5) – however due to the lack of periodic weeding as mentioned before, this study could not characterize measurements by species. The weekly ET data are also included in Supplementary Material (online).

*3.6 Correlation of lysimeter with other methods*

Monthly ET averaged forthe five weighing-type lysimeters with *P.notatum* correlated significantly with FAWN ET (r2 = 0.71, p = 0.0006, Fig. 6 - B) and eddy covariance ET (r2 = 0.65, p = 0.005, Fig. 6 - A). Points fall below the 1:1 line indicating that the lysimeters had higher ET values than either FAWN or eddy flux, possibly reflecting that water availability for plants in the lysimeters was higher than that in the field, leading to higher ET losses. When comparing weighing-type lysimeter average ET with FAO-PM and Modified Turc models, there was no significant correlation observed (Fig 6 C and D). The data points plotted above the 1:1 line indicating that the weighing-type lysimeter had values lower than the models (PET), suggesting a degree of water limitation in the lysimeters.

Because the eddy covariance ET data is missing for February and March, Table 1 shows the weighing and water level lysimeter ET data summed over the same ten months to facilitate comparison. Table 3 summarizes the uncertainty inherent in these low cost lysimeters as well as eddy covariance and the vapor transport models utilized in this study.

The water level lysimeter average monthly ET (n = 31) correlated significantly with FAWN monthly ET data (r2 = 0.35, p = 0.04, Fig.7-B), while no significant correlation existed with either eddy covariance ET or model ET data (Fig.7-A, C, D). Again, water level lysimeter ET data (averaged over 31 lysimeters) are higher than both FAWN and eddy covariance ET data, but lower than the PET models. Note that the water level lysimeters vary widely in their species and plant communities (which have not been recorded), and hence that can contribute to the lower correlations observed (Fig.7).

4. **Discussion**

In general agreement with our expectations, both types of low-cost lysimeters described in this study yielded ET values that lay within the range of magnitude, whose lower end was the eddy covariance ET and upper end was the models’ reference ET (Fig 3, 4). Furthermore, the fact that the unusually low ET in May 2018 as shown by all other methods was also picked up by the low-cost lysimeters points to the sensitivity of these lysimeters in tracking ET. Despite the fact that each method differs in its underlying concepts, assumptions and thereby the form of ET output (Table 3), this similarity in both range of magnitude and seasonality indicates the potential of these lysimeters to provide reasonably accurate ET data, especially in much of the world lacking expensive eddy covariance instrumentation.

It should be noted that the eddy covariance method yields actual ET, models yield PET while the low-cost lysimeters and FAWN data yield ET values between potential and actual ET. For the lysimeters this is likely a result of the periodic watering regime that was intended to keep plants functionally healthy. Soil moisture conditions in the weighing-type lysimeters periodically varied between field capacity (just after watering) and nearly dry (every 2-3 days). Likewise, soils in the water level lysimeters got drier as the water level dropped over the week. in comparison, FAO-PM calculates reference ET that is associated with a field of alfalfa under well-irrigated conditions (no water limitation at all). Actual ET would be lower, especially in the dry season, even though subtropical grazinglands in South Florida include partially-inundated wetlands and are also partly irrigated in the dry season.

Hence it is encouraging to note that both types of lysimeters yielded annual ET values similar to other methods (especially close to FAWN data – 1061mm, that is used for irrigation decisions in the region). These data also lie within the range of ET estimated by other studies in subtropical and tropical grasslands and wetlands. At the humid end, ET in the equatorial wetlands in the Amazon is 1300-1550 mm/yr (Fleischmann *et al.*, 2021) and the subtropical wetland savanna in the Everglades National Park sees around 1200 mm/yr (Saha *et al.*, 2012). With decreasing rainfall and wetlands transitioning to grasslands, ET also decreases; for instance 960 mm/yr in Eucalypt savannas in Australia (Khan et al 2021) and 690-820 mm/yr in the Brazilian cerrado savanna woodlands (Giambelluca *et al.*, 2009). At the semi-arid end of the range, ET was 630 mm/yr at a high-altitude Andean water-limited paramo grassland in Ecuador (Ochoa-Sanchez *et al.*, 2019) and 266-391 mm/yr in Mediterranean grasslands in California (Ryu *et al.* 2008), which is getting into the temperate climate zone.

*Plant species differences in ET*

The sensitivity to species-level ET differences exhibited by the weighing-type low-cost lysimeters (Fig 5) suggests that these lysimeters can also support ecophysiological research on water uptake differences amongst plant species occurring across hydrologic or soil moisture gradients. *Rhynchospora colorata* (n = 5) consistently exhibited the highest ET every month (Fig 5). This sedge occurs in wetland margins and wet prairies having inundation hydroperiods between 2-8 months and thus is associated with a longer period of water availability than the other three species in this study. Wetland species generally have higher ET rates than terrestrial species (Pauliukonis & Schneider 2001, Sun et al 2001, Pedescoll et al 2013). The forb *Phyla nodiflora* is known to have medium drought tolerance and low anerobic soil condition tolerance (USDA plant profile), suggesting this plant is not associated with long-inundated soils. Therefore, this species likely has a more conservative water use strategy as compared to *R. colorata* thereby manifesting in lower ET as well. The grass *Axonopus fissifolius* showed the lowest monthly ET (Fig. 5), and its range at Buck Island Ranch is mostly drier upland habitats.

A knowledge of species-specific ET could aid understanding how landscape species change can affect water balance (eg Loheide & Gorelick 2005, Irmak et al 2013), thereby also aiding in the choice of species for restoration of wetlands, floodplains and distubed sites (Melesse et al 2006, Milani et al 2019). The link between ET/water use of a plant species or community and water availability in the respective native range can thus be investigated further using these low-cost lysimeters. Different watering regimes (ranging from well-watered to simulated drought) can be employed and combined with plant physiological studies (such as measuring stomatal conductance and leaf water potential. These low-cost lysimeters can thus enable exploring how heterogenous plant communities might differ in ET not only in space but through time. Dominant species or communities can be set up in the lysimeters, and ET data thus generated be used to model and predict ET in diverse landscapes varying in plant composition and structure.

*Low-cost lysimeters – limitations and considerations*

There are some points to be borne in mind while operating these lysimeters for accurate measurement and interpretation of the data. Firstly, the use of pots (as opposed to planting in the ground in-situ) has edge effects (sides can get heated by the sun) and limits the rooting volume for water and nutrient access, particularly fine roots, thus possibly restricting photosynthesis and thereby lowering transpiration (Wu et al 2011 but see Ray & Sinclair (1998) who found that soil moisture had a greater role to play than pot size in affecting transpiration). The use of large pots can overcome this limitation to an extent, but the heavier weight can pose operational challenges for a single operator. Secondly, as a consequence of the periodic watering schedule, rainfall exclusion and the lack of access to groundwater; the soil moisture conditions in pots would not exactly resemble the actual soil moisture conditions prevailing in the field at an instant of time. Periodic watering leads to soil moisture conditions varying between field capacity and dryness, hence the ET measurements obtained are less than PET. However, the frequency of watering can be adjusted to yield a soil moisture regime similar to field conditions at the site/region of interest. In addition, measuring and recording the amount of water applied at each watering event can later allow comparison with the amount of rainfall, as a check on the similarity between water inputs.

It should thus be noted that these lysimeters are not intended to measure the actual ET prevailing in the field, which changes daily as a function of weather and spatially as a function of soil moisture and land use. Instead, these lysimeters measure plant water use and evapotranspiration in controlled watering conditions with an irrigation frequency that strikes a balance between productivity and drought (so as to maintain the plants healthy). These data provide independent measurements of ET, that can calibrate models which otherwise do not have any local plant or field component. Adherence to standardized protocols can minimize operator error, such as waiting a predetermined time after a pot is watered to saturation in order to drain and obtain the weight at field capacity. Adding soil moisture sensors to the lysimeters and to plots outside (actual field conditions) could serve to compare the soil moisture conditions, to know how representative the lysimeters are to actual field conditions.

*Low-cost lysimeters – enabling ET measurements in data-poor regions of the world.*

The low-cost lysimeters can be especially useful for measuring grassland/wetland ET in data-poor regions of the world, given that more than three-quarters of the world’s population lives in these areas. In his classic paper on water balance in tropical regions, Thornthwaite (1951) had stated that in many parts of the tropics, virtually nothing is known about climate and the spatiotemporal distribution of ET. The same was mentioned by deBruin (1983) and the situation remains true today (Mueller et al 2013), as also noted by the corresponding author while working with water management agencies in Africa, South America and South Asia. Much of the world lacks environmental monitoring instrumentation and data (Markwitz & Siebicke, 2019) because of the expenses involved in purchasing and maintaining them, short technology obsolescence cycles, a shortage of personnel trained to operate and maintain these sophisticated systems and the risks of theft and damage by livestock or wildlife. A glimpse at eddy covariance tower locations in global networks such as Fluxnet (Falge *et al.*, 2016) shows that more than 90% of the towers are concentrated within ‘developed’ countries in North America, Europe, Australia, Japan and recently China, with extremely sparse representation in Africa, much of Asia and South America (eg. Ochoa-Sanchez *et al.*, 2019). Ecosystems, climate and land use are very different in parts of the world that are sparely represented than those with abundant flux tower coverage. Even across Canada, Wang et al (2015) mention that eddy covariance ET results are only applicable across very small areas, rendering model validation difficult at the national or continental scale. Likewise, the meteorological parameters required for the FAO-Penman- model, in particular net solar radiation, are also expensive to measure, store and transmit. In under-represented countries, meteorological stations are in agricultural research centers, far and few in between, with data for a location extrapolated across thousands of square kilometers with very different land use and climates, accompanied by a concomitant increase in uncertainty that is very difficult to even quantify.

In comparison, setting up low-cost lysimeters is very inexpensive and training operators is very simple, almost at the level of schoolyard science. There are two sources of globally available ET data that can be calibrated locally using low-cost lysimeters to improve accuracy of ET estimates for landscapes that include grasslands and wetlands. The first is air temperature, on which a variety of ET models are based on. Examples include Hemon’s ET model (Hemon, 1966), the FAO-24 Blaney-Criddle model that was found to be the most appropriate model for the mountainous region in Northeastern India (Pandey *et al.*, 2016) and Iran (Babaee et al 2019) and the Enku-Melesse maximum temperature model developed for Ethiopia in comparison with other models (Enku & Melesse, 2013). Air temperature data is available in these data-sparse areas because of installations at airports and other government meteorological and institutional facilities. The second dataset is MODIS-16 (Mu *et al.*, 2007) that is freely available at a 1 sq km resolution from 2001 onwards, with a reasonably accurate spatial topographic resolution but at times questionable magnitude. For instance, a study using MODIS-16 data to characterize ET (AET) in the Wami Ruvu Basin of Tanzania (GLOWS-FIU, 2014) found expectedly higher ET in headwater Eastern Arcs mountains and riparian floodplains as compared to semi-arid areas, but the magnitudes of ET were strangely much higher than rainfall (2000-2400 mm annual ET while annual rainfall is around 1100 mm). Such overestimation of ET was also seen elsewhere in studies assessing the reliability of MODIS ET products for vegetation in the semi-arid Caatinga, Brazil (Miranda *et al.*, 2016), Australia (Khan *et al.*, 2020), South African savanna (Ramoelo *et al.*, 2014) and Arizona (Ha *et al.*, 2019). A possible contributor to this uncertainty is that MODIS-16 datasets are calculated using the Penman-Monteith model (that yields PET) and calibrated by Fluxnet, which as mentioned earlier, does not have good representation in much of the world.

**Conclusion**

The lysimeters described in this study enable daily or weekly direct observation of evapotranspiration from single species or mixed-species grassland and wetland plant communities with the caveat being this ET is from controlled watering conditions that can differ from actual field conditions. The low cost and operational simplicity make them particularly relevant in the vast areas of the world lacking eddy covariance or meteorological instrumentation in order to locally validate remotely sensed ET data. While the main driver for this study has been to design and examine low-cost lysimeters for the un-instrumented world, much of which is in the tropics and subtropics, these lysimeters can also be employed in grassland and wetland biomes across the world, as long as the plants can be grown to maturity with a soil moisture regime approximately resembling field conditions. Furthermore, the sensitivity to species can also enable research into plant ecophysiology, phenology and water relations of these species and communities.

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**References**

Abtew, W. (1996). Evapotranspiration measurements and modeling for three wetland systems in South Florida. *Water Resources Bulletin Paper No. 95078*. <https://doi.org/10.1111/j.1752-1688.1996.tb04044.x>

Allan, J.D. & Johnson, L.B. (1997). Catchment-scale analysis of aquatic ecosystems. *Freshwater Biology; Special Applied Issues Section (37):*107-111.

Allen, R.G., L.S. Pereira, D. Raes, M. Smith. (1998). Crop evapotranspiration – Guidelines for computing crop water requirements – *FAO irrigation and drainage paper 56.* Food and Agriculture Organization of the United Nations.

Allen, R.G.; Fisher, D. K. (1990). Low-cost electronic weighing lysimeters. *Transactions of the ASAE, v.33*, p.1823-1832.

Babaee M, Shokat-Naghadeh A, Ahmadpari H and Nabi-Jalali M. 2019. Comparison of different methods with lysimeter measurements in estimation of rice evapotranspiration in Sari RegionRevista INGENIERÍA UC, vol. 26, no. 2, pp. 175-184, 2019 https://www.redalyc.org/journal/707/70760276006/html/

Baffaut, C., Baker, J., Biederman, .J, Bosch, D., Brooks, E., Buda, A., Demaria, E., Elias, E., Flerchinger, G., Goodrich, D., Hamilton, S., Hardegree, S., Harmel, R., Hoover, D., King, K., Kleinman, H., Liebig, M., McCarty, G., Moglen, G., Moorman, T., Moriasi, D., Okalebo, J., Pierson, F., Russell, E., Saliendra, N., Saha, A., Smith, D,. Yasarer, L. (2020). Comparative analysis of water budgets across the US long-term agroecosystem research network. *Journal of Hydrology*, *588*, 125021.

Baldocchi, D. D., & Wilson, K. B. (2001). Modeling CO2 and water vapor exchange of a temperate broadleaved forest across hourly to decadal time scales. *Ecological Modelling*, *142*(1-2), 155-184. https://doi.org:10.1016/S0304-3800(01)00287-3

Baldocchi, D. D., & Ryu, Y. (2011). A synthesis of forest evaporation fluxes–from days to years–as measured with eddy covariance. In *Forest Hydrology and Biogeochemistry* (pp. 101-116). Springer, Dordrecht. DOI 10.1007/978-94-007-1363-5\_5

Bidlake, W. R., Woodham, W. M., & Lopez, M. A. (1993). *Evapotranspiration from areas of native vegetation in west-central Florida* (No. 93-415). US Geological Survey; USGS Earth Science Information Center, Open-File Reports Section [distributor],.

Boughton, E. H., Quintana‐Ascencio, P. F., Bohlen, P. J., Jenkins, D. G., & Pickert, R. (2010). Land‐use and isolation interact to affect wetland plant assemblages. *Ecography*, *33*(3), 461-470.

Cai, X., Riley, W. J., Zhu, Q., Tang, J., Zeng, Z., Bisht, G., and Randerson, J. T. (2019), Improving Representation of Deforestation Effects on Evapotranspiration in the E3SM Land Model, *J. Adv. Model. Earth Syst.*, 11, 2412– 2427. doi:<https://doi.org/10.1029/2018MS001551>.

Chamberlain SD, Groffman PM, Boughton EH, et al (2017) The impact of water management practices on subtropical pasture methane emissions and ecosystem service payments. Ecol Appl. https://doi.org/10.1002/eap.1514

Denager, T., Looms, M. C., Sonnenborg, T. O., & Jensen, K. H. (2020). Comparison of evapotranspiration estimates using the water balance and the eddy covariance methods. *Vadose Zone Journal*, *19*(1), e20032. <https://doi.org/10.1002/vzj2.20032>

De Bruin, H. A. R. (1983, August). Evapotranspiration in humid tropical regions. In *Proceeding of the Hamburg Symposium* (pp. 299-311). IAHS Publ. no. 140.

Drexler, J. Z., Snyder, R. L., Spano, D., & Paw U, K. T. (2004). A review of models and micrometeorological methods used to estimate wetland evapotranspiration. *Hydrological processes*, *18*(11), 2071-2101. doi:[10.1002/hyp.1462](https://doi.org/10.1002/hyp.1462)

Enku, T., & Melesse, A. M. (2014). A simple temperature method for the estimation of evapotranspiration. *Hydrological Processes*, *28*(6), 2945-2960.

Falge E, Baldocchi D, Olson R, et al (2001) Gap filling strategies for long term energy flux data sets. Agric For Meteorol 107:71–77. https://doi.org/10.1016/S0168-1923(00)00235-5

Falge, E., Aubinet, M., Bakwin, P. S., Baldocchi, D., Berbigier, P., Bernhofer, C., ... & Wofsy, S. C. (2017). FLUXNET research network site characteristics, investigators, and bibliography, 2016. *ORNL DAAC*. <https://doi.org/10.3334/ORNLDAAC/1530>

Fisher, J. B., Malhi, Y., Bonal, D., Da Rocha, H. R., De Araujo, A. C., Gamo, M., ... & Von Randow, C. (2009). The land–atmosphere water flux in the tropics. *Global Change Biology*, *15*(11), 2694-2714. doi:[10.1111/j.1365-2486.2008.01813.x](https://doi.org/10.1111/j.1365-2486.2008.01813.x)

Fisher, J. B., Melton, F., Middleton, E., Hain, C., Anderson, M., Allen, R., ... & Wood, E. F. (2017). The future of evapotranspiration: Global requirements for ecosystem functioning, carbon and climate feedbacks, agricultural management, and water resources. *Water Resources Research*, *53*(4), 2618-2626. doi:10.1002/2016WR020175.

Fleischmann A, Laipelt L, Papa F, *et al.* (2021).Patterns and drivers of evapotranspiration in South American wetlands. Research Square Pre-print. DOI: 10.21203/rs.3.rs-353527/v1.

Foken, T. (2008). The energy balance closure problem: an overview. *Ecological Applications*, *18*(6), 1351-1367. https://doi.org/10.1890/06-0922.1.

GLOWS – FIU. (2014). Climate, Forest Cover and Water Resources Vulnerability, Wami/Ruvu Basin, Tanzania. 87 p. *Technical Report for USAID*. ISBN: 978-1-941993-03-3

Giambelluca, Thomas & Scholz, Fabian & Bucci, Sandra & Meinzer, Frederick & Goldstein, Guillermo & Hoffmann, William & Franco, Augusto & Buchert, Martin. (2009). Evapotranspiration and energy balance of Brazilian savannas with contrasting tree density. Agricultural and Forest Meteorology. 149. 10.1016/j.agrformet.2009.03.006.

Gomez-Casanovas N, DeLucia NJ, Bernacchi CJ, et al (2018) Grazing alters net ecosystem C fluxes and the global warming potential of a subtropical pasture. Ecol Appl. https://doi.org/10.1002/eap.1670

Ha, W., Kolb, T.E., Springer, A.E., Dore, S., O'Donnell, F.C., Martinez Morales, R., Masek Lopez, S., Koch, G.W. (2019). Evapotranspiration comparisons between eddy covariance measurements and meteorological and remote-sensing-based models in disturbed ponderosa pine forests. *Ecohydrology Volume 8, Issue 7*, October 2015, Pages 1335-1350.

Holmes, J.W. (1984). Measuring evapotranspiration by hydrological methods, *Agricultural Water Management, Volume 8, Issues 1–3,* 1984, Pages 29-40, ISSN 0378-3774, https://doi.org/10.1016/0378-3774(84)90044-1.

Institute for Regional Conservation

<https://www.regionalconservation.org/beta/nfyn/plantdetail.asp?tx=Rhyncolo>

Irmak, S., Kabenge, I., Rudnick, D., Knezevic, S., Woodward, D., Moravek, M. (2013).

Evapotranspiration crop coefficients for mixed riparian plant community and transpiration crop coefficients for Common reed, Cottonwood and Peach-leaf willow in the Platte River Basin, Nebraska-USA, *Journal of Hydrology,*Volume 481, 2013, Pages 177-190, ISSN 0022-1694,

https://doi.org/10.1016/j.jhydrol.2012.12.032.

Khan, M.S., Baik, J., Choi, M. (2020). Inter-comparison of evapotranspiration datasets over heterogeneous landscapes across Australia. Advances in Space Research 66(3): 533-545,

ISSN 0273-1177, <https://doi.org/10.1016/j.asr.2020.04.037>.

Kleinman, P.J.A., Spiegal, S., Rigby, J.R., Goslee, S.C., Baker, J.M., Bestelmeyer, B.T., Boughton, R.K., Bryant, R.B., Cavigelli, M.A., Derner, J.D., Duncan, E.W., Goodrich, D.C., Huggins, D.R., King, K.W., Liebig, M.A., Locke, M.A., Mirsky, S.B., Moglen, G.E., Moorman, T.B., Pierson, F.B., Robertson, G.P., Sadler, E.J., Shortle, J.S., Steiner, J.L., Strickland, T.C., Swain, H.M., Tsegaye, T., Williams, M.R. and Walthall, C.L. (2018), Advancing the Sustainability of US Agriculture through Long‐Term Research. J. Environ. Qual., 47: 1412-1425. <https://doi.org/10.2134/jeq2018.05.0171>

Koerselmann, W., and B. Beltman. (1988). Evapotranspiration from fens in relation to Penman’s potential free water evaporation and pan evaporation. *Aquatic Botany 31(3–4)*: 307–320.

Loheide II, S. P., & Gorelick, S. M. (2005). A local-scale, high-resolution evapotranspiration mapping algorithm (ETMA) with hydroecological applications at riparian meadow restoration sites. *Remote Sensing of Environment*, *98*(2-3), 182-200.

Lott, R. B., & Hunt, R. J. (2001). Estimating evapotranspiration in natural and constructed wetlands. *Wetlands*, *21*(4), 614-628.

Lu Y, Ma D, Chen X and Zhang J. (2018). A simple method for estimating field crop evapotranspiration from pot experiments. *Water* 2018,10,1823 doi:10.3390/w10121823

Mariano, D. D. C., Faria, R. T. D., Freitas, P. S. L. D., Lena, B. P., & Johann, A. L. (2015). Construction and calibration of a bar weighing lysimeter. *Acta Scientiarum. Agronomy*, *37*(3), 271-278. <https://doi.org/10.4025/actasciagron.v37i3.19368>

Markwitz, C., & Siebicke, L. (2019). Low-cost eddy covariance: a case study of evapotranspiration over agroforestry in Germany. *Atmospheric Measurement Techniques*, *12*(9), 4677-4696.

Mauder, M., Cuntz, M., Drüe, C., Graf, A., Rebmann, C., Schmid, H. P., ... & Steinbrecher, R. (2013). A strategy for quality and uncertainty assessment of long-term eddy-covariance measurements. *Agricultural and Forest Meteorology*, *169*, 122-135. doi: 10.1016/j.agrformet.2012.09.006

Melesse, A. M., Oberg, J., Nangia, V., Beeri, O., & Baumgartner, D. (2006). Spatiotemporal dynamics of evapotranspiration at the Glacial Ridge prairie restoration in northwestern Minnesota. *Hydrological Processes: An International Journal*, *20*(7), 1451-1464.

Milani, M., Marzo, A., Toscano, A., Consoli, S., Cirelli, G. L., Ventura, D., & Barbagallo, S. (2019). Evapotranspiration from horizontal subsurface flow constructed wetlands planted with different perennial plant species. *Water*, *11*(10), 2159.

Mitchell, M. W. (2004). *Evaluation of the agricultural field scale irrigation requirement simulation (AFSIRS) in predicting golf course irrigation requirements with site-specific data* (Doctoral dissertation, University of Florida).

https://ufdcimages.uflib.ufl.edu/UF/E0/00/73/60/00001/mitchell\_m.pdf

Miranda, R. D. Q., Galvíncio, J. D., Moura, M. S. B. D., Jones, C. A., & Srinivasan, R. (2017). Reliability of MODIS evapotranspiration products for heterogeneous dry forest: a study case of Caatinga. *Advances in Meteorology*, *2017*.

<https://doi.org/10.1155/2017/9314801>

Moncrieff J, Clement R, Finnigan J, Meyers T (2004) Averaging, Detrending, and Filtering of Eddy Covariance Time Series. In: Lee X, Massman W, Law B (eds) Handbook of Micrometeorology. Springer Netherlands, pp 7–31

Moncrieff JB, Massheder JM, de Bruin H, et al (1997) A system to measure surface fluxes of momentum, sensible heat, water vapour and carbon dioxide. J Hydrol 188:589–611. https://doi.org/10.1016/S0022-1694(96)03194-0

Moorhead, J. E., Marek, G. W., Gowda, P. H., Lin, X., Colaizzi, P. D., Evett, S. R., & Kutikoff, S. (2019). Evaluation of evapotranspiration from Eddy covariance using large weighing lysimeters. *Agronomy*, *9*(2), 99. doi:10.3390/agronomy9020099

Mu, Q., Heinsch, F. A., Zhao, M., & Running, S. W. (2007). Development of a global evapotranspiration algorithm based on MODIS and global meteorology data. *Remote sensing of Environment*, *111*(4), 519-536.

Mueller, B., Hirschi, M., Jimenez, C., Ciais, P., Dirmeyer, P. A., Dolman, A. J., ... & Seneviratne, S. I. (2013). Benchmark products for land evapotranspiration: LandFlux-EVAL multi-data set synthesis. *Hydrology and Earth System Sciences*, *17*(10), 3707-3720.

Nouri, H., Beecham, S., Kazemi, F., Hassanli, A. M., & Anderson, S. (2013). Remote sensing techniques for predicting evapotranspiration from mixed vegetated surfaces. *Hydrology and Earth System Sciences Discussions*, *10*(3), 3897-3925.

Ochoa-Sánchez, A., Crespo, P., Carrillo-Rojas, G., Sucozhañay, A., & Célleri, R. (2019). Actual evapotranspiration in the high Andean grasslands: A comparison of measurement and estimation methods. *Frontiers in Earth Science*, *7*, 55. doi: 10.3389/feart.2019.00055

Panda, R.K., Patra , S. and Halder , D. (2014). Low Cost Pvc Hydraulic Weighing Lysimeter For Measurement Of Crop Evapotranspiration. Acta Horticultura. 1015, 317-324  
DOI: 10.17660/ActaHortic.2014.1015.34  
<https://doi.org/10.17660/ActaHortic.2014.1015.34>

Pandey, P. K., Dabral, P. P., & Pandey, V. (2016). Evaluation of reference evapotranspiration methods for the northeastern region of India. *International Soil and Water Conservation Research*, *4*(1), 52-63.

Pauliukonis, N., & Schneider, R. (2001). Temporal patterns in evapotranspiration from lysimeters with three common wetland plant species in the eastern United States. *Aquatic Botany*, *71*(1), 35-46.

Pedescoll, A., Sidrach-Cardona, R., Sánchez, J. C., & Bécares, E. (2013). Evapotranspiration affecting redox conditions in horizontal constructed wetlands under Mediterranean climate: Influence of plant species. *Ecological Engineering*, *58*, 335-343.

Peters, T. (2016) Water Balance in Tropical Regions. In: Pancel L., Köhl M. (eds) Tropical Forestry Handbook. Springer, Berlin, Heidelberg. https://doi.org/10.1007/978-3-642-54601-3\_40

Ramoelo A, Majozi N, Mathieu R, Jovanovic N, Nickless A, Dzikiti S. Validation of Global Evapotranspiration Product (MOD16) using Flux Tower Data in the African Savanna, South Africa. Remote Sensing. 2014; 6(8):7406-7423. https://doi.org/10.3390/rs6087406

Rana, G., & Katerji, N. (2000). Measurement and estimation of actual evapotranspiration in the field under Mediterranean climate: a review. *European Journal of agronomy*, *13*(2-3), 125-153. doi: 10.1016/S1161-0301(00)00070-8

Ray, J.D.; Sinclair, T.R. (1998). The effect of pot size on growth and transpiration of maize and soybean during water deficit stress. *J. Exp. Bot.* 1998, 49, 1381–1386.

Rose, C. W., & Sharma, M. L. (1984). Summary and Recommendations of the Workshop on “Evapotranspiration from plant communities”. In *Developments in Agricultural and Managed Forest Ecology* (Vol. 13, pp. 325-342). Elsevier. doi: 10.1016/0378-3774(84)90061-1

Ruiz-Peñalver, L., Vera-Repullo, J. A., Jiménez-Buendía, M., Guzmán, I., & Molina-Martínez, J. M. (2015). Development of an innovative low cost weighing lysimeter for potted plants: Application in lysimetric stations. *Agricultural Water Management*, *151*, 103-113 <https://doi.org/10.1016/j.agwat.2014.09.020>.

Ryu, Y., Baldocchi, D. D., Ma, S., and Hehn, T. (2008), Interannual variability of evapotranspiration and energy exchange over an annual grassland in California, *J. Geophys. Res.*, 113, D09104, doi:[10.1029/2007JD009263](https://doi.org/10.1029/2007JD009263).

Saha, A. K., Moses, C. S., Price, R. M., Engel, V., Smith, T. J., & Anderson, G. (2012). A hydrological budget (2002–2008) for a large subtropical wetland ecosystem indicates marine groundwater discharge accompanies diminished freshwater flow. *Estuaries and Coasts*, *35*(2), 459-474. <https://doi.org/10.1007/s12237-011-9454-y>

Shuttleworth, J. 1992. Evaporation. In *Handbook of hydrology*, ed. D. Maidment, 4.1–4.53. New York: McGraw-Hill.

Sun, G., McNulty, S. G., Shepard, J. P., Amatya, D. M., Riekerk, H., Comerford, N. B., ... & Swift Jr, L. (2001). Effects of timber management on the hydrology of wetland forests in the southern United States. *Forest Ecology and Management*, *143*(1-3), 227-236.

Thornthwaite, C. W. (1951). The water balance in tropical climates. *Bulletin of the American Meteorological Society*, *32*(5), 166-173.

Turc, L. (1961). Valuation Des Besoins En Eau D’Irrigation, vapotranspiration Potentielle: Formule Climatique Simplifiée Et Mise. *Journal Annual Agronomie 12(1)*: 13–49.

USDA plant profile <https://plants.usda.gov/java/charProfile?symbol=PHNO2>

Wang, S., Pan, M., Mu, Q., Shi, X., Mao, J., Brümmer, C., ... & Black, T. A. (2015). Comparing evapotranspiration from eddy covariance measurements, water budgets, remote sensing, and land surface models over Canada. *Journal of Hydrometeorology*, *16*(4), 1540-1560. <https://doi.org/10.1175/JHM-D-14-0189.1>.

Webb EK, Pearman GI, Leuning R (1980) Correction of flux measurements for density effects due to heat and water vapour transfer. Q J R Meteorol Soc 106:85–100. https://doi.org/10.1002/qj.49710644707

Wohlfahrt, G., Irschick, C., Thalinger, B., Hörtnagl, L., Obojes, N., & Hammerle, A. (2010). Multiple constraints on grassland evapotranspiration: implications for closing the energy balance. *Vadose zone journal: VZJ*, *9*(4).

Wu, Y., Huang, M., Warrington, DN. (2011). Growth and transpiration of maize and winter wheat in response to water deficits in pots and plots, *Environmental and Experimental Botany*,

Volume 71, Issue 1, 2011, Pages 65-71, ISSN 0098-8472,

https://doi.org/10.1016/j.envexpbot.2010.10.015.

Zemp, D. C., Schleussner, C. F., Barbosa, H., & Rammig, A. (2017). Deforestation effects on Amazon forest resilience. *Geophysical Research Letters*, *44*(12), 6182-6190. doi:[10.1002/2017GL072955](https://doi.org/10.1002/2017GL072955). Table 1: 10-month ET for eddy covariance and low-cost lysimeters in 2018 at BIR. Data for February and March are missing for eddy covariance and hence also excluded here for the lysimeters to enable comparison over the same time period. *R.colorata (rhycol). P.nodiflora (phynod). P.notatum (pasnot) and A.fissifolius (axofis)*

|  |  |  |
| --- | --- | --- |
| **Method** | **ET (mm) for 10 months** | **ET spatial scope** |
| Eddy Covariance | 722 | Flux Tower footprint: improved pasture |
| Weighing Type Lysimeter *(AxoFis)* | 751 | Single species in a pot (n=5 lysimeters) |
| Weighing Type Lysimeter *(PhyNod)* | 789 | Single species in a pot (n=5 lysimeters) |
| Weighing Type Lysimeter *(PasNot)* | 885 | Single species in a pot (n=5 lysimeters) |
| Weighing Type Lysimeter *(RhyCol)* | 1043 | Single species in a pot (n=5 lysimeters) |
| Water level lysimeter | 874 | Plant community in pots (n=31 lysimeters) |

Table 2: Results of correlation analysis of monthly ET between four species in weighing-type lysimeters (n=5 per species) for R.colorata (rhycol). P.nodiflora (phynod). P.notatum (pasnot) and A.fissifolius (axofis)

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | *rhycol\_ET* | *phynod\_ET* | *pasnot\_ET* | *axofur\_ET* |
| rhycol\_ET | 1 |  |  |  |
| phynod\_ET | 0.902675 | 1 |  |  |
| pasnot\_ET | 0.942951 | 0.865694 | 1 |  |
| axofis\_ET | 0.868501 | 0.837209 | 0.929527 | 1 |

Table 3: Advantages and disadvantages of ET techniques utilized in this study. Uncertainty is obtained from the literature for established methods and estimated for the low-cost lysimeters.

|  |  |  |  |
| --- | --- | --- | --- |
| **Method** | **Advantages** | **Disadvantages** | **Uncertainty** |
| Eddy covariance | Ecosystem-level measurement of Actual ET that’s integrated over plant species; continuous measurements over time (eg. every 30 minutes). | High cost, complex technical maintenance and data analysis; accuracy affected by lack of energy balance closure, heterogeneity in vegetation within tower footprint, unfavorable wind directions and gap-filling necessitated by sensor/power failures. | 5-20% |
| Vapor transport models | Depending on model, require few meteorological parameters that are often publicly available. Globally standardized for irrigated agriculture. | No measured vegetation component; needs calibration from eddy covariance or agriculture lysimeters. Yields Potential ET, and not Actual ET. | 10-25% |
| Low-cost lysimeters | Low cost; species or plant community-level measurement possible; no need of technically-trained staff. | Temporally limited data (in this study, 2-3 days for weighing, weekly for water level); limited root zone and edge effects; watering regime not the same as field conditions, yields ET between Potential and Actual. | 10-20% |

List of Figure Captions

Figure 1: The 4200 ha. Archbold Biological Station’s Buck Island Ranch, Florida, USA with managed pastures, semi-native grasslands, wetlands and oak-palm woodlands – plant communities typical of rangelands across Southcentral Florida.

Figure 2: Weighing-type (WT) and Water level (WL) Lysimeter schematic diagrams. WT(a) - saturated; WT(b) - moist-dry after a few days. WL(a) - water level lysimeter with water at mark; WL(b) - water level dropped after a week

Figure 3: Monthly ET from Evapotranspiration models, FAWN ET data AND eddy covariance ET estimates along with monthly rainfall at BIR for 2018. Eddy flux ET is missing data for February and March.

Figure 4: Monthly evapotranspiration for weighing-type lysimeters (n=5 per species, 6 letter codes indicate species) and water level lysimeters (n=31). Error bars indicate one standard deviation. Rhynchospora colorata (RhyCol) had the highest monthly ET, Phyla nodiflora (PhyNod) and Paspalum notatum (PasNot) have intermediate ET, while Axonopus fissifolius (AxoFis) the lowest. Monthly average air temperature is shown by red dots.

*Figure 5: Weekly evapotranspiration (mm) for water level lysimeters (n = 31) over 2018; error bars indicate 1 standard deviation.*

*Figure 6: Correlation of ET data between weighing-type lysimeter planted with P.notatum (Bahiagrass, n = 5) and eddy covariance (A), FAWN data (B), FAO-PM (C) and Modified Turc models (D).*

*Figure 7: Correlation of ET data between water level lysimeter (n = 31) and eddy covariance(A), FAWN data(B), FAO-PM (C) and Modified Turc models (D).*

Supplementary Tables

Table 4: Monthly ET and standard deviation in millimeters for 4 species R.colorata, P.nodiflora, P.notatum and A.furcatus.

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| month | rhycol | phynod | pasnot | axofur | rhycol\_std | phynod\_std | pasnot\_std | axofur\_std |
| J | 53 | 44 | 45 | 46 | 10 | 3 | 5 | 4 |
| F | 102 | 78 | 80 | 54 | 8 | 6 | 9 | 12 |
| M | 133 | 115 | 95 | 76 | 8 | 10 | 2 | 10 |
| A | 153 | 132 | 128 | 101 | 10 | 5 | 13 | 18 |
| M | 87 | 77 | 80 | 65 | 12 | 12 | 11 | 8 |
| J | 139 | 108 | 106 | 95 | 20 | 21 | 12 | 20 |
| J | 120 | 80 | 95 | 77 | 23 | 9 | 17 | 5 |
| A | 147 | 88 | 115 | 86 | 21 | 22 | 9 | 18 |
| S | 109 | 73 | 100 | 79 | 13 | 6 | 11 | 14 |
| O | 95 | 81 | 97 | 81 | 17 | 15 | 12 | 11 |
| N | 78 | 66 | 67 | 69 | 13 | 13 | 7 | 13 |
| D | 61 | 41 | 52 | 52 | 11 | 3 | 6 | 12 |
| TOTAL | 1278 | 982 | 1060 | 881 |  |  |  |  |
| Daily average ET | 3.5 | 2.7 | 2.9 | 2.4 |  |  |  |  |

Table 5: Monthly ET (cm) for each water level lysimeter

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Lys\_id | jan | feb | mar | apr | may | jun | jul | aug | sep | oct | nov | dec | ANNUAL |
| 1 | 7.044877 | 16.09296 | 21.73514 | 13.49512 | 9.45099 | 11.6423 | 9.157741 | 11.67257 | 8.08353 | 9.154995 | 12.24208 | 7.851586 | 137.6239 |
| 2 | 5.217473 | 9.397326 | 10.88029 | 6.498381 | 5.678481 | 11.61829 | 4.834848 | 2.573303 | 8.1935 | 6.748261 | 5.911954 | 4.436889 | 81.989 |
| 3 | 14.38798 | 13.96908 | 17.19184 | 13.34214 | 13.63724 | 26.76141 | 14.16922 | 21.20829 | 20.75195 | 21.67077 | 14.93981 | 9.622126 | 201.6519 |
| 4 | 5.958166 | 8.422449 | 17.50931 | 14.25128 | 6.923083 | 8.184061 | 7.237766 | 10.65608 | 9.6929 | 9.22415 | 7.948113 | 3.513919 | 109.5213 |
| 5 | 7.631564 | 9.128279 | 13.2615 | 10.1766 | 7.87598 | 16.11102 | 13.63914 | 13.26051 | 8.574771 | 7.748316 | 7.863373 | 2.609017 | 117.8801 |
| 7 | 4.755189 | 5.960087 | 11.77431 | 7.393015 | 5.181021 | 5.185736 | 6.174234 | 6.206287 | 9.690656 | 11.14837 | 12.7611 | 6.893659 | 93.12366 |
| 8 | 10.23784 | 4.991105 | 8.646727 | 5.986231 | 4.67971 | 11.19697 | 1.848271 | 4.422396 | 7.925053 | 9.775654 | 9.88486 | 3.288629 | 82.88344 |
| 9 | 7.584221 | 10.62532 | 12.51991 | 7.850956 | 5.116206 | 13.81618 | 7.574198 | 8.878403 | 7.82562 | 8.426705 | 9.701237 | 5.491126 | 105.4101 |
| 10 | 1.404398 | 5.927888 | 7.645444 | 3.50354 | 0.983657 | 8.339355 | 7.229261 | 6.686827 | 3.681123 | 2.521206 | 3.970287 | 2.104483 | 53.99747 |
| 11 | 13.03634 | 7.731106 | 10.11889 | 8.284428 | 6.979895 | 4.880096 | 23.113 | 9.8923 | 15.83435 | 23.47979 | 19.09425 | 8.210529 | 150.655 |
| 12 | 6.207883 | 8.507711 | 9.674453 | 7.539025 | 7.463077 | 17.7224 | 10.53962 | 5.46711 | 7.773996 | 7.698506 | 7.334092 | 4.262129 | 100.19 |
| 13 | 2.035512 | 6.515399 | 10.59873 | 8.315021 | 6.847043 | 14.84299 | 11.98836 | 10.28483 | 12.74255 | 11.80761 | 17.22321 | 9.921052 | 123.1223 |
| 14 | 5.86822 | 11.25403 | 10.35009 | 7.351282 | 7.149968 | 12.69009 | 10.9776 | 5.861138 | 11.07288 | 10.09974 | 10.15052 | 7.06632 | 109.8919 |
| 15 | 2.541941 | 7.790832 | 8.833623 | 6.933367 | 4.999479 | 14.21461 | 7.500449 | 10.77446 | 9.982419 | 9.798052 | 7.101744 | 4.837758 | 95.30873 |
| 16 | 5.451697 | 4.134207 | 10.15034 | 7.101017 | 2.860226 | 9.404581 | 8.778728 | 3.95006 | 7.611866 | 6.535776 | 7.325563 | 1.08005 | 74.38411 |
| 17 | 3.58681 | 8.187524 | 11.54563 | 9.847136 | 6.593391 | 13.75661 | 10.30934 | 11.33677 | 9.673379 | 8.729308 | 5.746495 | 3.209042 | 102.5214 |
| 19 | 2.670891 | 8.545134 | 13.2955 | 11.5207 | 3.527034 | 17.63174 | 7.571323 | 10.49632 | 7.609798 | 8.559609 | 3.160937 | 4.375824 | 98.96481 |
| 21 | 10.67436 | 8.816596 | 6.575297 | 1.39491 | 7.394368 | 11.66009 | 9.719937 | 8.706074 | 9.920874 | 8.990964 | 8.694499 | 10.09498 | 102.643 |
| 23 | 3.333242 | 10.60095 | 13.50767 | 4.970949 | 5.845004 | 13.77748 | 16.35789 | 7.428431 | 13.04901 | 0.519985 | 0.700917 | 5.213227 | 95.30475 |
| 24 | 3.970119 | 10.03216 | 16.05373 | 7.724107 | 4.79171 | 14.50976 | 6.721427 | 15.24361 | 7.988746 | 14.11734 | 20.62408 | 9.168959 | 130.9457 |
| 25 | 1.203941 | 14.87827 | 8.96476 | 8.048738 | 5.708114 | 11.75427 | 19.04934 | 19.46852 | 14.19943 | 8.157373 | 7.633395 | 2.965554 | 122.0317 |
| 26 | 3.499429 | 4.355198 | 21.01056 | 6.076899 | 3.890292 | 16.84043 | 7.16278 | 8.391275 | 7.067596 | 9.020966 | 9.813049 | 10.36167 | 107.4901 |
| 27 | 5.099882 | 13.64437 | 11.4066 | 15.13785 | 11.4209 | 9.531582 | 17.95312 | 14.92475 | 15.03729 | 10.05079 | 5.901783 | 8.729645 | 138.8386 |
| 28 | 7.750237 | 9.121069 | 7.840242 | 8.661905 | 5.550138 | 26.73988 | 8.397793 | 13.80457 | 9.885083 | 12.15244 | 17.69405 | 8.056236 | 135.6536 |
| 29 | 5.741253 | 11.19553 | 21.04337 | 7.085829 | 8.745481 | 11.78572 | 9.479187 | 9.527849 | 8.333458 | 9.859196 | 7.954968 | 3.266474 | 114.0183 |
| 30 | 2.176901 | 18.16355 | 7.641752 | 9.591669 | 11.48057 | 10.19083 | 14.40403 | 15.33233 | 18.17617 | 9.355775 | 11.38737 | 1.601612 | 129.5026 |
| 31 | 1.404397 | 7.111038 | 7.322247 | 5.31704 | 4.500801 | 20.07758 | 7.001773 | 6.746628 | 6.297852 | 22.19221 | 13.66787 | 2.803667 | 104.4431 |