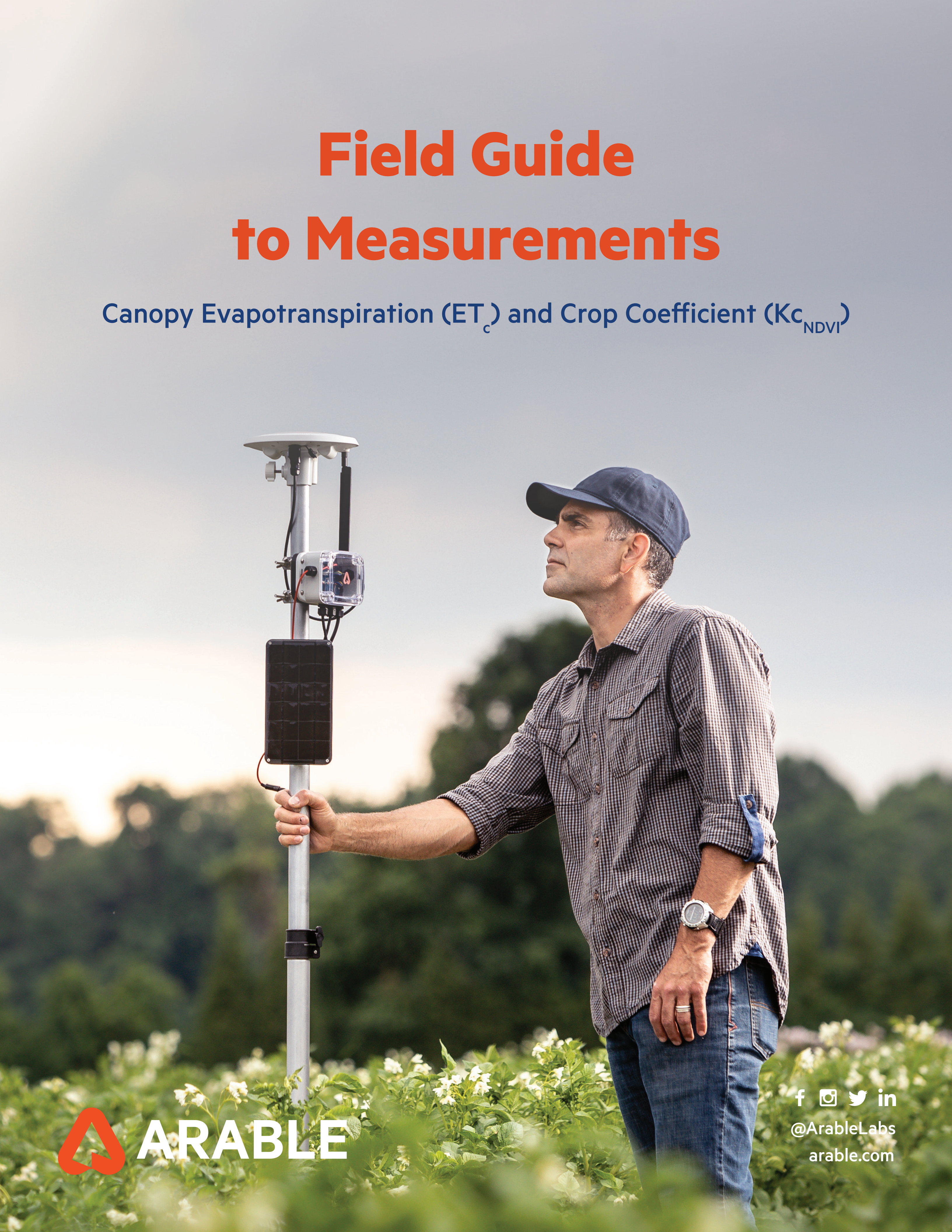
Field Guide to Measurements

Canopy Evapotranspiration (ET_c) and Crop Coefficient (Kc_{NDVI})



ARABLE

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CANOPY EVAPOTRANSPIRATION AND CROP COEFFICIENT

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APPLICATIONS:

Irrigation scheduling, plant stress monitoring, water use efficiency, crop protection

OTHER RELATED MARK MEASUREMENTS:

Relative humidity (RH)
Air temperature (T)
Crop water demand (CWD)
Precipitation (Precip)
Leaf Wetness (LFW)
Normalized Difference Vegetation Index (NDVI)
Heat Stress

What is it?

Evapotranspiration (ET) is the measurement of the amount of water a plant loses in a day. It is the combined loss of water from the processes of evaporation (the movement of water from surfaces or water bodies to the air) and transpiration (the loss of water vapor through the plant's stomata to the atmosphere). Since the actual amount of water lost through transpiration depends on the plant species and the growth stage of the plant, a more precise field measurement that takes the canopy cover into account is **canopy evapotranspiration (ET_c)**.

Why do we measure it?

The tendency to overwater a field is very common because the risk of under-watering is so great. However, overwatering has many associated risks such as disease inoculation, nutrient leaching, and soil erosion. Moreover, agricultural **water use efficiency (WUE)** is an increasingly important concept as droughts, the surge in atmospheric CO2, and denser plantings demand higher water intake and groundwater depletion. By monitoring a field's ET_c, we can appropriately budget irrigation inputs based on our management plans, such as by replacing only the water that was lost since the last irrigation, or by adding only what we can determine a plant needs at a given time. This is the most practical, economical, and sustainable approach to irrigation management, and is crucial to anyone who needs to comply with irrigation regulations such as California's Sustainable Ground Management Act (SGMA). See appendix for a table of irrigation management methods.

How do we measure it?

Determining how much water a specific field is losing in real-time is a three step process based on a number of environmental and plant conditions that Arable monitors:

ENVIRONMENTAL CONDITIONS

- Air and canopy temperature (T)
- Relative humidity (RH)
- Saturated vapor pressure (e_{sat})
- Actual vapor pressure (e_a)
- Vapor pressure deficit (e_{sat} - e_a)
- Net radiation (R_n)
- Precipitation (Precip)

PLANT CONDITIONS

- Normalized Difference Vegetation Index (NDVI)
- Crop coefficient (Kc_{NDVI})

First, we derive the **field evapotranspiration (ET_f)**, which is akin to reference evapotranspiration (ET_o) or the hypothetical evapotranspiration under a grass reference surface. We use Arable's unique machine learning (ML) model to predict this ET_f value, which makes use of the environmental variables listed above. The feature inputs into this ML model are similar to those inputs required for physical models, like the FAO Penman-Monteith method, but we achieve greater accuracies using the ML model, which is able to correct for errors and capture patterns that inflexible physical models do not. As a backup, when the ML model cannot be applied (only under rare circumstances), we use the FAO Penman-Monteith method with the Dong et al net radiation approach. ET_f is a baseline (not species-specific) evapotranspiration rate based on your field's actual weather conditions over a homogeneous area. Having infield weather data is critical to calculating an accurate ET_f value, since it quantifies the evaporation power of the atmosphere. But using it for irrigation is risky because it can change based on crop characteristics and physiology. To get around this, we measure the **Normalized Difference Vegetation Index (NDVI)**, which quantifies the health and stage of the crop's growth, to calculate the **crop coefficient (Kc_{NDVI})** via the linear regression method developed by Kamble et al. (2013).

NDVI is a measure of the "greenness" of a plant based on the canopy reflectance of light. The Kc depends on the species and changes throughout the growing season. By using Arable's daily NDVI measurements, we calculate a **dynamic Kc**.

$$Kc_{NDVI} = 1.457 \times NDVI - 0.1725$$

Finally, we multiply your field's ET_f by your plants' Kc to get an ET_c value unique to your plants in your field. You can use this value to devise a precise irrigation plan.

$$ET_c = ET_f \times Kc_{NDVI}$$

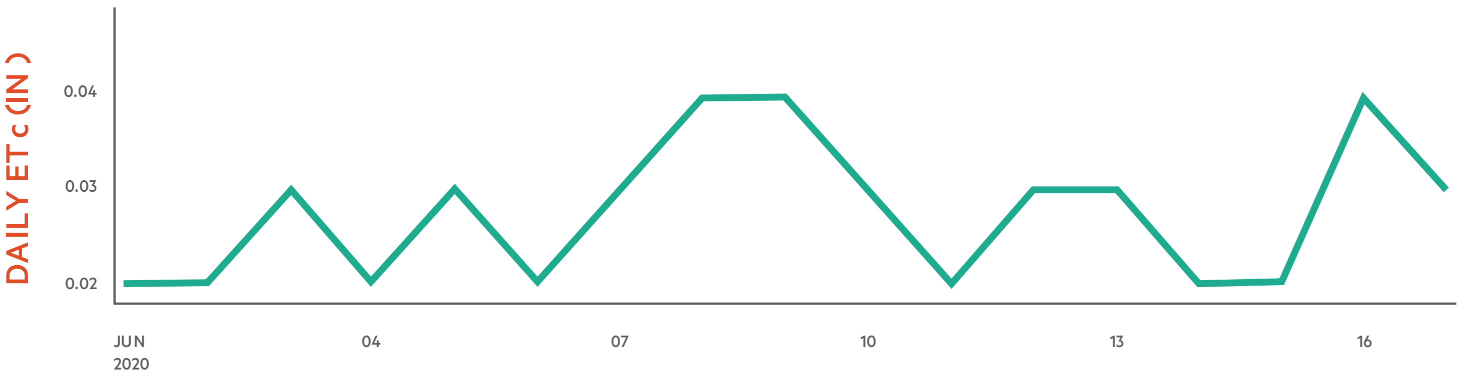
HOW DOES USING ARABLE'S ET_c COMPARE TO OTHER IRRIGATION MANAGEMENT METHODS?

As any grower knows, there are many different ways to approach irrigation management. Arable's method is unique in two ways. First, it uses the dynamic NDVI to calculate Kc_{NDVI} as discussed above, so you don't rely on pre-established Kc_{NDVI} tables. Second, it calculates a hyperlocal ET_f based on weather conditions around the Mark in your field instead of using a remote weather station. This provides a more precise value of evapotranspiration, highly representative of the conditions in ***your*** management area. See Appendix for a full comparison between different irrigation management methodologies.

PHOTO: TOM PEETERS

What does the data look like?

You can choose the units you want ET_c to be reported in your dashboard (mm or in of water vapor/day.)



Daily ET_c for a farm in Australia in June, 2020.

How can you use it?

By using ET_c, the Arable Mark can help you determine the first step in irrigation planning: **crop water demand (CWD)**. This is also known as the irrigation water requirement. Knowing exactly how much water your crop requires will improve your irrigation WUE and help you make evidence-based management choices by calculating precise, real-world needs. Other considerations about your irrigation system such as soil type, field size, irrigation system flow rate and system efficiency will dictate the exact timing and amount of water applied. By starting with CWD, you can ensure you are not over- or underestimating the amount of water needed to keep your plants healthy.

$$CWD = Precip - ET_c$$

Example use cases

IRRIGATION OVERVIEW					11 JUNE 2020	17 WED 2020	< >
TYPE	THUR 11	FRI 12	SAT 13	SUN 14	MON 15	TUES 16	WED 17	WEEKLY INSIGHTS
ET_c	0.02”	0.03”	0.03”	0.02”	0.02”	0.04”	0.03”	0.19” TOTAL
PRECIPITATION	0.19”	0.11”	0”	0.01”	0”	0”	0.18”	0.49” TOTAL

Available in the Arable data export, CWD is calculated by subtracting the amount of water lost to Et_c from the amount of water added by **precipitation (Precip)**. In the example shown above, a Mark in Australia reported a total input of 0.46” of rain over the past week. The same Mark reported an ET_c of 0.19”. Since precipitation—the input—exceeds the amount of water lost to evapotranspiration, we know it is not necessary to irrigate at this time.

IRRIGATION OVERVIEW					11 JUNE 2020	17 WED 2020	< >
TYPE	THUR 11	FRI 12	SAT 13	SUN 14	MON 15	TUES 16	WED 17	WEEKLY INSIGHTS
ET_c	0.09”	0.08”	0.1”	0.12”	0.11”	0.14”	0.04”	0.68” TOTAL
PRECIPITATION	0.01”	0.17”	0.01”	0.02”	0.02”	0.02”	0.05”	0.3” TOTAL

On the other hand, a field in California reported precipitation of 0.3” and an ET_c of 0.68” for the same week. There is a water deficit of -0.38” of water (CWD= 0.3” Precip - 0.68” ET_c), which means that the field needs 0.38 acre-inches of water to replenish the losses from that week. At this point, you have an exact amount of water that needs to be added back into the field.

Putting it into practice

Your next steps for irrigation scheduling might include calculating in-system inefficiencies and determining timing. These are based on your specific setup, such as your irrigation system, number of lines per row, and flow rate. Armed with a rich, infield climate and plant dataset, you can build an evidence-based schedule that best helps you define and achieve goals at each stage of the growing season.

CITATIONS

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Appendix

Compare Arable to other methods of irrigation management

	ARABLE MARK	WEATHER STATIONS	CIMIS*	SURFACE RENEWAL	SOIL MOISTURE SENSORS	SAP FLOW SENSORS	AERIAL IMAGING	PRESSURE CHAMBERS	FIELD VISIT
HOW IT WORKS	Unique ML model to predict ET_f value achieving greater accuracy than Penman-Monteith method. Canopy ET (ET_c) is the product of ET_f and dynamic Kc_{NDVI}	Energy balance method with some assumptions	Energy balance method with some assumptions, at some distance away	Energy balance method with more assumptions	Measures water loss from changing soil water balance	Measures velocity of water movement inside one woody plant	Snapshot of crop coeffient and water stress	Integrated soil water balance determined from plant measurement	Touching the plant and soil
OBSTACLES TO USING QUANTITATIVELY	Subject to details of canopy architecture as it affects Kc and cover crop	Subject to assumptions on Kc and proximity	Subject to assumptions on Kc and proximity	Subject to assumptions based on energy balance and cover crop	Subject to spatial variability and placement in the root zone	Subject to assumptions on sapwood area and leaf area	Subject to assumptions on energy balance	Subject to assumptions on soil water holding	Not quantitative
MEASURES PLANT PLUS WATER STATUS?	Yes; multiple measures of stress	No	No	Yes; ET in relation to potential ET	No	Yes	Yes	Yes	Yes
LABOR REQUIREMENT	Automatic	Automatic	Automatic	Automatic	Manual or Automatic	Automatic	Automatic	Manual	Manual
DATA FREQUENCY	Hourly or Daily	Hourly or Daily	Hourly or Daily	Daily	Hourly or Daily	Hourly or Daily	Weekly to sporadic	Weekly to sporadic	Weekly to sporadic
MEASUREMENT ZONE	1-160 acres	Whole farm	Nearby, not in your field	1-160 acres	2" radius from the sensor	Single plant	Many acres	Single plant	Single plant
REPLACEMENT AND MAINTENANCE	Simple install or replacement	Annual calibration recommended	Government maintained	Included in the service contract	Can require removal for field operations	Included in the service contract	N/A	N/A	N/A
LIMITATIONS	When ML model cannot be applied to incoming data, the output is a fall back to the Penman-Monteith method	Assumes Rn with no measure of albedo or longwave radiation	Assumes Rn with no measure of albedo or longwave radiation; distant from the field	Sensitive thermocouple can break easily; requires a large area, or "fetch"	Finding a representative spot to install	Finding a representative spot to install	Requires additional data to calculate ET	Data is noisy without proper training; measurement windows are narrow	Reflects impacts that have already happened; unreliable measure without extensive experience

*http://wwwcimis.water.ca.gov/Content/PDF/CIMIS%20Equation.pdf

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