METHODS OF ESTIMATING CROP EVAPOTRANSPIRATION WITH REMOTE SENSING:

ADVANTAGES AND LIMITATIONS

Key Messages

- Crop evapotranspiration (ET) is a key component of consumptive water use, so it is important to quantify.
- New technologies (such as those used for OpenET) make it possible to access crop ET estimates for a given place and time frame in the western United States.
- Because crop ET estimation involves many factors that vary with location, time, weather, and crop type, there is always some uncertainty (reported as error).
- Based on the methods used and data available, crop ET estimates tend to be more reliable over longer time frames (growing season vs. day) and larger areas (watershed vs. field).
- When used appropriately, crop ET estimates can inform water use estimates and irrigation system design and management.

Why Estimate Crop Evapotranspiration?

Crop water use includes water that is used by plants and transpired through their leaves and into the air or evaporated from wet soil and leaves. Together, these processes that move water into the air as water vapor are referred to as evapotranspiration, or *ET*. ET is the main component of consumptive use, which is the water lost from the watershed as water vapor to support plant growth. New methods are emerging to estimate crop ET, which can better inform irrigation system design and management and help document beneficial use. To generate and appropriately use crop ET estimates, it is important to consider the balances of water and energy and include data on weather, soil conditions, and crop characteristics in a given field. This publication describes recent advances in methods to estimate crop ET and advances that broaden free access to these estimates to improve the ability to plan and track consumptive use.

Large volumes of water are used by plants or are lost via evaporation from plants and soil. *Although the water lost via crop ET is not visible, it is the large majority of consumptive water use*. Typical crop ET rates are anywhere from 11 to 36 inches of water per season in Washington. This amounts to huge quantities of water (300,000 to 1,000,000 gallons per acre, per season) especially when added up over large areas. Inefficient irrigation systems (especially high pressure sprinkler irrigation systems) also lose additional water to evaporation, which is another form of consumptive use.

There are many reasons to want to know how much water is being lost to crop ET. Crop ET information is used to determine how much water is needed for irrigation, when are the best times to irrigate, or to document beneficial use for water rights decisions. Crop ET estimates are also used to inform irrigation system or evaporation pond designs (Gaznayee et al. 2023), crop irrigation management (Calera et al. 2017), water trading or leasing (Schwabe et al. 2020), and water usage tracking (Kharrou et al. 2021).

Crop evapotranspiration changes with place, conditions, and time. The rate of water moving from plants to the air depends on crop condition, energy from the sun, air temperature, air humidity, wind speeds, and other soil and water conditions. It is important to know how consumptive use changes with crop type, season, weather, and soil conditions. However, it is impossible to directly measure crop ET at all places and times, so having a way to estimate crop ET for any place and time is useful.

Crop ET estimates can fill data gaps to improve water management and profitability. Various ET estimation methods are available. To select the most appropriate method, one needs to know why ET is being estimated, the size of the area for which it is being estimated, the time frame of interest, and what data are available. For example, some methods can provide long-term historical ET averages for specific crops. These are most suitable for irrigation system design or regulatory purposes that require an understanding of long-term average ET. Other methods can provide area-based (spatial) crop ET estimates. Appropriate applications of area-based estimates depend on the amount of area they cover and the level of detail they provide. These estimates are potentially useful for precision irrigation applications, understanding ET over larger areas, or understanding ET over defined time periods such as one or more growing seasons. Each estimation method has potential uses and limitations, and it is important to understand the sources and amount of error associated with any crop ET estimates one might use.

How Much Water Is Lost to Crop ET?

Balance of Water Inputs and Outputs

From a soil-water balance perspective, water is "lost" from a crop root zone via crop ET but can also leave the field as runoff or deep percolation into groundwater (Figure 1). The concept of a water balance allows us to add up the water inputs (blue arrows) from precipitation, irrigation, and capillarity rise and subtract the amount of water lost (red arrows) to calculate the change in soil water storage in the root zone. Alternatively, if we know how much water is stored in the soil, we can fill in all known amounts in the water balance equation to estimate crop ET.

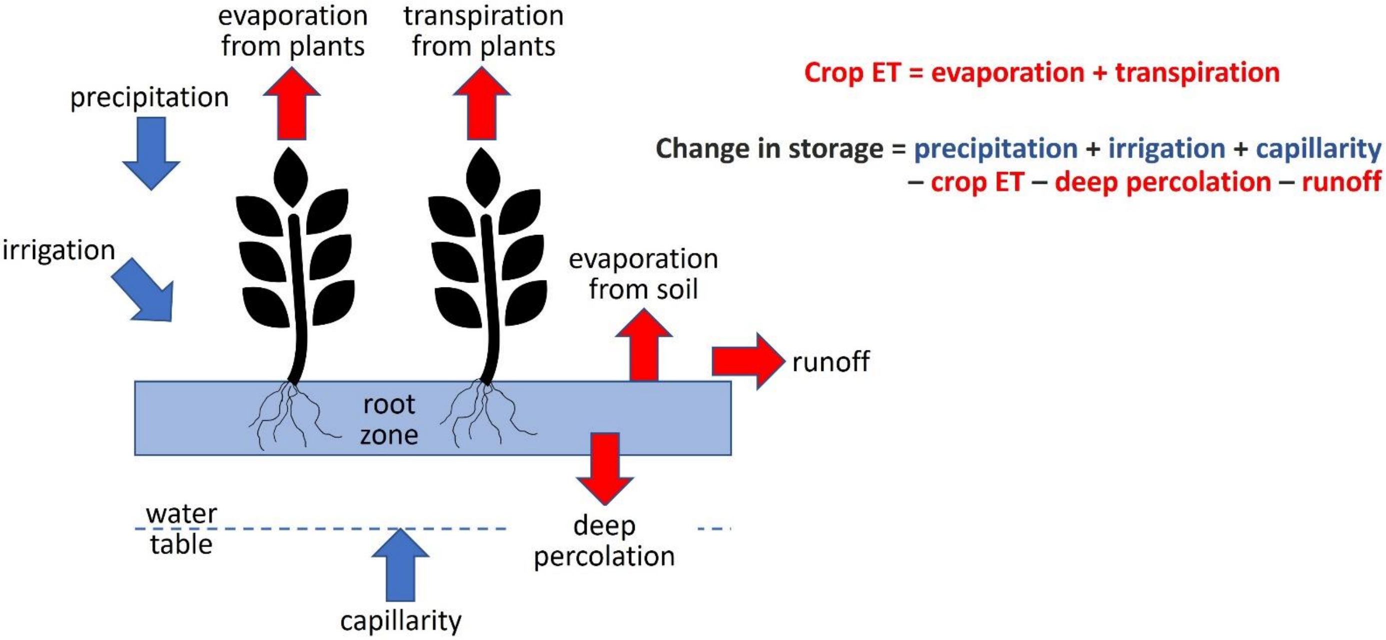


Figure 1. Crop evapotranspiration is the combined loss of water from evaporation and transpiration to the air as water vapor from plants and the soil surface.

Direct Measurements of Crop ET

Two different methods are used for measuring crop ET, though neither is practical outside of research settings.

Weighing lysimeters (Figure 2) are containers of soil with crops planted in them that are located in the middle of fields such that the water use of the crops in them represents the water use of the surrounding crops. This heavy container of soil is continuously weighed so that evaporating and transpiring water volumes can be measured. Due to the complexity and sensitivity of these setups, such measurements are extremely intensive in terms of cost, labor, and required skills. Lysimeters are impractical to use outside of major research-supported settings. Long-term lysimeter data are only available from limited United States Department of Agriculture (USDA) Agricultural Research Service stations in the US. Each of these lysimeters cost more than $500,000 to set up (and could cost about twice that amount today) and also has high ongoing maintenance and operating costs. The only direct way to measure ET is via these weighing lysimeters, and the information gathered from these instruments is used to establish and calibrate all other ET estimation methods.

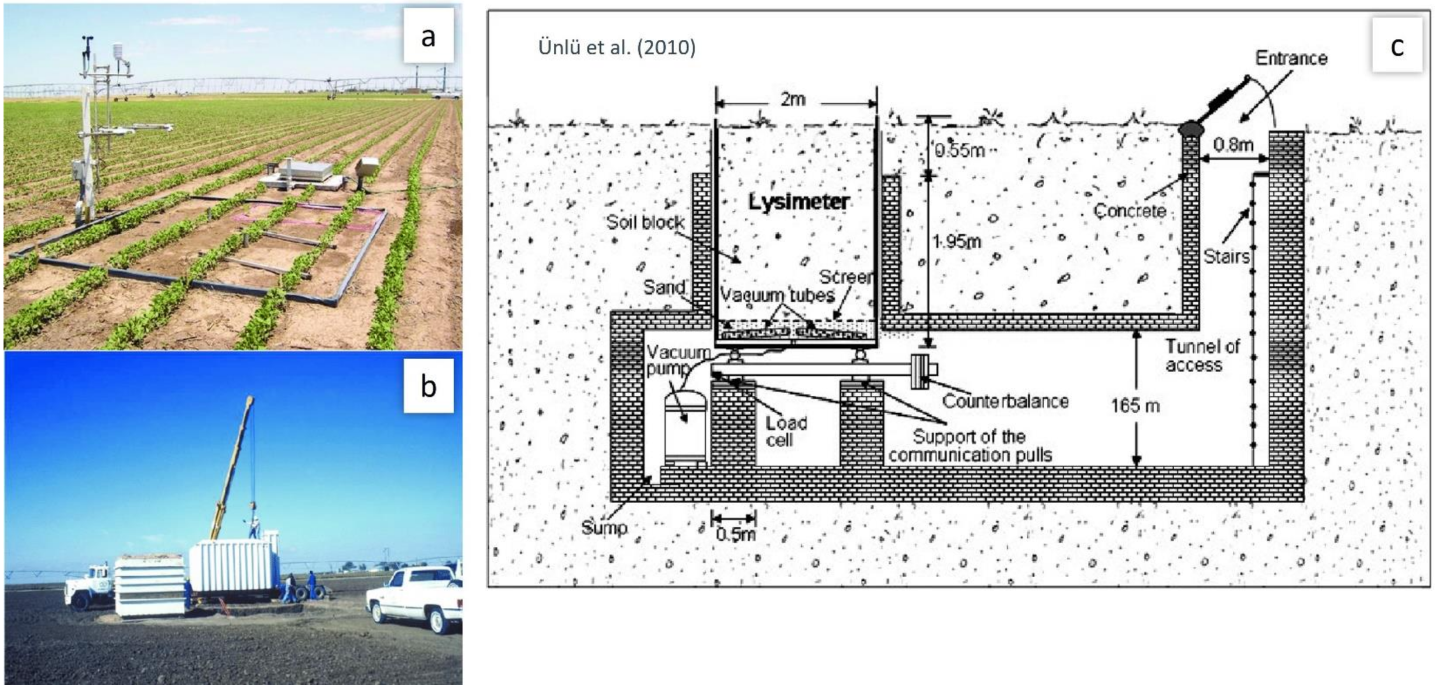


Figure 2. Weighing lysimeters (a, b, c) provide a way to directly measure crop evapotranspiration. Photographs “a” and “b" are reprinted from Moorhead (2019). Diagram “c” is reprinted from Ünlü et al. (2010).

Flux towers (Figure 3) collect measurements of air and water vapor movement. These are used to measure crop ET at a given place and point in time. Although still costly ($50,000–$60,000 each), they are less costly to install and operate than weighing lysimeters. Because of this, models for satellite-based estimates of ET often use flux tower data points for ground-truthing or validation. The most common type of flux tower is an eddy-covariance system.

Figure 3. A flux tower is used to measure crop ET by measuring the flux of water vapor and performing calculations based on principles from the conservation of energy. Reprinted from Joy and Chavez (2021).

Because both the *energy available for evaporation of water* and the *actual water vapor flux* are measured by eddy-covariance towers, it should be possible to close the energy balance equation (i.e., energy in should equal energy out). However, there are always errors in this system (termed “closure errors”), indicating problems with either the measurements or the theory behind the method. The errors vary with installation but can range from 10% to 45% of the measured ET values, although they are typically closer to 20%.

How Does Satellite Data Help Remote Crop ET Estimation?

Satellite remote sensing data or images are increasingly available with global coverage at finer resolution and with shorter intervals between passes (images). Model developers have been working to use these satellite-based images to estimate crop ET. These images could potentially make more accurate and timely ET information accessible.

Satellite-mounted sensors can be used to detect the amount of solar energy reflected or emitted in a number of different radiation bands including infrared, which indicates the ground surface reflectances and surface temperatures at the day and time when the satellite passes over a given area. These sensors together provide some or all the information needed for the energy balance calculations to estimate crop ET, depending on the satellite and model that are being used.

How Can You Access Freely Available Crop ET Estimates?

There are several groups working to make ET estimates publicly available. One of the leading groups created an online platform called OpenET. OpenET enables anyone to explore satellite-based ET estimates at the field scale (or larger areas) across the western US. It is freely and publicly available, requiring only internet access and a web browser. OpenET combines a collection of several different satellite-based ET estimation models with freely available data sources in an attempt to provide ET estimates. The developers are continually improving the platform to increase its accuracy (OpenET 2023, 2024a).

Under the Hood: What the OpenET Models Do

OpenET addresses factors related to weather conditions, time of year, and crop type (OpenET 2024b). The OpenET combination model attempts to reduce error by averaging ET estimates from several models:

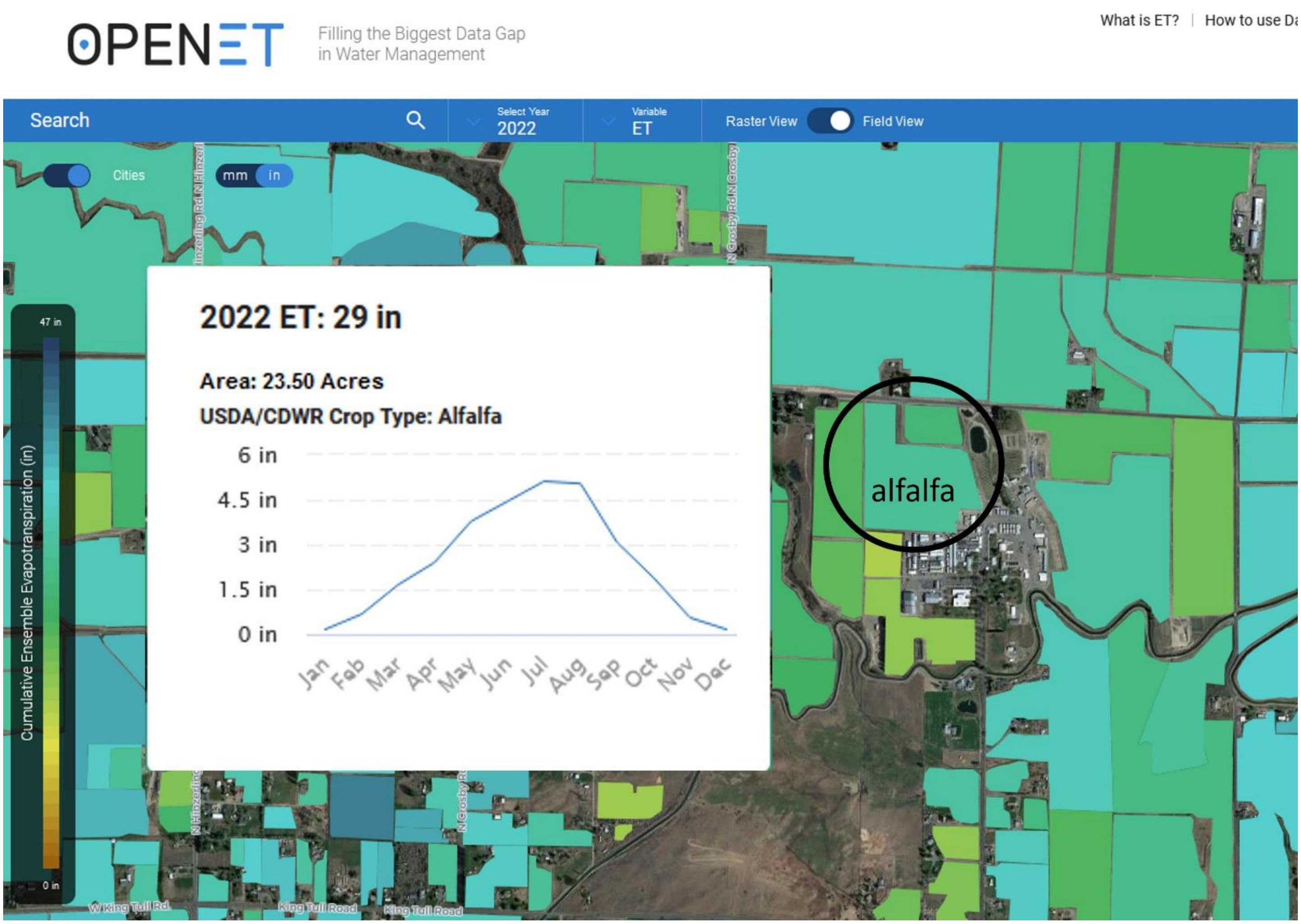
- Three of these models use different types of satellite data to estimate each component of the energy balance, including mapping evapotranspiration with internalized calibration (METRIC) (Allen et al. 2007), Google Earth Engine implementation of the surface energy balance algorithm for land (geeSEBAL) (Bastiaanssen et al. 1998; Laipelt et al. 2021), and Atmosphere-Land Exchange Inverse/Disaggregation of the Atmosphere-Land Exchange Inverse (ALEXI/DisALEXI) (Anderson et al. 2007, 2018).
- Two other models execute a simpler version of the energy balance. These models are the Operational Simplified Surface Energy Balance (SSEBop) (Senay et al. 2013; Senay 2018) and the Priestley-Taylor Jet Propulsion Laboratory (PT-JPL) model (Fisher et al. 2008).
- One final model uses satellite data and crop type (see sidebar Using Crop Coefficients) to compute ET as related to canopy density, the Satellite Irrigation Management Support (SIMS) model (Melton et al. 2012; Pereira et al. 2020).

A combination or ensemble model is simply the average from the outputs of all of these different models after outliers have been removed. The components of the calculations come from satellite data (mainly Landsat) and available weather data from ground-based automatic weather stations that includes air temperature, humidity, solar radiation, wind speed, and precipitation. The level of detail and accuracy makes the OpenET ensemble model appropriate for estimating watershed-scale and even field-scale changes in water use. Learn more details at OpenET's Methodologies page.

How to View Data: The OpenET User Interface

On the OpenET website, the user must first create a free account. They can then choose to display ET by field or by satellite image pixel (Raster View). The ensemble model will then provide estimated ET values for the field or pixels of interest (Figure 4). Crop types are also displayed (where available, from the USDA) to help users interpret the ET values. Note that crop ET estimates are provided even if the crop type label for a field is “Unavailable” or outdated, because the combination model does not require crop type as an input. (Crop type is used in the SIMS model, but the combination model can run without the SIMS model if data are lacking.)

Once a field or area has been selected, the estimated values can be viewed in different ways. First, a pop-up window displays the cumulative (total number of inches) of ET for that field for the last year plus a graph showing the monthly values for that year (Figure 4). Clicking on the field then opens a variety of options, including graphs showing monthly ET values for that field since 2017 (Figure 5). These graphs enable the user to see patterns in ET over each growing season over several years for that field.



Select Year 2022

Variable ET

2022 ET: 29 in

Area: 23.50 Acres

USDA/CDWR Crop Type: Alfalfa

Figure 4. Example of estimated ET values for an alfalfa field at WSU Prosser in OpenET.

How Accurate Are Crop ET Estimates from OpenET?

OpenET estimates are tested against flux tower values, which, as previously discussed, have their own measurement errors. To date, OpenET has only been tested with one flux station in Washington State and one in Oregon, due to a lack of available data sets with the attributes required for ground-truthing in those states (OpenET 2024a). Based on the general testing (using flux towers across the western US), the combination model has a 10% average error for estimates over a year or a growing season (Table 1; OpenET 2023, 2024a). Accuracies are lower for monthly and daily values (17% and 24% average errors, respectively)—the OpenET group is working to improve the accuracy of these calculations. Over larger areas, some of the errors causing differences among the models cancel out, reducing the error in estimated crop ET. For example, when evaluated across the western US, the overall average growing season ET from the OpenET ensemble is within 2% of the flux tower values (OpenET 2023, 2024a). This is why any observed changes in crop ET should be interpreted as real change but only over areas much larger than one field. (For a more technical explanation, see Allen et al., 2007).

Table 1 and Figure 6 summarize the error rates reported by OpenET at the time of this publication. The developers noted that it is more complicated to estimate crop ET for irrigated fields that are surrounded by drylands, so the error values in Table 1 and Figure 6 should be considered as minimum error estimates for eastern Washington. In other words, the error rate for eastern Washington could be higher. The OpenET developers have since refined the models to improve their estimates in drier regions, but error measurements specifically for eastern Washington or Oregon are missing due to a lack of complete flux tower data sets in the region. Regardless of the setting (moist or dry), the OpenET combination model provides more accurate estimates than individual models, particularly over large areas (Figure 7).

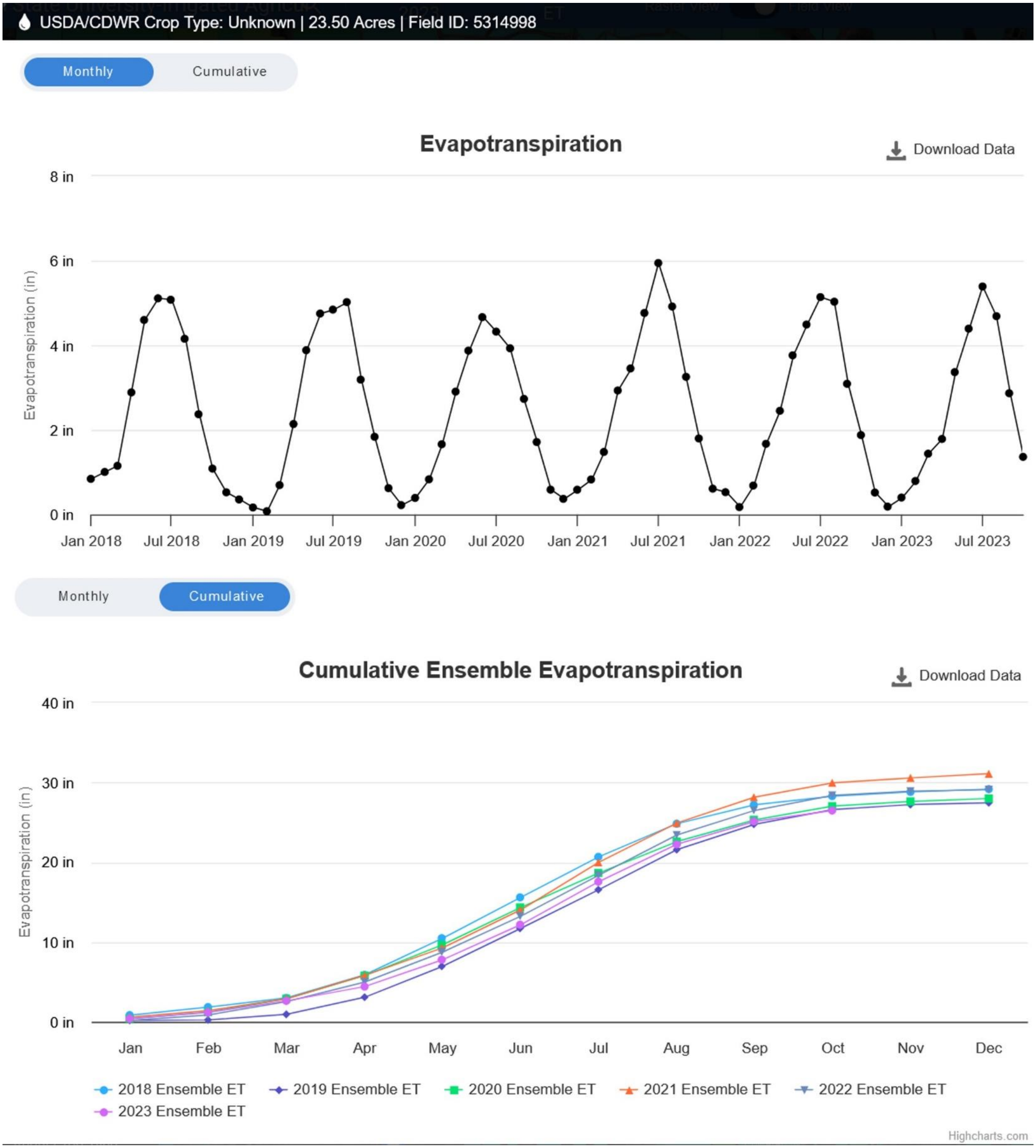


Figure 5. OpenET-estimated monthly ET values since 2018 (top) and cumulative ET each year (bottom) for an alfalfa field at WSU Prosser. *Source*: OpenET (2024b).

Table 1. Accuracy summary for croplands for the OpenET modeled ET value.

Time Period	Average Absolute Error (%)	Average Absolute Error (inches)	Average Flux Tower ET (inches)
Water Year	11.3%	4.4	39.0
Growing Season	12.9%	3.1	23.5
Monthly	17.1%	0.6	3.6
Daily	23.6%	0.0	0.1

Source: https://openetdata.org/accuracy/.

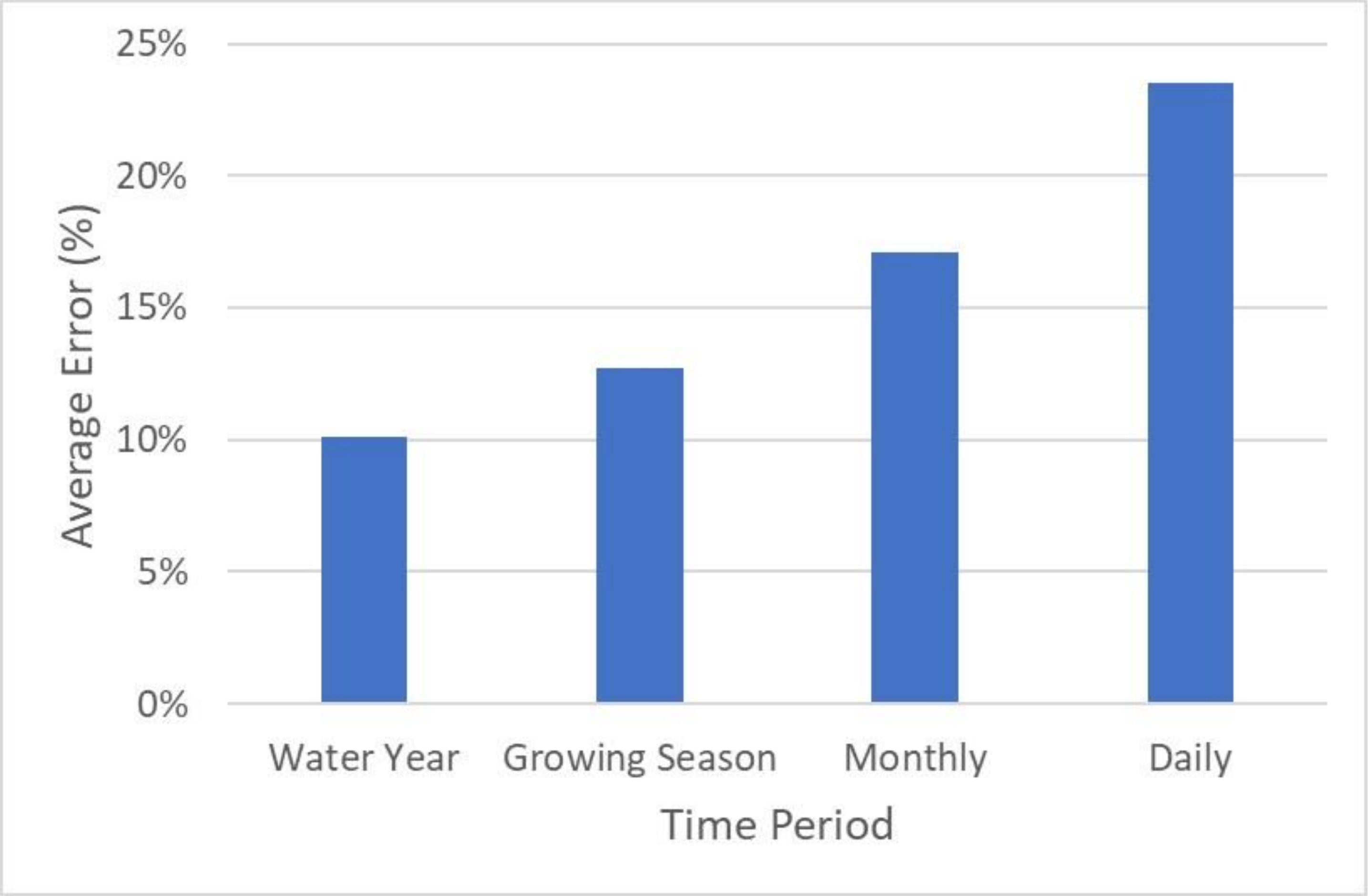
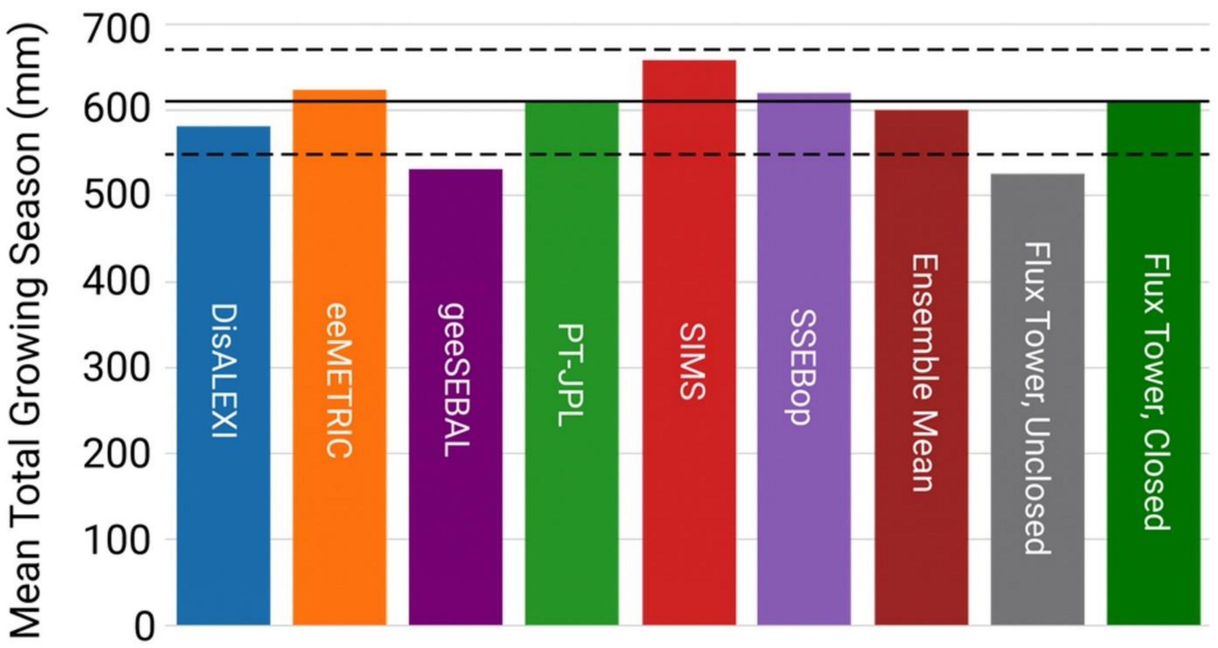


Figure 6. Average error (%) for US croplands for the OpenET modeled ET value over different time periods. *Source*: https://openetdata.org/accuracy/.

Drone- or Aircraft-Based Estimates of ET

Drone or aircraft-mounted sensors can collect data similar to the data collected by satellite-mounted sensors. Satellite-based methods for estimating crop ET can therefore be adapted to work with drone-based data inputs. This is of significant interest to increase the resolution of the remote-sensed estimates of ET as well as have more control over the timing and frequency of these data collection without being subject to cloud limitations that are typical of satellite imagery.

The potential for drone or aircraft-based data to improve crop ET estimates is currently being actively researched, and the results show significant variability in errors thus far. Some drone-based approaches, like flying high-resolution sensors, show promise for accurately estimating daily and seasonal crop ET for small fields (for example, see Tunca et al., 2022).



Average Total Growing Season ET (n=39 sites and 153 total growing seasons). The solid line indicates the mean closed station ET for croplands and the dashed lines represent +/- 10% of the mean. *Source:* https://openetdata.org/accuracy/

Figure 7. Average total growing season ET for 39 sites and 153 growing season estimates from each of the models in OpenET. The Ensemble Mean is the average estimate from the combination model. The solid line shows the average from corrected flux tower measurements. The dashed lines show 10% departure from the corrected flux tower average. *Source*: https://openetdata.org/accuracy/.

What Are Appropriate Uses and Limitations of Remote Crop ET Estimates?

It is essential to understand how certain a remote estimation is before deciding whether you can rely on it for a particular purpose. OpenET scientists reported that satellite-based crop ET estimates typically have about 24% error when compared to flux tower measurements on a daily basis, and 13% error over the growing season. Flux towers are also shown to have about 10%–15% error when compared to large weighing lysimeters (Moorhead et al. 2019), compounding the uncertainty further. This means that remote crop ET estimates *cannot be used as evidence of small changes in water use*. Rather, these estimates *can be used to show significant changes over one or more fields within or across growing seasons*. They can be used to indicate the presence of irrigation in arid areas but are not necessarily accurate enough to quantify legal water rights decisions or irrigation efficiency estimates for that field. Estimates are more reliable across a county, watershed, or irrigation district than within an individual field.

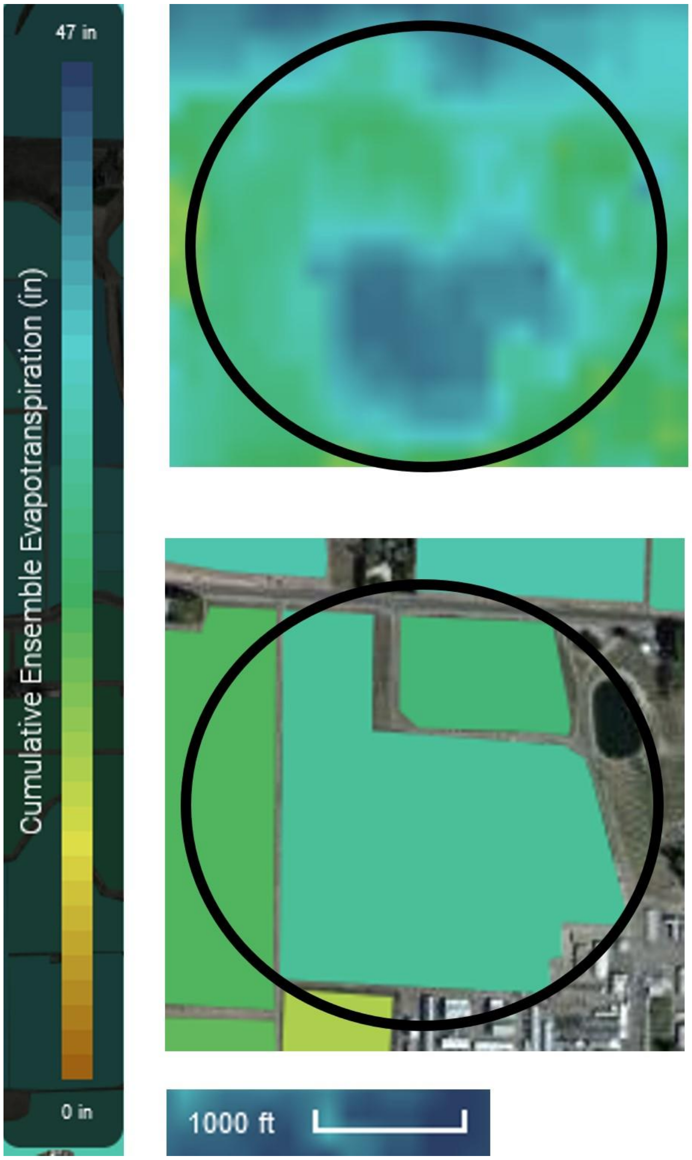
Sources of Error in Remote Crop ET Estimates

There are multiple factors affecting the accuracy of remote crop ET estimates. The most common sources of error are associated with timing, data availability, and level of detail.

- **Timing**. *Remote estimation is more accurate over longer time periods of months, seasons, or years than over days or weeks*. This means that crop ET changes within a few days cannot be reliably detected. One technological limitation is that the satellites that produce freely available images pass over a place about one to four times per month. Other data sources may be updated even less often.
- **Data availability**. *Remote crop ET estimates are most accurate when all data sources are available and reliable for the place and time requested*. Crop ET estimates always have some error, depending on the method or model used. The error (or accuracy) that is reported usually assumes that all data are available for the place and time requested. However, data may be missing from

images collected on days with cloud cover, and some of the models require ground-based data. For example, the SIMS (Satellite Irrigation Management Support) model requires crop type information. If the necessary data are not available for your place and time, the missing data will be filled in with estimates, so the ET estimate from the combination model may be less accurate. In OpenET, the user can display the output from each of the models separately, the combination model output, and the range among all models to get a sense of how different the models are for that place and time. This interface will not inform the user if there were missing or estimated data, so individual model values should be interpreted with caution.

- **Detail**. *Remote crop ET estimates are most accurate at the field scale or broader scales*. Within-field variability or small volume changes in water use cannot be accurately detected with current remote estimation methods. The resolution of satellite images (typically 0.2 acres per image pixel) is too coarse to capture the emergence of individual plants, particularly if they are widely spaced. The smallest area that can be accurately detected with current satellite-based models is a whole field or several fields (Figure 8). Any changes the user observes in individual field-scale graphs (such as those between the different years shown in Figure 6) cannot reliably be interpreted as real change, because the model uncertainty is greater than those changes.



ET is estimated for every image pixel.

ET estimates are also averaged out to each field.

Figure 8. Example map display of remotely estimated crop ET values in both raw (by pixel) and field (polygon) views. *Source*: OpenET (2024b).

Given all the above advantages and limitations for remote crop ET estimation, we can make some generalizations about scientifically sound uses of this information to fill data gaps or inform decisions:

Examples of Appropriate Uses for Satellite-Based ET Estimates…

- To show whether a 40-acre field was irrigated or not for each of the last five growing seasons,
- To determine whether a change in crop type or practices is causing a significant decrease in water use per growing season, or
- To discover persistent leaking from a canal over time that is causing significant water loss.

Examples of Inappropriate Uses for Satellite-Based ET Estimates…

- To show small differences in water use (inches per year or sub-field scale),
- To quantify "beneficial use" to set a water right quantity for a particular land parcel,
- To test whether actual water use was more or less than water rights in a given season, or
- To set up variable rate irrigation systems based on in-field water use variability.

Example Use Cases for OpenET

- Increasing agricultural resilience by enabling alfalfa and grass hay growers to track and demonstrate the effectiveness of their changes in irrigation practices to reduce water use (Diamond Valley, Nevada).
- Providing information to support community-based water use planning and accounting to decrease groundwater use while sustaining the economy and ecosystems (Harney County, Oregon).

For more details and other example use cases, visit OpenET Use Cases.

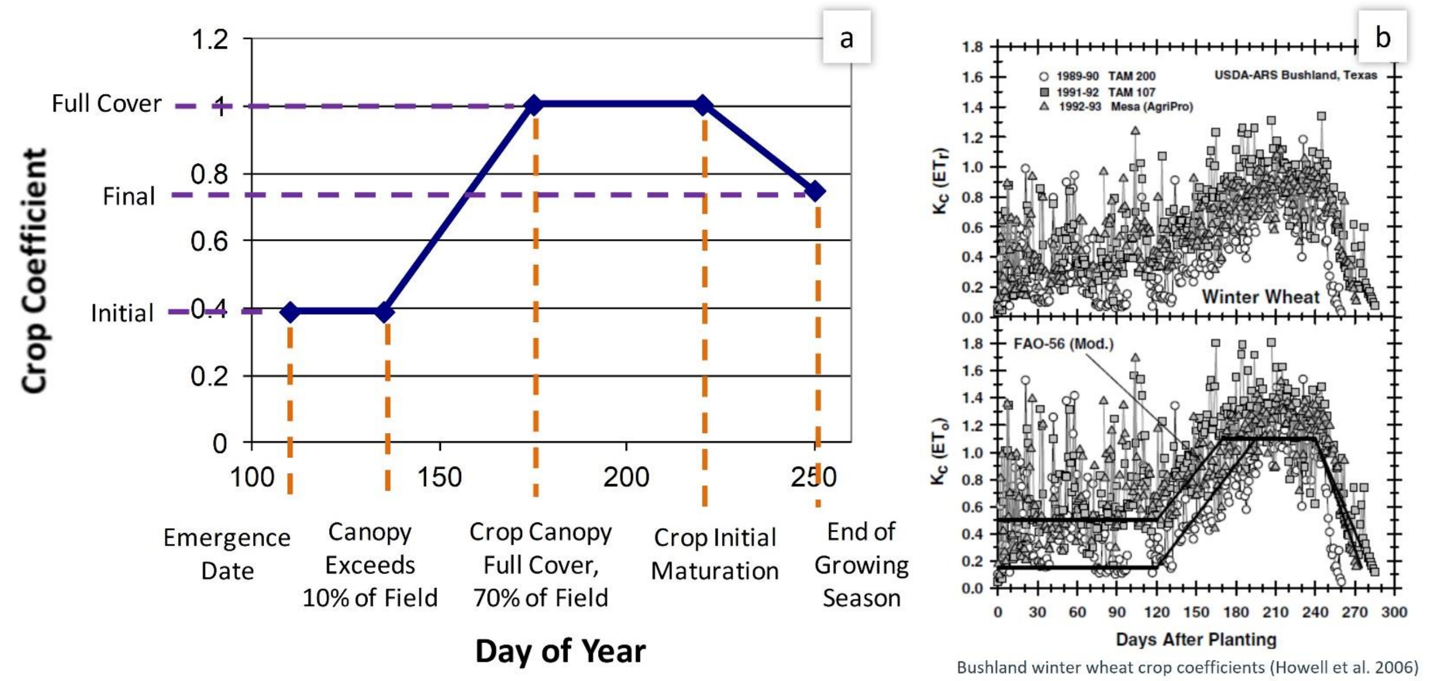
How Does Washington State Currently Estimate Crop ET?

Tracking crop ET in Washington has typically involved recording and storing historical weather data at a variety of relevant locations. This daily weather data is combined with a crop coefficient that depends on the crop and that crop's growth stage to estimate crop ET. (See sidebar Using Crop Coefficients; see also Erpenbeck, 1981; Peters et al., 2014; and Pickering et al., 2021). This type of method, for example, is used in the 1992 Washington Irrigation Guide (1992 WIG) (NRCS 1985/1992), which remains the standard reference used by the Washington State Department of Ecology for most irrigation water right evaluation. The 1992 WIG relies on two different methods for estimating ET: the Blaney Criddle (BC) method modified by the Food and Agriculture Organization (FAO24-BC) and another similar version by the Natural Resources Conservation Service (NRCS-BC). The summary information in the WIG remains in widespread use, even though information on weather years, crop coefficients, and exact methodologies is uncertain (Pickering et al. 2021).

As more data and techniques for estimating crop ET become available, Washington State has the opportunity to improve the accuracy of its consumptive use tracking. This is important because water banks and water right appraisers use estimates of consumptive use (estimated by adding the ET and the portion of the applied water that is consumed by direct evaporation to the atmosphere) in quantifying water rights available for trade, in order to limit impairment to river flows, and for existing water rights when water trades occur.

Using Crop Coefficients

The ET characteristics of each crop in relation to that of a reference crop of clipped grass or alfalfa are described mathematically using a crop coefficient as Crop ET = Reference Crop ET × Crop Coefficient. The general pattern we observe for a given crop is shown in Figure 9a. Typically, the crop coefficient is highest in the full cover stage, then decreases in crops that dry up or senesce. However, the natural variability associated with crop coefficients can cause substantial errors in estimated crop ET values. Calculations of a crop coefficient for a particular crop (for example, winter wheat in Figure 9b) follow the pattern in Figure 9a but have substantial variability—many points fall far from the trend line. Because there is natural variability in conditions for a given crop within the day, week, month, growing season, and across years, these calculations are difficult to complete with good accuracy.



Bushland winter wheat crop coefficients (Howell et al. 2006)

Figure 9. Changes in a typical crop coefficient (a) or in winter wheat (b) during a growing season. *Source*: Howell et al. (2006).

The graphs in Figure 9 show changes in a typical crop coefficient (a) or in winter wheat (b) during a growing season. Crop coefficients determined at weighing lysimeter stations apply only to the specific crop type, variety, timing, and conditions at the research station where they were determined. To apply to any other crop or field, we need to account for the specific crop variety, growth stage, and local conditions. In concept, the crop coefficient represents crop (variety) characteristics, which are independent from location, conditions, and climate. However, research has shown that, in reality, crop coefficients *do* change with location and climate. Any model that uses crop coefficients should report the possible error associated with their use in a setting other than the one in which they were experimentally determined.

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