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Quantitative Assessments of Water and Salt Balance for Cropping Systems in Lower Colorado River Irrigation Districts

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The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

Disclaimer

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Quantitative Assessments of Water and Salt Balance for Cropping Systems in Lower Colorado River Irrigation Districts

Final Report ST-2020-7107

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Peer Review

Bureau of Reclamation
Research and Development Office
Science and Technology Program

Final Report ST-2020-7107

Quantitative Assessments of Water and Salt Balance for Cropping Systems in Lower Colorado River Irrigation Districts

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Executive Summary

Efficient water management remains a high priority in the southwestern United States. In these efforts, stakeholders use irrigation water wisely, but there is a fine line between conserving water and risking soil health and reducing crop yield due to salts in the agricultural water and salts in the soils across typical crop production systems and rotations or after a period of fallowing. If there is no clear understanding on water and salt balances during a growing season, the risks are that either too much water will be used (over irrigation) or not enough water will be used (excess salt within soils) leading to reduced crop yield. Long term, this poses a risk for both soil health and available water within the Lower Colorado River Basin. Developing ways to have a reliable estimate of the quantity of water needed for effective salt leaching to keep soils and crops healthy is critical to Reclamation's mission of managing, developing, and protecting water and related resources in an environmentally and economically sound matter.

Researchers used electromagnetic surveys (EM38) augmented with soil samples to estimate spatial and depth-related salinity distributions. Water measurement flumes and data loggers were used to measure inflow hydrographs during irrigation events and quantify the water delivered. Water depth sensors and recorders were used to measure infiltrations in transects across the field from the inlet end to the downstream boundary during irrigation events. Eddy-Covariance (ECV) and large aperture scintillometer (LAS) instrumentation and towers were used to track water evaporation losses from fields during irrigation events. The use data loggers with sensors in these transects capture the effects of infiltration opportunity time, which is the greatest on the inlet end of a field and least near the downstream border for the level basin and impounded furrow systems typically utilized in Yuma. Researchers also collected soil samples on key time intervals to corroborate data collected in near real-time with data loggers and sensors. One-dimensional (basins) and two-dimensional (furrow) models will be used to describe water and salt transport processes. These models include one-and two-dimensional Richard's and advection-dispersion equations to characterize water and salt transport processes. The specialized modern instrumentation for this research was provided by USDA.

Measurement data from over a dozen crops and cropping patterns – some new and some replicating past measurements was used to identify any anomalies. Measurements include crop ET, irrigation efficiencies, and soil salinity loading and leaching. Systems evaluated include pre-irrigation scenarios, and crops such as iceberg lettuce, spinach, durum wheat, Sudan grass, barley, romaine Lettuce, leaf lettuce, cantaloupe, watermelon, cauliflower, broccoli, and cotton.

Crop water use data for modern production systems was needed. In many cases, figures show slightly higher crop water use (10-20%) as compared to a half-century ago, yet crop yields have in some cases doubled. Researchers found most vegetable crops irrigation efficiencies are so high (80-100%) that salt leaching does not need to take place. Except Sudan grass, the normal rotation crops are also salt loading or only slightly leaching events. Data shows, with the exception of a Sudan grass rotation, the fall pre-irrigation is necessary to leach the salts that have accumulated in the root zone during the cropping season. This valuable data will enable agriculture industry be even more efficient in their irrigation practices and conserve water without reducing crop yield.

Appendix A

Final Report from The University of Arizona, Yuma Center of Excellence for Desert Agriculture

THE UNIVERSITY OF ARIZONA
Yuma Center of Excellence for Desert Agriculture

FINAL PERFORMANCE REPORT

July 14, 2020

United States Department of the Interior Bureau of Reclamation

Project Title	**Quantitative Assessments of Water and Salt Balance for Cropping Systems in Lower Colorado River Irrigation Districts**
Issuing Office	U.S. Bureau of Reclamation, Lower Colorado Region
Project Manager	Paul Brierley Yuma Center of Excellence for Desert Agriculture University of Arizona
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Project Summary

Water and salt management are vital to agricultural sustainability in Yuma, Arizona, which is located within the Lower Colorado River Basin. Efficient water management and maximum productivity remain high priorities in the southwestern United States during an extended drought. Irrigation water contains salts and because the shallow ground water in the valleys, which fluxes up through the fine textured soil by capillarity, also contains salts, some level of excess irrigation (beyond consumptive use) must be applied to leach salts below the crop root zone. Effective leaching is especially important in the Lower Colorado River Basin because many of the crops produced are sensitive to salinity (Sanchez and Silvertooth, 1996). Without a quantitative understanding of water and salt balances during a full-year cropping season, the risks are that either too much water will be used (over-irrigation) or not enough water will be used (causing excess salt buildup within soils and reduced crop yield). In the long term, these pose risks for both soil health and water availability within the Lower Colorado River Basin.

This report provides a final summary of output for the water and salt management project sponsored in part by the United States Bureau of Reclamation Science & Technology program. During the ensuing years since the project started in 2016, additional funding and research partners joined the larger project managed by the University of Arizona Yuma Center of Excellence for Desert Agriculture, leading to additional equipment and manpower being

deployed and thus the magnitude of data collected and analyzed was much greater than initially planned. These funding and research partners included the Yuma County Agriculture Water Coalition (made up of irrigation districts in the Yuma area), the USDA Arid Land Agricultural Research Center (ALARC), the USDA/ADA Specialty Crop Block Grant Program, Arizona Grain Research and Promotion Council, Arizona Iceberg Lettuce Research Council, Arizona Citrus Research Council, NASA/JPL, and the University of Arizona's Technology and Research Initiative Fund (TRIF) Water, Environmental, and Energy Solutions (WEES) initiative and Agricultural Experiment Station Strategic Research Investment Fund, and. Dr. Charles Sanchez of the University of Arizona Department of Environmental Science and Dr. Andrew French of the USDA-ARS ALARC were the primary researchers.

This multi-year project undertook quantitative assessments of water and salt balance for cropping systems in the Lower Colorado River irrigation districts across typical Yuma crop production systems and rotations. The main goals and objectives included:

1. Precise measurement of water application and salinity movement during entire cropping seasons;
2. Conduct soil sampling in concurrence with data logging instrumentation readings;
3. Compile data for cropping seasons;
4. Perform data analysis, dissemination and reporting;
5. Develop a mobile irrigation management App incorporating the data from goals 1-4.

Goals 1-4 were accomplished at a much higher level than originally envisioned, thanks to extra research and funding partners, and extra equipment and personnel. For example, we expanded our Eddy Covariance devices from two to eight. The findings from goals 1-4 have created a unique database incorporating updated crop water use (ET) coefficients and corresponding soil salinity balance, across the full seasonal rotation of crops in the Yuma area. This data can be used to evaluate irrigation practices and crop rotation or summer fallow, as well as their impacts on soil salinity levels. The data is being utilized by the irrigation/salinity management App under final development, and will be made available to researchers, USBR and its stakeholders via both a web interface at the YCEDA website and the AmeriFlux Network. AmeriFlux is a network of PI-managed sites measuring ecosystem CO2, water, and energy fluxes in North, Central and South America. It was established to connect research on field sites representing major climate and ecological biomes, including tundra, grasslands, savanna, crops, and conifer, deciduous, and tropical forest.

Goal 5 is not as far along as envisioned, but is progressing nicely none-the-less and is well on the way to completion. Efforts to adapt current irrigation management tools such as AZSCHED to accommodate our unique database of crop water use and soil salinity as well as satellite imaging were not successful, so we contracted with the University of Arizona Communication and Cyber Technology (CCT) team to develop a mobile App that will be more full-featured than originally envisioned. This will tie nicely to their efforts to connect our database to the AmeriFlux research network and give a web interface to the data from the YCEDA website. Delays associated with COVID-19 have slowed development and field testing of the App, but through weekly Zoom meetings we have continued progress toward a final product.

Summary of Activities

This report summarizes methods used and examples of the types of data collected. A summary of sites where data has been collected over a four-year period is provided in Tables 1 through 4. Examples of instrumentation and data collected are shown in Figures 1 through 20. An example utilizing weather-based data and satellite imagery for forecasting irrigation needs in wheat is shown in Figures 21 and 22. These data and the approach outlined for wheat have been utilized to develop the irrigation and salinity management Mobile App.

Eddy Covariance Systems

Estimating water used by crops was accomplished by measuring evapotranspiration (ET) with an instrument system known as Eddy Covariance (ECV) (Figure 1). ECV obtains ET by measuring incoming and outgoing energy fluxes over the cropped landscape. The ECV measures four energy flux components- net radiation (Rn), ground heat flux (G), sensible heat flux (H), and latent heat flux (LE). Rn represents absorbed solar and infrared radiation, G is heat transported into the soil, H is turbulent heat above the crop due to air temperature gradients, and LE is latent heat energy due to ET. While ET can be estimated from just the LE component, accurate estimates require collecting all four components. ECV data values are reported in energy flux units (W/m^2), with water-specific quantities also reported as depths over time (e.g. mm/day).

Each ECV system requires sensors, one or more data loggers, power supplies, and mechanical supports. Sensors measure air temperature, humidity, wind speed, wind direction, water vapor concentration, CO2 concentration, soil temperatures, soil moisture, solar and infrared radiation, all at sample rates up to 20 Hz. Data loggers collect, analyze, and store analog and digital signals from the sensors; in some cases, they are connected to a cellphone modem for transmitting synopses of data and system health information to one of our home offices. Power supplies consist of 12V batteries, voltage regulators, grounding rods, and solar panels. The mechanical supports include tripods, masts, lightning rods, anchors, and guy wires to ensure the sensors, loggers, and power supplies remain accurately aligned in all weather conditions. These are large, expensive scientific devices. Through additional external partnerships and funding we have obtained additional ECV systems. We used two ECV systems in 2016-2017, seven in 2017-2018, and eight in 2018-2019 and 2019-2020 allowing much more data collection, such as multiple replications of crops and a wider variety of crops. A summary of all deployments to date are shown in Tables 1, 2, 3, and 4. Selected data from the ECV systems are shown in Figures 2 through 8. As of the writing of this report water application efficiencies, expressed as a basis of ET relative to water applied, for full season vegetables range from 80 to over 100%.

<u>Large Aperture Scintillometry</u>

As part of our effort to scale up ET measurements we obtained a new Large Aperature Scintillometer (LAS) that was deployed in 2017-2018 (Figure 9). LAS data is an established methodology for accurately measuring sensible heat flux over 1-5 km distances, a scale range greatly exceeding typical distances observed for H flux data collected with ECV systems, 100 – 200m typical for deployment at 2m heights above crops.   However, LAS approximates ET using residuals in energy balance calculations. Latent heat is what is not accounted for in other measurements or estimates. During 2017-2018 we used LAS and ECV systems across the four fields monitored by LAS. We also used the LAS systems during the summer-fall to calibrate a new space-based satellite sensor. These LAS systems were re-located to citrus in May 2018.

<u>Satellite Imagery</u>

As part of our on-going collboration with NASA-JPL we are obtaining imagery from the Sentinel 2a/2b and Landsat 8 satellites (Figure 10). More recently since the last report we have been using data from the ECOSTRESS and VENuS missions which provides imagery every other day. An example of the normalized difference vegetation index (NDVI), where NDVI=(NIR-Red)/(NIR+Red), generated from Sentinel data for wheat is shown in Figure 11.

<u>Unmanned Aerial Vehicle (UAV) and Manned-Aircraft Sensors</u>

Some of the satellite imagery had to be downscaled mathematically to get resolutions useful to us in agricultural fields. We utilized UAV and manned aircraft sensors to validate algorithms for down-scaled satellite imagery. With the assistance of students from the UA-Yuma Systems Engineering Senior Design program, we have a functional UAV thermal imaging platform (Figues 12 and 13).

<u>Salinity Monitoring</u>

Salinity was monitored at multiple scales. At the point scale, sensors and data loggers measured soil moisture and bulk conductance. On a larger scale we used EM-38 electromagnetic conductance (EM-38) surveys. Both were ground-truthed with soil sampling.

Fields were surveyed using a Geonics Dual-dipole EM38 ground conductivity meter (Geonics Instruments, Ltd., Ontario, Canada) mounted on a mobilized assessment platform with an integrated sub-meter accuracy GPS system, with all survey and GPS position data logged into an on-board portable computer.   In baseline surveys, EM38 signal data was collected once every two seconds within transects spaced 10 to 20 meters apart, typically generating from 1000 to 5000 survey positions per field (transect spacing and the total number of survey positions depended on the field size). These data were analyzed using the ESAP software package and the spatial response surface sampling algorithm in the ESAP-RSSD program to determine the samples' number and location. At each sampling location, a single 1.2 m soil core was extracted using automated soil auguring equipment and split into four depth-specific 30 cm samples. The soil samples collected from each core were bagged, labeled, and subsequently used for the chemical and physical analyses. Subsets of all soil samples were oven-dried to determine soil moisture content. The remainder of the soil samples were air-dried prior to laboratory analysis. After obtaining saturated paste extracts from all soil samples, we determined electrical conductivity (ECe), which is used as a calibrated measure of salinity, and cation/anion quantities for Ca^{+2}, Mg^{+2}, Na^{+}, K+, Cl^{-}, $SO4^{-2}$, $NO3^{-}$ and CO3 by ion chromatography.

Perhaps the most common crop rotation in the Yuma area is fresh produce followed by wheat. Full season produce is typically established with solid set sprinklers and irrigated by furrow after stand establishment. Wheat might be established by planting into moisture, by sprinkler irrigation, or by basin irrigation. After stand establishment, wheat is irrigated in basins. The data presented in Figure 14 show the most common situation for loam or heavier textured soils. On this site in the Yuma Irrigation District (YID), both the lettuce and wheat cropping systems were net salt loading. The residual salt concentrations in the soil profile following wheat would exceed the salt tolerance threshold for lettuce and other vegetable crops. Using steady state mass balance, the continued production of lettuce with Colorado River water would require a leaching fraction of 23%. This was not achieved during the produce-wheat production cycle, so a pre-irrigation prior to planting produce in the fall would be required for salt management and sustainability. Many of the salinity ions are reactive in the soil, but Cl is not and often a better measure of leaching fraction. The pre-irrigation shows a pronounced reduction in Cl concentration. Another way of illustrating the data is with the field-wide salinity maps that we constructed from the EM-38 surveys. The data presented in Figure 15 show the field-wide salt distribution in the soil profile before and after wheat production in a field in the Bard Water District (BWD).

Another concern is sodium (Na). Beyond the osmotic stresses the Na ion causes along with other salinity ions, Na can adversely affect soil structure. As the proportion of Na in soils increases relative to divalent cations, soils tend to deflocculate, become impermeable to water and air, which induces water puddling. This phenomenon is called dispersion. The sodium adsorption ratio (SAR) of the saturated paste extract is used to monitor existing or emerging Na issues, and is defined as follows:

$$SAR_e=(Na)/(Ca+Mg)0.5$$

In these studies, we calculated SAR from the cations measured in the saturated paste extracts. Overall, the sodium hazard was not increased over the cropping rotation.

Less typical are produce-wheat rotations on lighter textured soils. (Figure 16). This loamy sand within the Yuma County Water Users Association (YCWUA) is not typical of the soils used for produce production in the irrigation districts in the former flood plains of the Gila and Colorado River valleys. On these lighter soils, leaching is achieved during the wheat-produce cropping season due to generally lower irrigation application efficiencies in-season, resulting in larger leaching fractions. However, as noted this is not the typical cropping scenario.

Less common than the produce-wheat rotation is the produce-Sudan grass rotation. Because of friction during irrigation, water advance down the field is obstructed and application efficiencies in the Sudan-grass cropping system are not as high as with wheat and sufficient leaching is achieved (Figure 17). Thus, a pre-irrigation for salt balance would not typically be required in this system. However, there are other beneficial uses of pre-irrigation including the facilitation of residue decomposition and land preparation.

Sprinklers irrigate many short season crops, such as spring mix and baby leaf spinach, all season. Data for soil salinity before and after spinach are shown in Figure 18. Seasonal irrigation efficiencies (ETc/Water Applied) ranged from 66 to 99% (Table 5). Interestingly, for sites where water application efficiencies exceeded 80% (YID 17e, YID 18a, and YID 19a), total salt (ECe) and chloride (Cl) of the saturated paste extracts increased in the soil surface. The threshold tolerance of salinity for spinach is estimated at 2 dS/m and using steady state assumption and the average salinity of Colorado River water, a leaching requirement of 12% is required to maintain salt balance. However, the most sensitive crop in the rotation, which is lettuce, often dictates salt management, and steady state leaching would be 23%. As noted above, many growers delay the required leaching needed for salt management into a pre-irrigation, which enables better management of N fertilizer and diseases within the crop production cycle. With the exception of the YCWUA 18A site, we observed no changes in SAR over the spinach season. In the YCWUA, SARe decreased, reflecting a leaching of Na.

A final situation we wish to address in this discusion is summer fallow. At present, this is most relevant to the Bard Water District (BWD), which participates in a program funded by the Los Angeles Metropolitan Water Distirct (LAMWD). The water saved by foregoing a spring or summer crop within BWD is transfereed to the LAMWD. The data presented in Figure 19 show total salts (ECe) before summer fallow, after summer fallow, and after a pre-irrigation prior to produce planting. Because of capillary rise driven by evaporation, there is significant salt accumulation in the soil rooting zone following summer fallowing. Thus, pre-irrigation is required following summer fallowing to reduce soil salinity below the tolerances of the vegetable crops commonly grown. This reduces the expected water savings that can be achieved from fallowing programs. The quantitative data achieved through this project will be directly used by stakeholders to examine and perhaps change their irrigation practices.

The above discusion focuses on steady state leaching. However, steady state leaching may be too conservative due to the reactive nature of many soil salinity ions. Therefore, we are currently working on calibrating a transient model which accounts for major ion chemistry. We hope to share results from this model development in the future.

Water Balance

Along with atmospheric water measurements we tracked water applied. For sprinkler irrigation systems we used in-line meters (i.e. ESSFIFLO Ultrasonic Flowmeter) and pressure data logging instruments (i.e. Pollardwater Pres/Temp logger). For flood irrigation we used flumes with depth sensors and data loggers at the ditch outlet to create in-flow hydrographs, and we used water depth sensors (Troll 100 water depth sensor and logger) to create water depth profiles in transects along the irrigation run (inlet to downstream border). Data were downloaded and processed after each irrigation event. While it would be overwhelming to show each instrumentation layout utilized, an example in-flow hydrograph and water depth profile for one surface irrigation event is shown in Figure 20.

Testing Satellite Imagery Ground-truthed with Durum Wheat

An example of how weather-based information and satellite data will be used for crops in the lower Colorado River region is shown for wheat in Figures 21 and 22. These data clearly show that remote sensing of NDVI and modeled K_{cb} accurately estimated K_c and crop ET during mid-season through senescence. (Kcb is basal crops coefficient and Kc is crop coefficient for ET. Kcb+Ke=Kc where Ke is evaporation form the soils.) However, NDVI-based estimation performed less well during early season (<60 days after planting), when observed ET_c was highly variable due to frequent rain and irrigation at low crop cover. Mid-season K_c values observed for the seven wheat fields were from 0.92 to 1.2, and end of season K_c values ranged from about 0.20 to 0.40, in close agreement to values reported elsewhere. Seasonal Vegetation Index (VI)-based transpiration and ET_c values ranged from 467 to 618 mm, closely agreeing with seasonal ECV data, which ranged 499 to 684 mm. Overall, these data show that augmenting weather-based data and crop coefficients with satellite data will provide a powerful tool for irrigation management in the lower Colorado River region.

Data Accessibility

The University of Arizona's Communication and Cyber Technology (CCT) team is contracted and working with us to provide access to the unique database assembled from this project in three ways: sharing the data with the AmeriFlux research network, making it accessible via a web interface on the YCEDA website, and through a fully functional mobile App that will integrate real-time weather data from the AZMET network and satellite imagery to track and make predictive recommendations for irrigation, based on soil type and weather conditions. This will allow producers to fine-tune irrigation timing and quantity to provide for actual crop water needs while managing salinity levels for productivity and sustainability, without the need for expensive and cumbersome field measurement devices that were utilized in this project.

The mobile application developed with the quantitative data will have practical use to assist USBR and stakeholders to understand where and for what purpose water is diverted and what the consequences are of over and under irrigating. These apps would be useful anywhere that additional water is used to leach salts in the soil.

The mobile App's cotton module has been developed with the help of data models from Dr. Doug Hunsaker at the USDA-ARS Arid Land Agricultural Research Center. Soil salinity functions, satellite imagery and a lettuce module are currently being added to the App, and a user survey is underway to make sure that the user interface is designed for maximum utilization. Once the App is user-tested, other crop modules will be added to it. Once the mobile application is sufficiently robust and user friendly, we will begin workshops to train producers and partners in the use of this technology. If UA and USBR provide our customers/stakeholders with valuable decision-making data and tools such as this, agriculture will be even more efficient in their irrigation practices to conserve water without reducing their crop yield, and fallowing program water-saving projections will be much more accurate.

Conclusion

During these past four years we have amassed measurement data from over a dozen crops and cropping patterns – some new and some replicating past measurements to identify any anomalies. Measurements include crop ET, irrigation efficiencies, and soil salinity loading and leaching. Systems evaluated include pre-irrigation scenarios, and crops such as iceberg lettuce, spinach, durum wheat, Sudan grass, barley, romaine Lettuce, leaf lettuce, cantaloupe (furrow, and drip w/ and w/out plastic mulching), watermelon, cauliflower, broccoli, and cotton.

Crop water use data for modern production systems was sorely needed. In many cases our figures show slightly higher crop water use (on the order of 10-20%) as compared to a half-century ago, but at the same time crop yields have in some cases doubled. Having accurate up-to-date crop water use numbers will assist in all types of planning for this precious resource.

We found that in many cases and for most vegetable crops, irrigation efficiencies are so high (80-100%) that the necessary salt leaching does not take place. With the exception of Sudan grass, the normal rotation crops are also salt loading or only slightly leaching events. The data shows that with the exception of a Sudan grass rotation, the fall pre-irrigation is necessary to leach the salts that have accumulated in the root zone during the cropping season.

This project has shown that augmenting weather-based data and crop coefficients with satellite data will provide a powerful tool for irrigation management in the lower Colorado River region. As our water and salinity management APP becomes fully developed, it will be made available to growers and researchers, as well as the USBR, USDA and other stakeholders.

Table 1. Field sites used to collect water and salt balance data in 2016-2017.

Station Label	Field	Crop	Planting Dates	Deployment Dates	Station Removal	Harvest Dates
ALARC 1	YID 16-1a	Pre-irrigation	NA	Aug 12, 2016	Aug 24, 2016	NA
ALARC 2	YCWUA 16-1a	Pre-irrigation	NA	Aug 25, 2016	Sep 14, 2016	NA
ALARC1	YID 16-1b	Romaine	Sep 26, 2016	Sep 26, 2016	Nov 28, 2016	Nov 29, 2016
ALARC 2	YCWUA 16-1b	Leaf	Oct 2, 2016	Oct 3, 2016	Dec 20, 2016	Dec 21, 2016
ALARC 1	YID 16-17-2	Wheat	Dec 13, 2016	Dec 14, 2016	May 5, 2017	May 6, 2017
ALARC 2	YCWUA 16-17-2	Wheat	Jan 11, 2017	Jan. 12, 2017	Jun 1, 2017	Jun 2, 2017
UA 1	BWD 17b	Sudan	Apr 8, 2017	Apr 9 (S) [a]; Jun 23, 2017	May 23 (S); Jul 7, 2017	May 24, 2017 & Jul 9, 2017
UA 2	BWD 17c	Fallow	NA	Apr 7, 2017	Jul 12, 2017	NA

ALARC 1 and 2 are USDA/ARS ECV stations; UA 1, 2, and 3 are University of Arizona/YCEDA ECV stations; JPL 1 and 2 are NASA/Jet Propulsion Lab ECV stations.

[a]Station removed from south-end of field (S) for cutting and re-deployed mid-field for inter-calibration study.

Table 2. Field sites used to collect water and salt balance data in 2017-2018.

Station Label	Field	Crop	Planting Dates	Deployment Dates	Station Removal	Harvest Dates
JPL 1	YID 17a	Romaine	Sep 11, 2017	Sep 13, 2017	Nov 14, 2017	Nov 13, 2017
JPL 2	YID 17b	Romaine	Sep 21, 2017	Sep 21, 2017	Dec 04, 2017	Dec 04, 2017
ALARC 1	YID 17c	Iceberg	Sep 24, 2017	Sep 24, 2017	Dec 05, 2017	Nov 27, 2017
ALARC 2	YID 17d	Iceberg	Oct 06, 2017	Oct 06, 2017	Dec 28, 2017	Jan 03, 2018
UA 1	YID 17e	Spinach	Oct 23, 2017	Oct 24, 2017	Nov 28, 2017	Nov 27, 2017
UA 2	YCWUA 17-18a	Iceberg	Nov 11, 2017	Nov 12, 2017	Feb 16, 2018	Feb 19, 2018
UA 3	YCWUA 17-18b	Iceberg	Nov 18, 2017	Nov 19, 2017	Mar 05, 2018	Mar 05, 2018
UA 1	YID 17f	Spinach	Dec 08, 2017	Dec 08, 2017	Jan 18, 2018	Jan 19, 2018
JPL 1	YID 17-18a	Wheat	Dec 15, 2017	Dec 18, 2017	Jun 01, 2018	Jun 07, 2018
ALARC 1	YID 17-18b	Wheat	Jan 05, 2018	Jan 05,2018	May 31, 2018	Jun 07, 2018
JPL 2	YID 17-18c	Wheat	Jan 06, 2018	Jan 08, 2018	May 31, 2018	Jun 07, 2018
ALARC 2	YID 17-18d	Wheat	Jan 24, 2018	Jan 29, 2018	June 01, 2018	Jun 07, 2018
UA 1	YCWUA 18a	Spinach	Feb 02, 2018	Feb 05, 2018	Mar 19, 2018	Mar 21, 2018
UA 2	YID 18a	Spinach	Mar 09, 2018	Mar 09, 2018	April 06, 2018	Apr 08, 2018
UA 3	YCWUA 17-18b	Sudan	Mar 09, 2018	Mar 09, 2018	Jun 27, 2018	Jul 02, 2018
UA 1	YCWUA 17-18b	Sudan	Mar 22, 2018	Mar 23, 2018	Jul 02, 2018	Jul 10, 2018

Table 3. Field sites used to collect water and salt balance data in 2018-2019 season.

Station Label	Field	Crop	Deployment Dates	ECV Removal
UA 2	SW 18	Cantaloupes	08/22/2018	10/29/2018
UA 1	BWD 18a	Cauliflower	09/07/2018	11/29/2018
UA 3	BWD 18b	Broccoli	09/07/2018	11/14/2018
Alarc 1	YID 18a	Cauliflower	09/18/2018	12/12/2018
JPL 1	YCWUA 18a	Iceberg	09/21/2018	12/10/2018
JPL 2	YID 18b	Iceberg	10/08/2018	01/04/2019
Alarc 2	WMIDD 18-19	Broccoli	11/27/2018	03/28/2019
UA 2	YID 18-19	Spring Mix	11/29/2018	01/29/2019
UA 1	MSIDD 19	Wheat	12/18/2018	05/24/2019
UA 3	AKC 19a	Barley	01/14/2019	05/29/2019
UA 2	BWD 19a	Spring Mix	02/07/2019	03/28/2019
Alarc 1	SW 18	Cantaloupes	02/15/2019	05/16/2019
JPL 2	YCWUA 19a	Cantaloupes	03/06/2019	06/05/2019
Alarc 2	YID 19b	Watermelon	04/10/2019	06/19/2019
JPL 1	BWD 18b	Cotton	02/25/2019	09/03/2019
Tuller	YID 19a	Spinach	03/04/2019	04/09/2019
Tuller	AKC 19b	Cotton	05/03/2019	10/04/2019

Table 4. Field sites initiated in 2019-2020 cropping season.

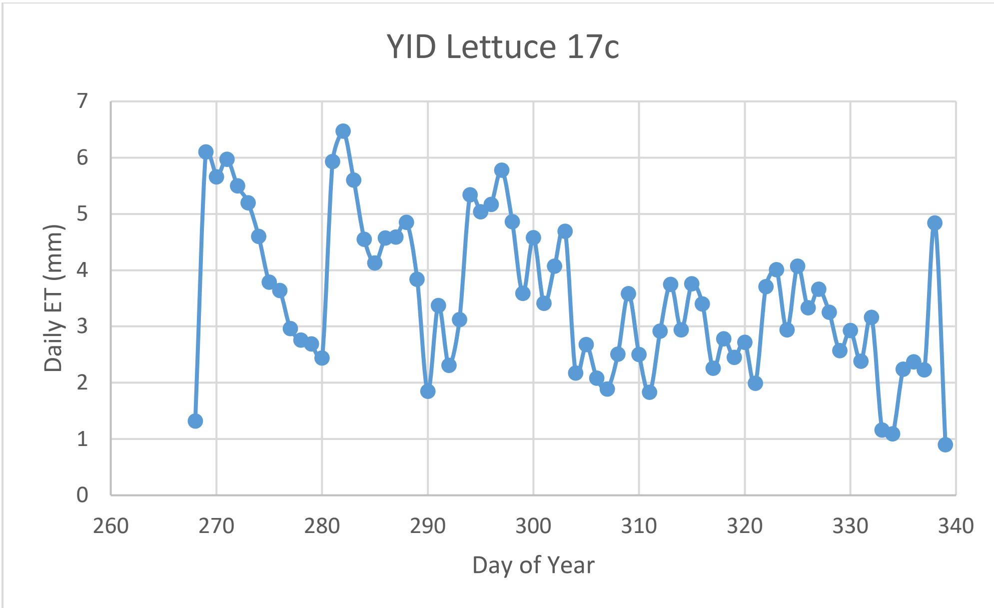
Station Label	Field	Crop	Deployment Dates	ECV Removal
UA 1	Sidewinder 19-20a	Cantaloupe	08/29/2019	11/18/2019
UA 2	BWD 19-20A	Broccoli	09/03/2019	11/25/2019
UA 3	BWD 19-20B	Cauliflower	09/10/2019	12/06/2019
ALARC 2	YCWUA 19-20A	Lettuce	09/23/2019	12/10/2019
ALARC 1	NGIDD 19-20A	Lettuce	10/14/2019	1/17/2020
TULLER	YID 19-20A	Lettuce	11/08/2019	2/182020
UA 1	YID 20A	Spinach	01/04/2020	02/17/2020
UA 2	YID 20B	Spinach	01/07/2020	02/25/2020
ALARC 2	YCWUA 20A	Spring Mix	02/19/2020	03/31/2020
UA 3	YMIDD 20A	Spring Mix	02/28/2020	03/29/2020
TULLER	BWD 20A	Cotton	03/17/2020	TBD
UA 1	YID 20C	Watermelon	04/07/2020	06/12/2020
UA 2	NGIDD 20A	Watermelon	04/13/2020	06/09/2020
UA 3	BWD 20B	Fallow	04/21/2020	07/29/2020
ALARC 1	AK CHIN 20A	Cotton	04/30/2020	TBD
ALARC 2	AK CHIN 20B	Cotton	04/30/2020	TBD

Table 5. Seasonal Water applied, average variation in measurement across gauges, and average salt load of water applied.

Site	Water Applied (mm)	Variation of Water Applied (CV)	Measured ET (mm)	Average Salt Load (kg/ha)
YID 17e	112	0.25	103	788
YID17f	127	0.15	80	897
YCWUA 18a	159	0.20	130	1121
YID 18a	133	0.25	103	937
YID 19a	101	0.33	100	712

Figure 1. Eddy Covariance (ECV) systems used in field sites for studies.

Shown are a typical deployment of three masts: net radiometer (left), eddy covariance main station (middle), and solar power supply (right).



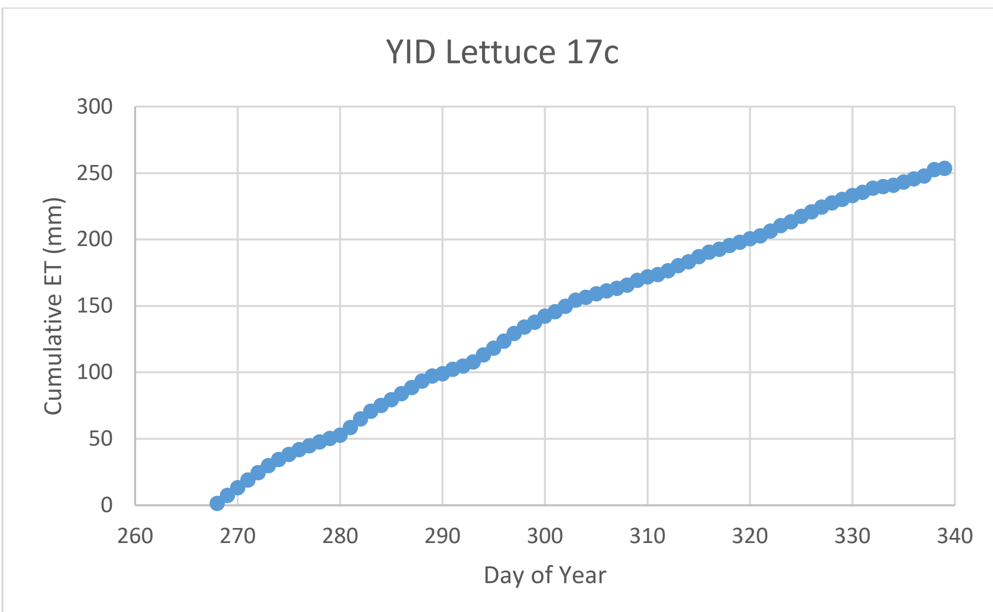
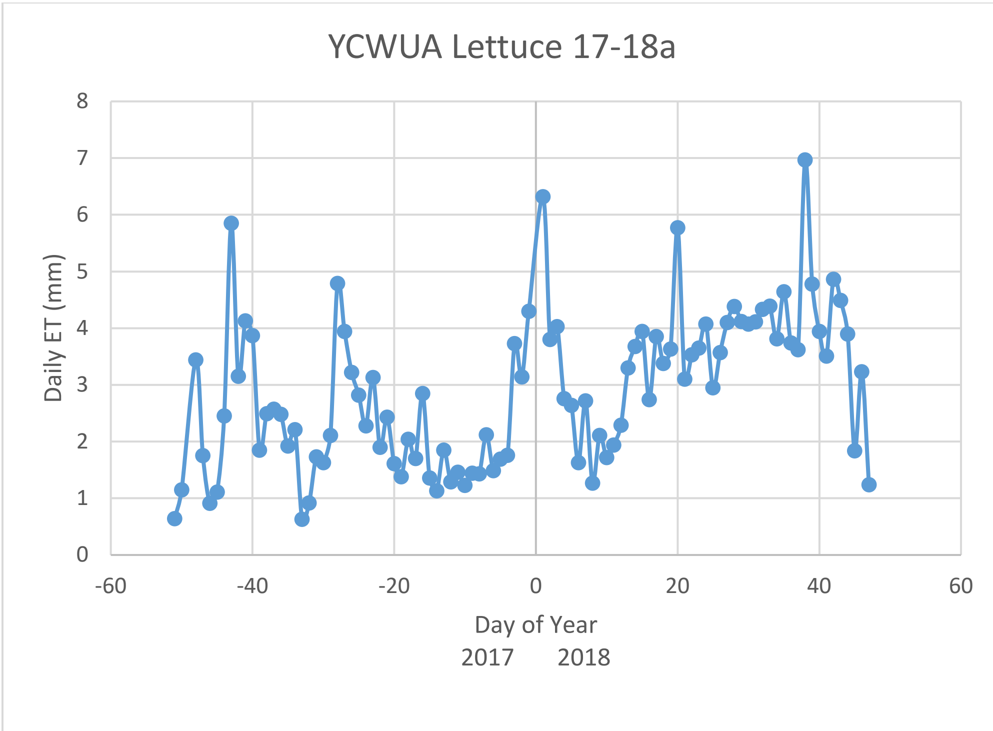


Figure 2. Measured daily and cumulative ET for YID 17c Lettuce.



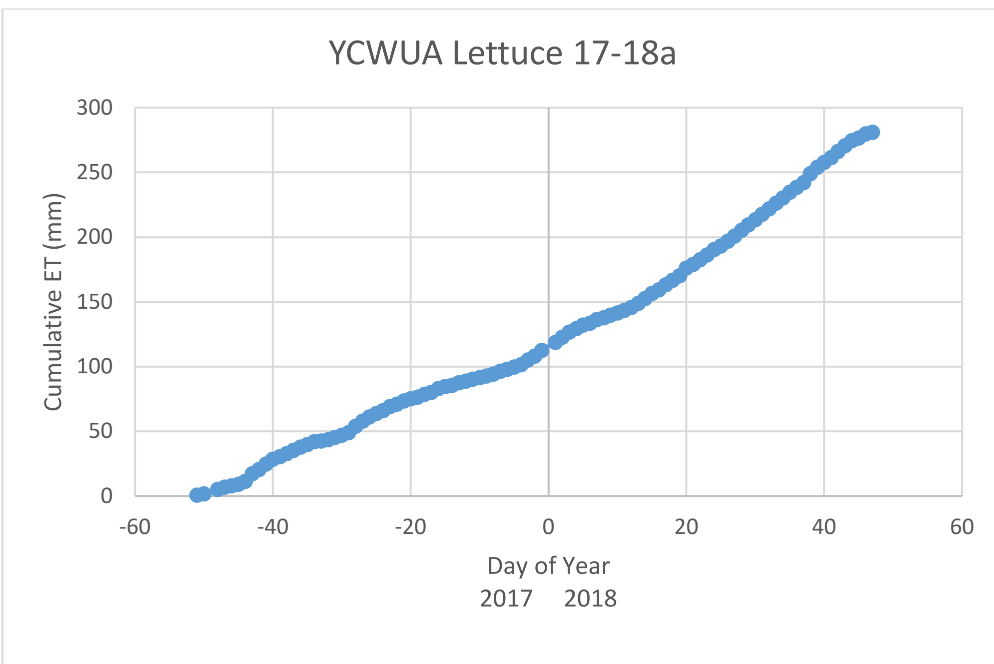
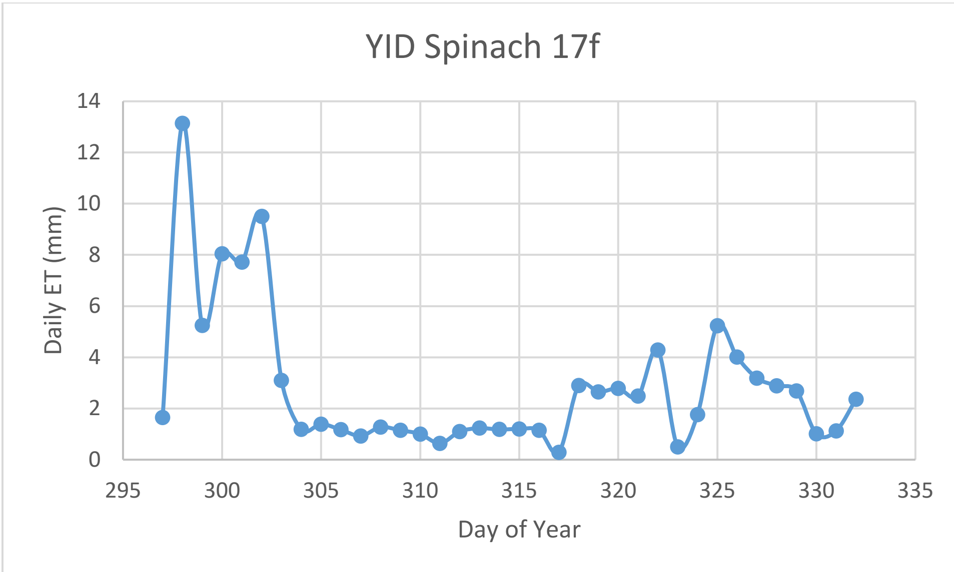


Figure 3. Measured daily and cumulative ET for YCWUA 17-18a Lettuce.



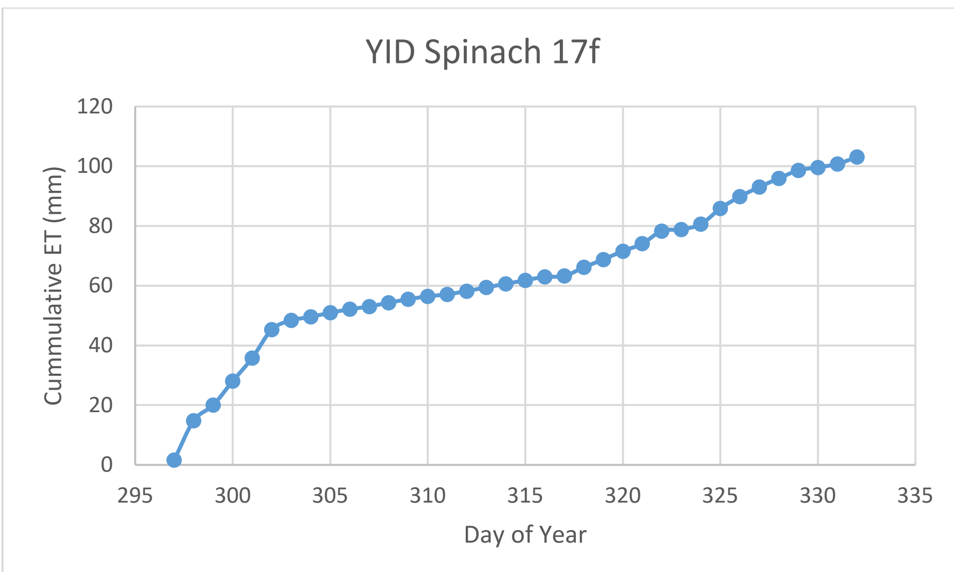
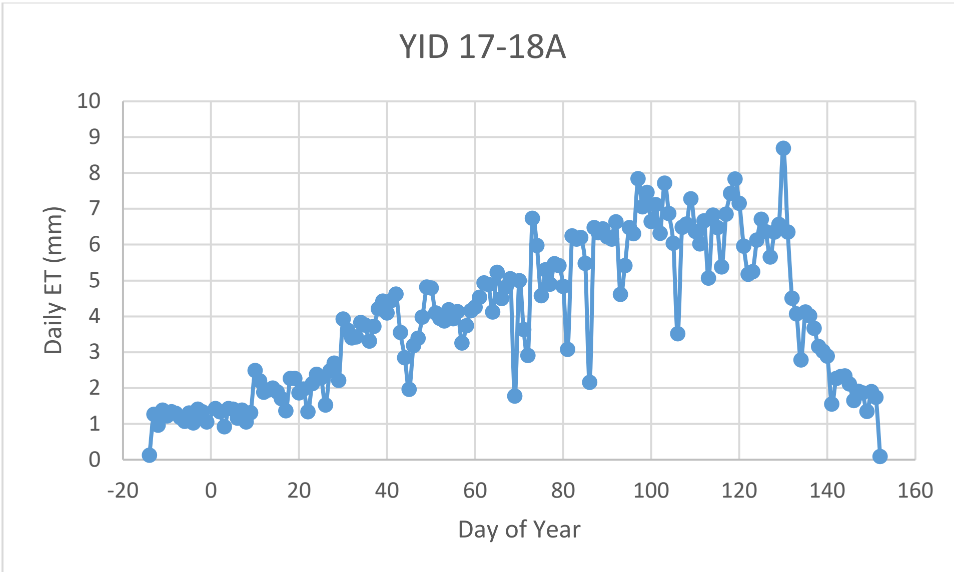


Figure 4. Measured daily and cumulative ET for spinach YID 17f.



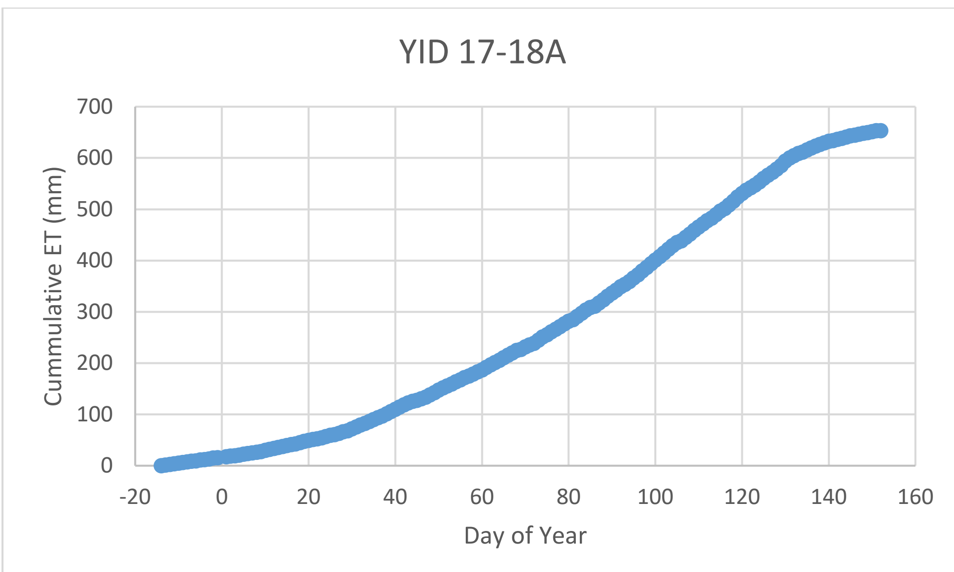
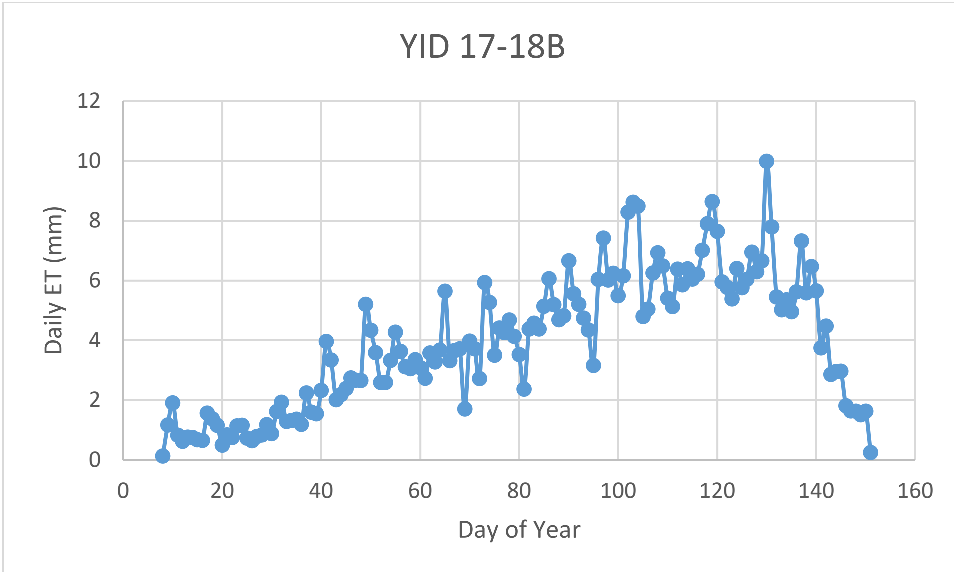


Figure 5. Daily and cumulative ET for Durum wheat in Yuma Irrigation District site A in 2017-2018.



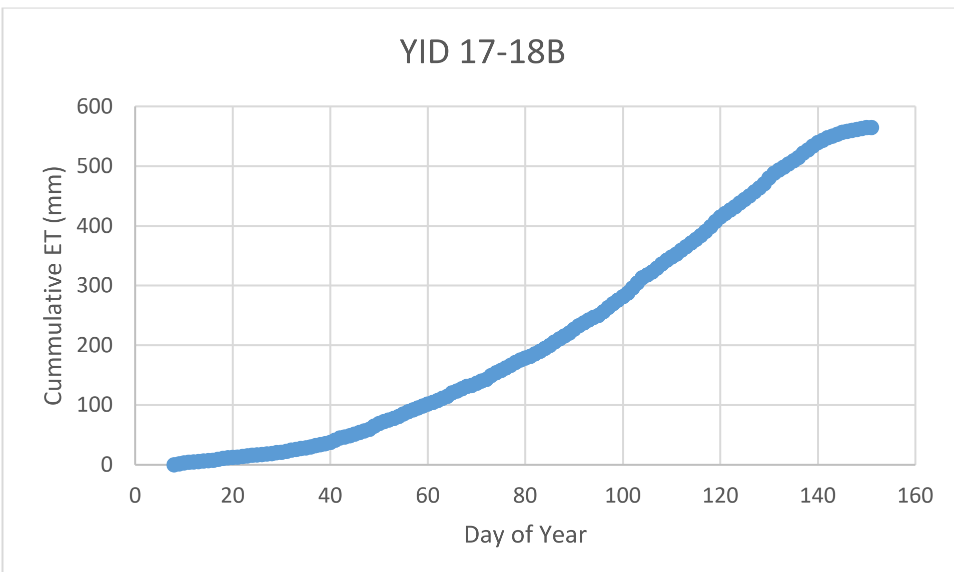
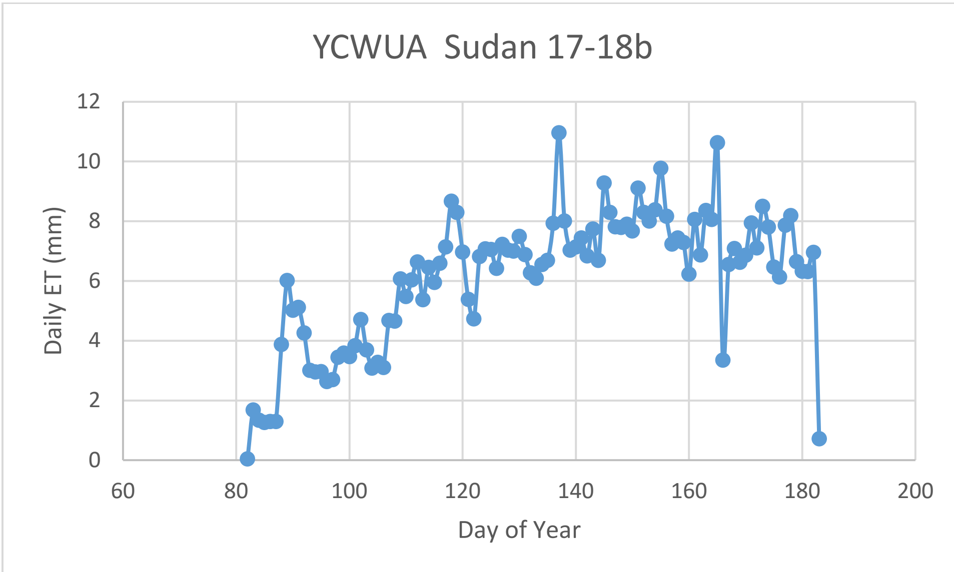


Figure 6. Daily and cumulative ET for Durum wheat in Yuma Irrigation District site B in 2018.



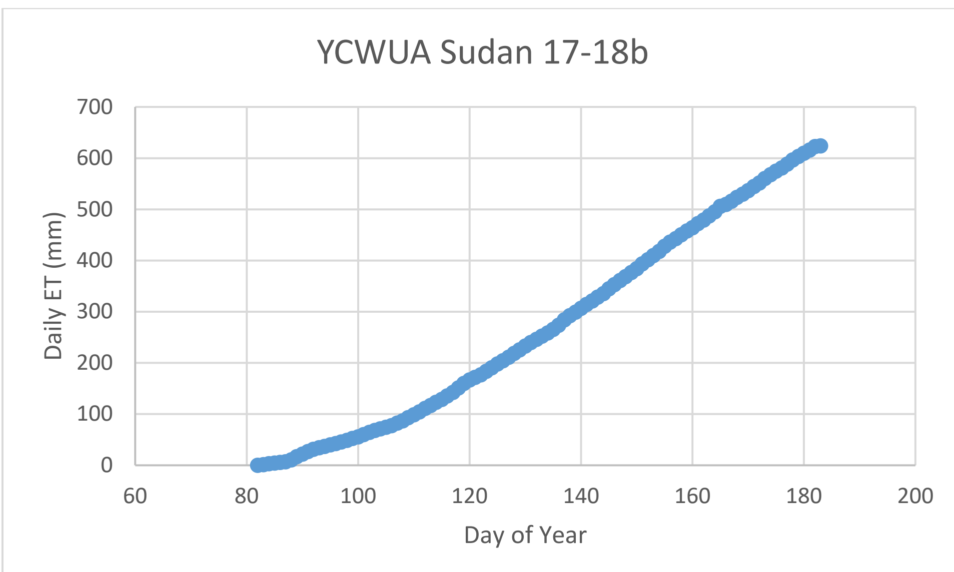


Figure 7. Daily and cumulative ET for Sudan grass in YCWUA 17-18b.

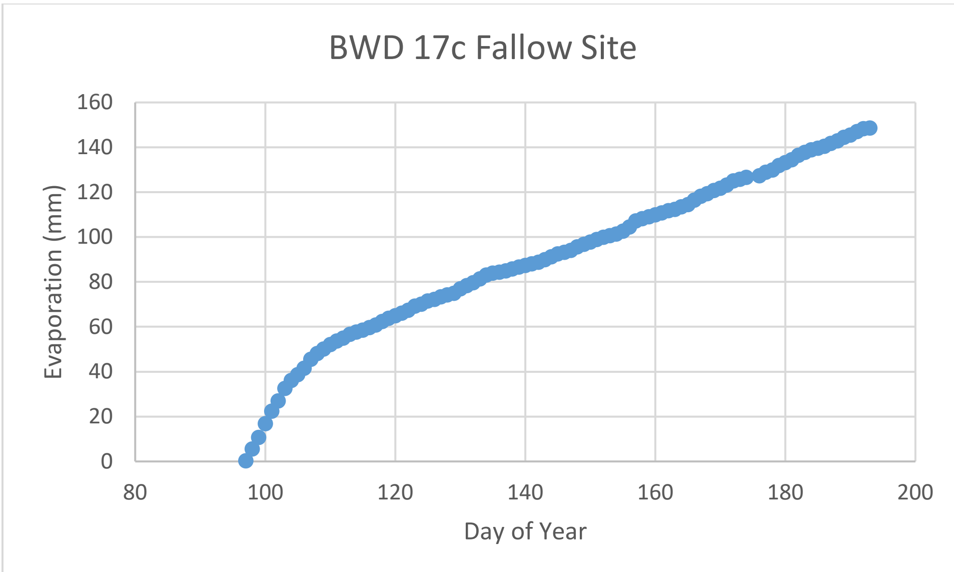


Figure 8. Measured cumulative evaporation from field participating in summer fallow program in BWD 17c.

Figure 9. Large Aperture Scintillometer used on durum wheat sites in 2017-2018. Each setup consists of transmitter-receiver pairs, where a collimated beam of near-infrared light is sent across a transect to detect scintillations due to changes in air refractive index. At the sampling wavelength, the scintillations are a representation of sensible heat flux from the soil and crops below the light path. In May 2018, this unit was relocated to a citrus site.

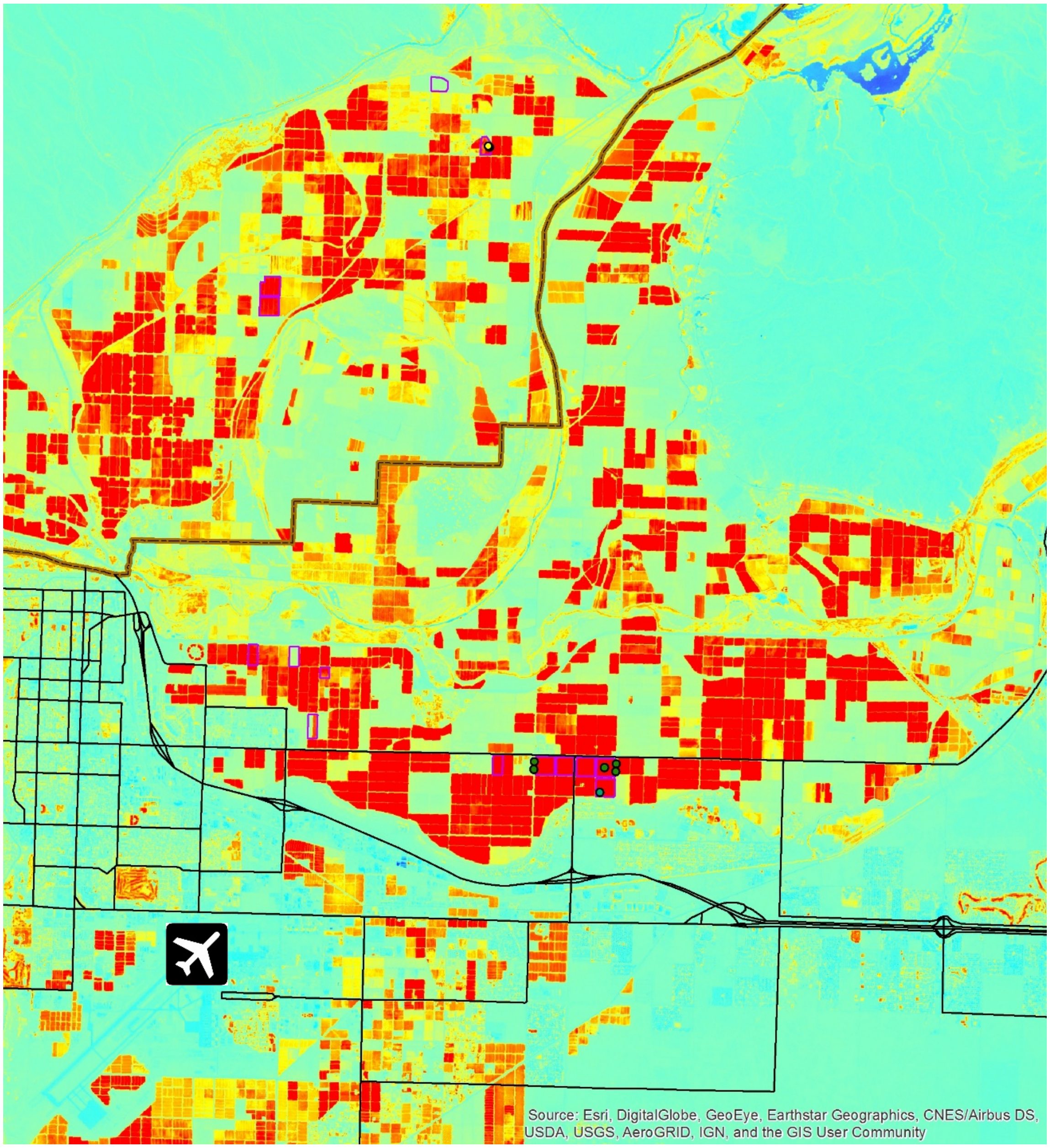


Figure 10. Sentinel 2 satellite image on April 6, 2018 of fields north of Yuma International airport. Red colors indicate dense healthy green vegetation, yellow colors sparse vegetation, and blue-green colors bare soil or man-made surfaces.

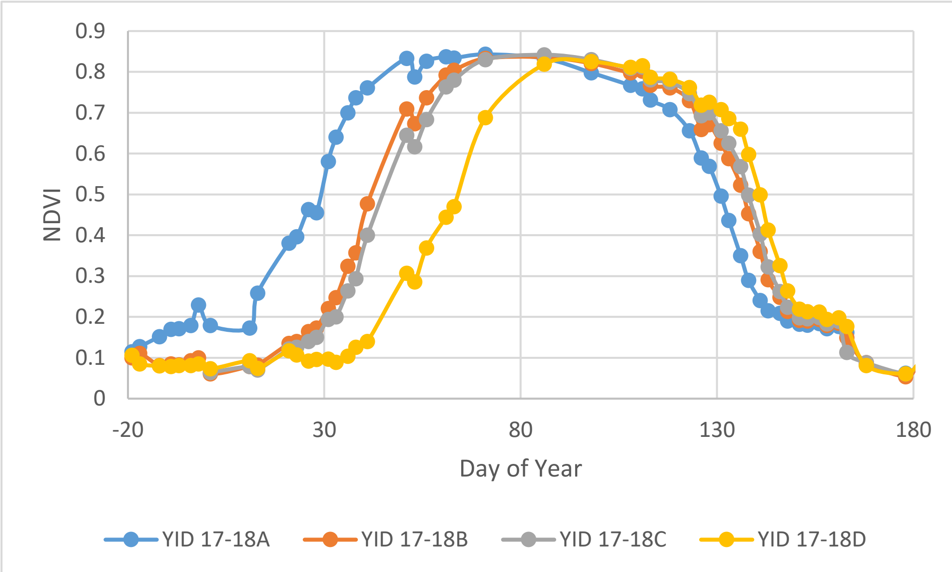


Figure 11. NDVI calculated from satellite imagery from four wheat sites in 2018.

Figure 12. UAV platform for ground-truthing satellite imaging data.

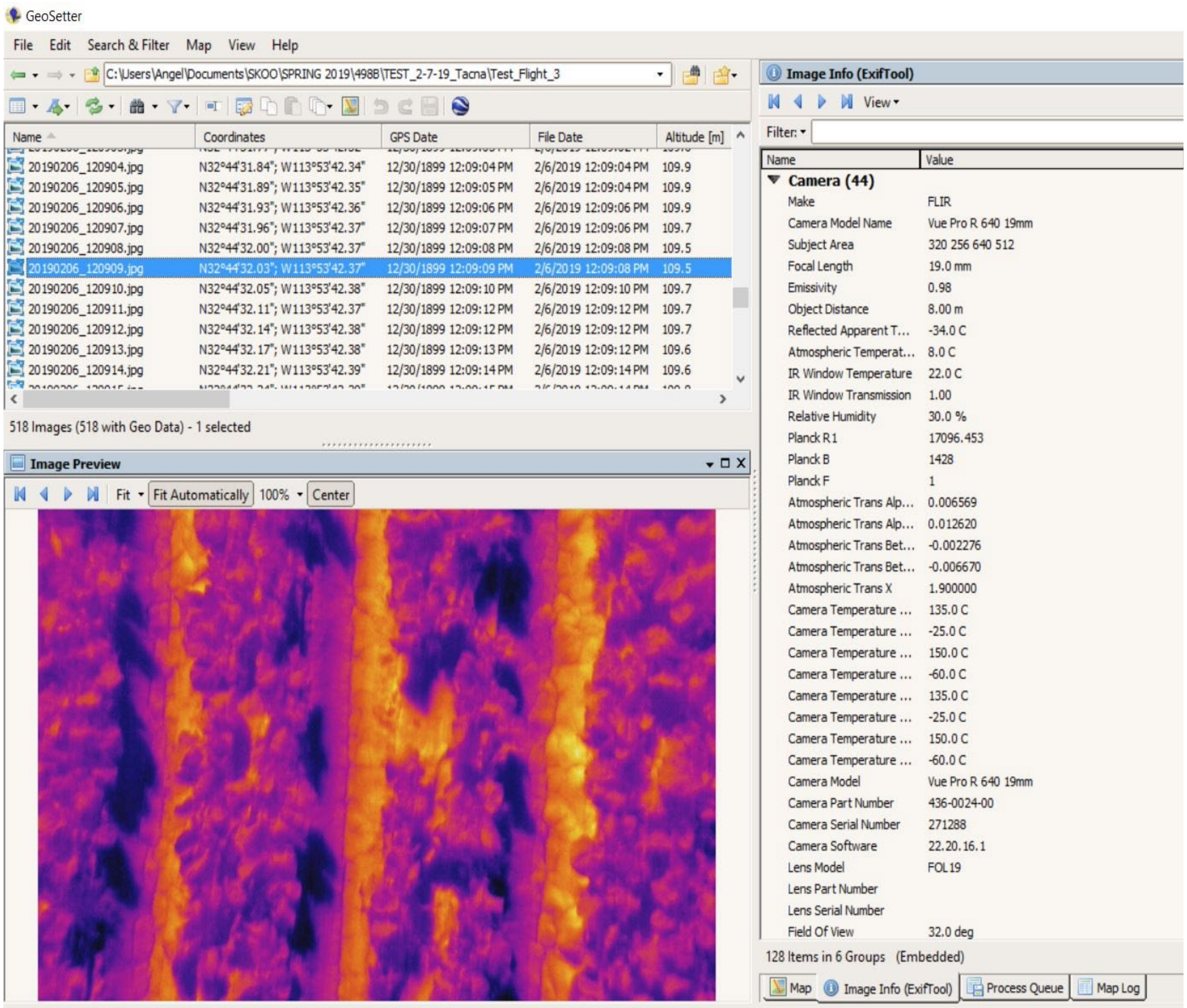


Figure 13. Example of data collected with UAV thermal imaging platform.

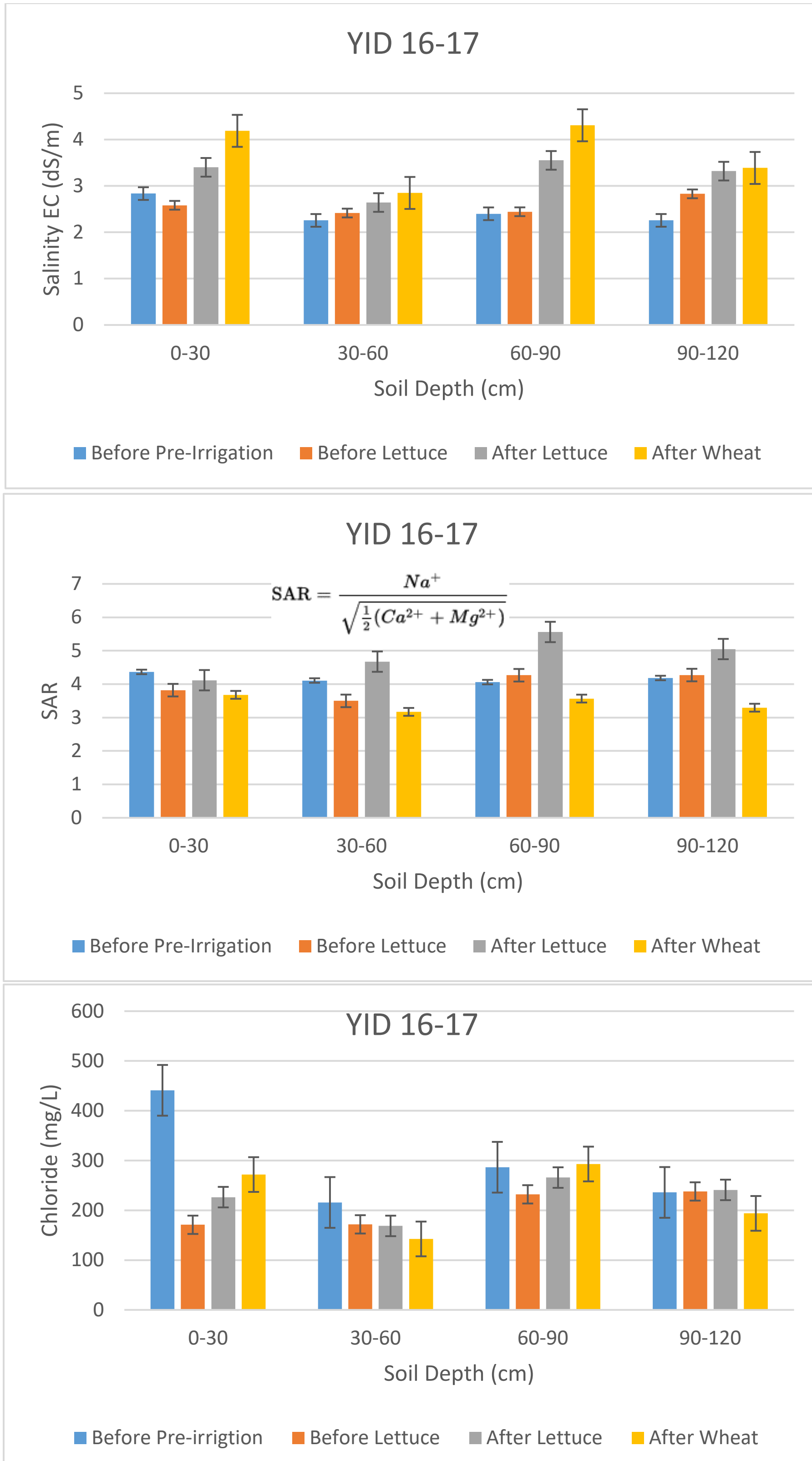


Figure 14. Total salinity (based on ECe), sodium adsorption ratio, and chloride in the saturated paste extract across a lettuce-wheat rotation system in a YID heavy-textured soil field.

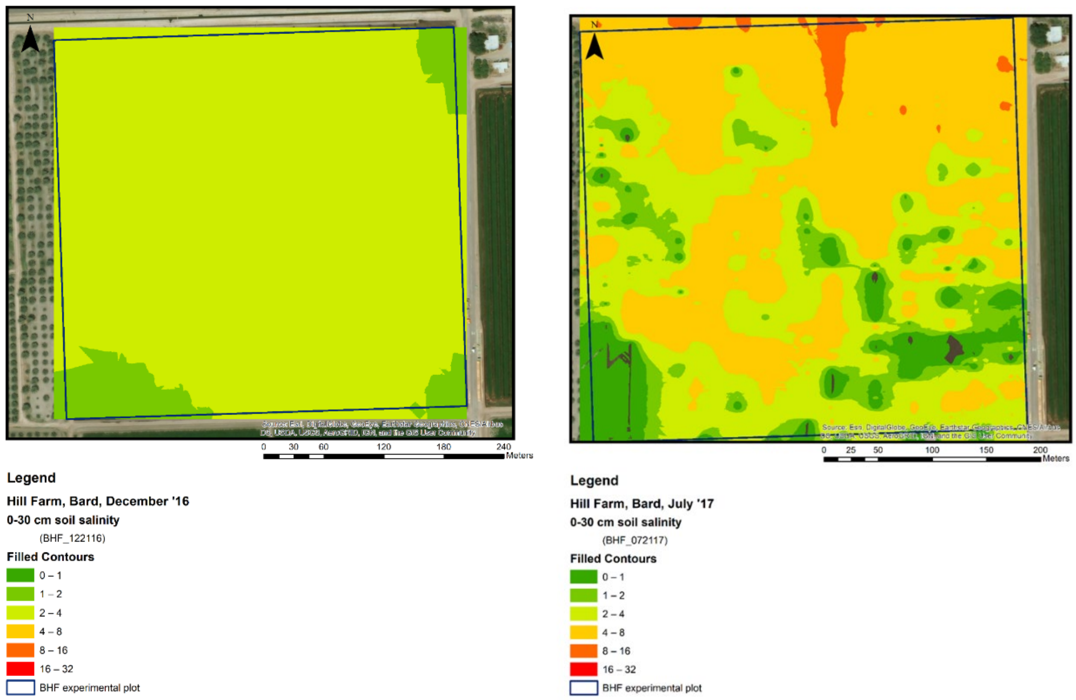


Figure 15. Field-wide salinity or conductance (dS/m) maps constructed from EM-38 ground conductance data before (December) and after (July) a wheat crop in the Bard Water District.

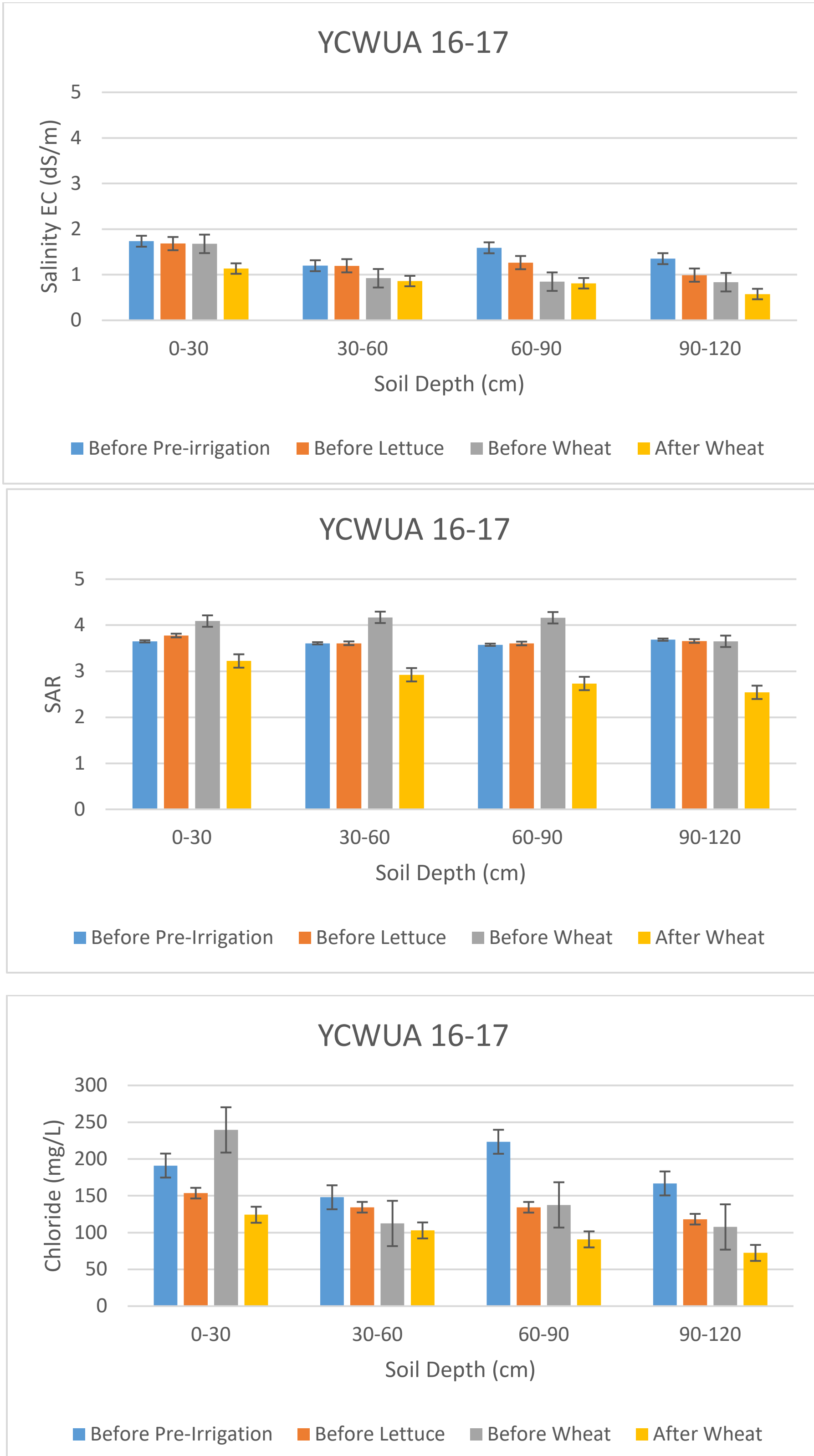


Figure 16. Total salinity (based on ECe), sodium adsorption ratio, and chloride in the saturated paste extract across a lettuce-wheat rotation system in a YCWUA loamy sand field.

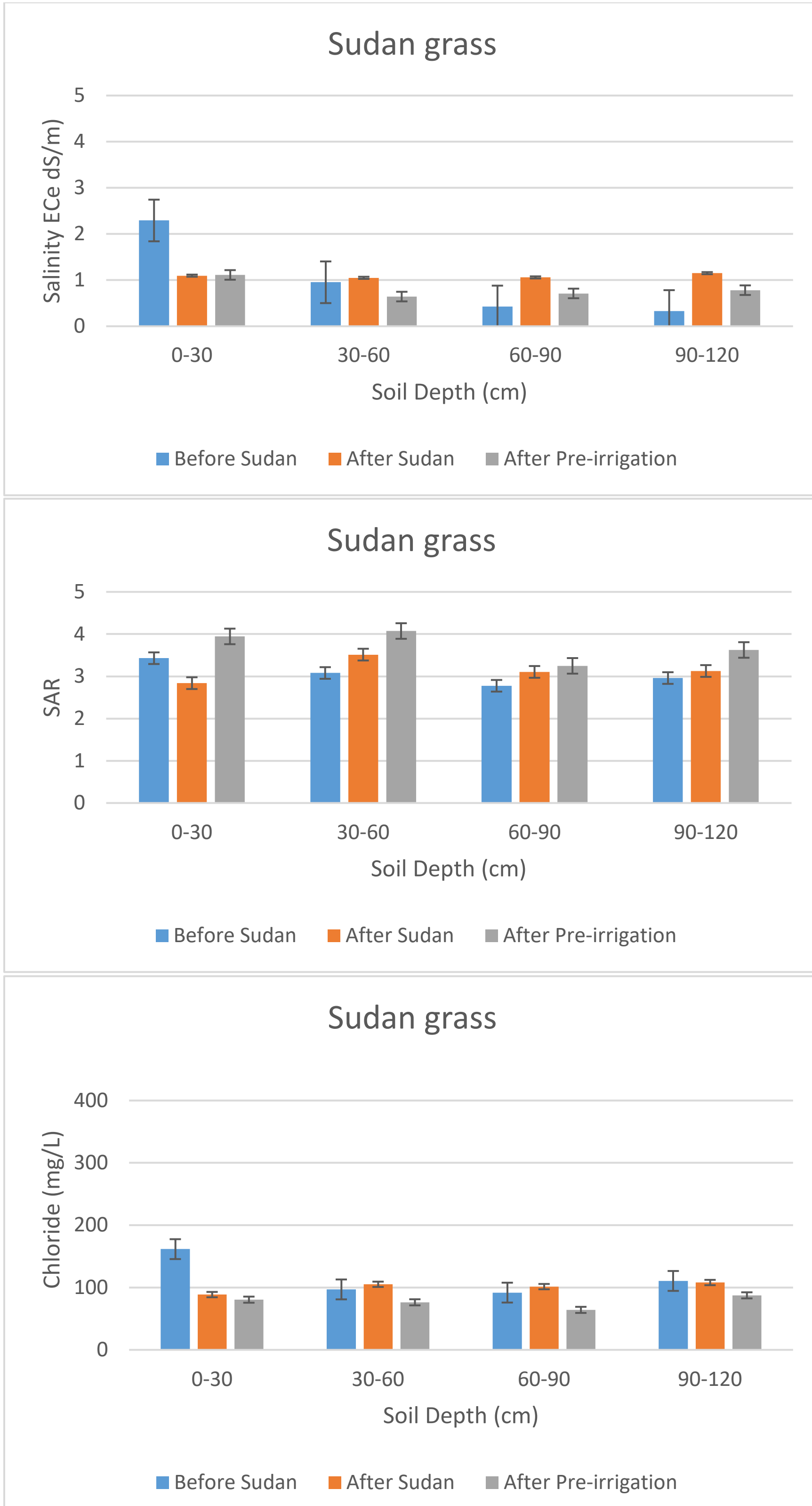


Figure 17. Total salinity (based on ECe), sodium adsorption ratio (SAR), and chloride in the saturated paste extract before Sudan grass, after Sudan grass, and after pre-irrigation.

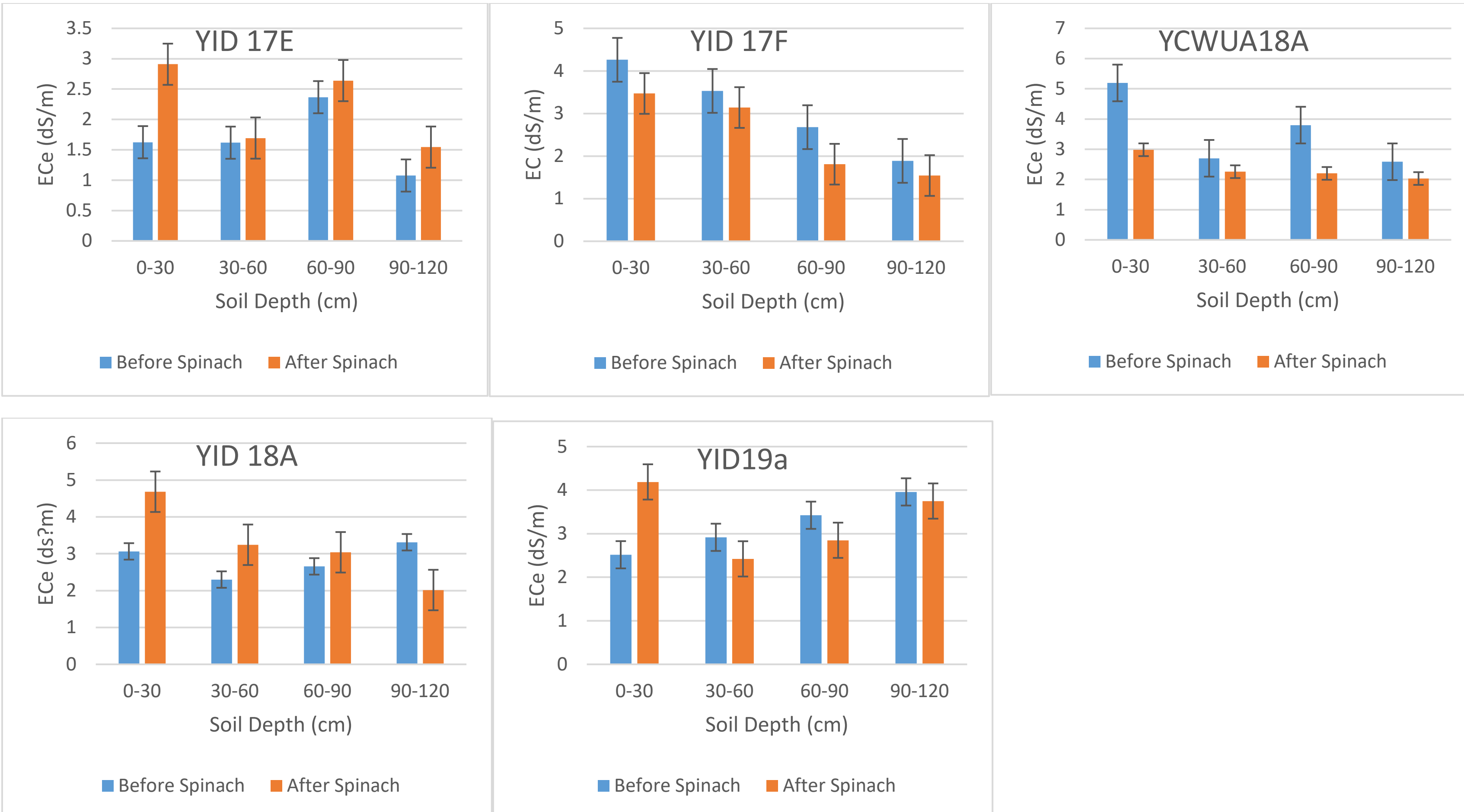


Figure 18. Total salts (based on ECe) before and after sprinkler-irrigated spinach.

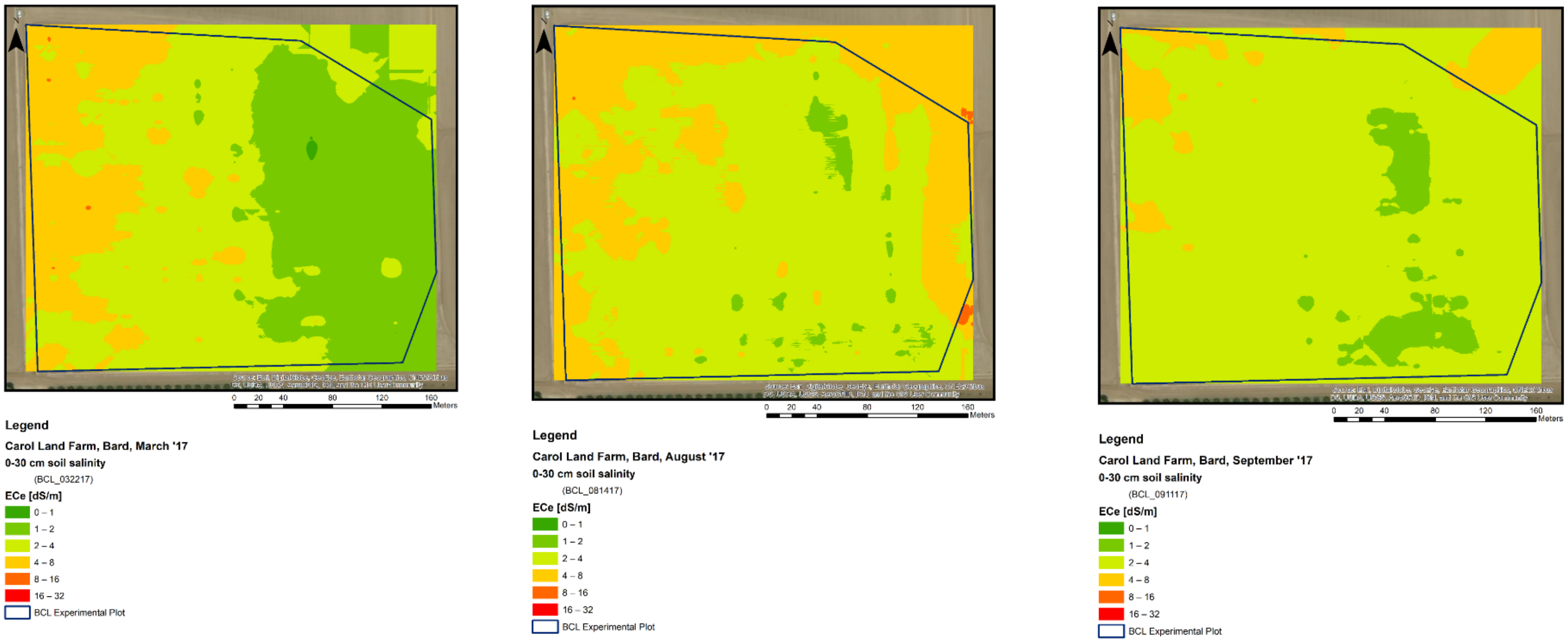


Figure 19. Soil salinity (based on ECe), before summer fallow, after summer fallow, and after pre-irrigation in crop rooting zone (Bard Water District).

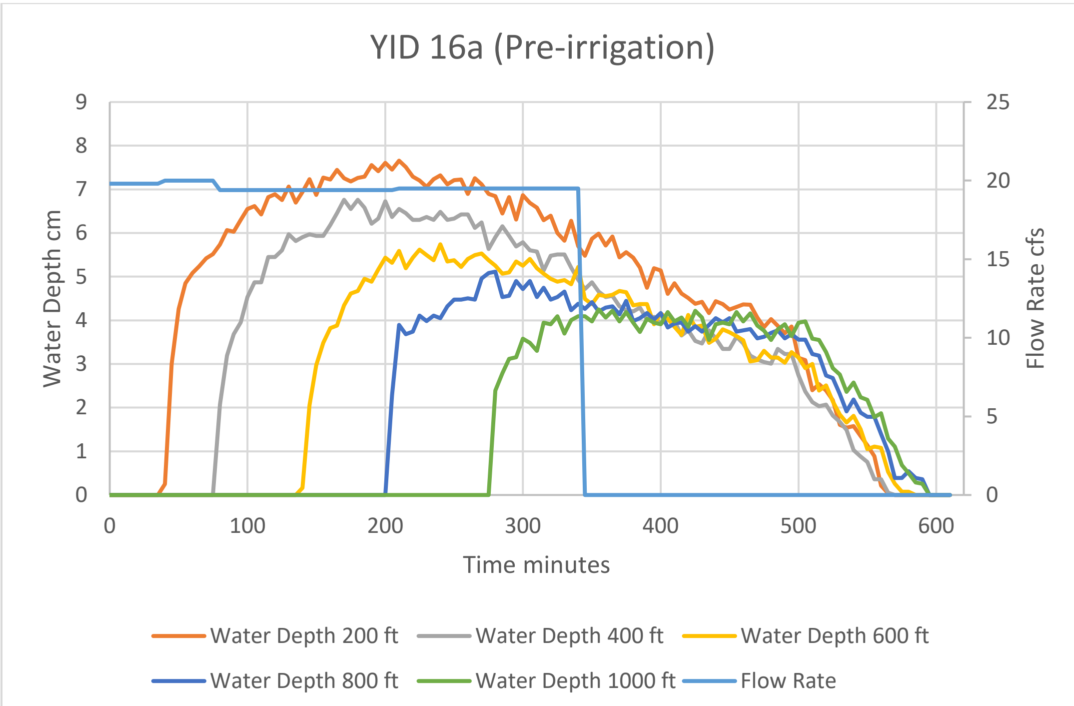


Figure 20. An example hydrograph of measured in-flow and water depth profiles during a pre-planting flood irrigation event in YID16-1a, using flumes with depth sensors and data loggers to create in-flow hydrographs, and water depth sensors (Troll 100 water depth sensor and logger) to create water depth profiles in transects along the irrigation run (inlet to downstream border).

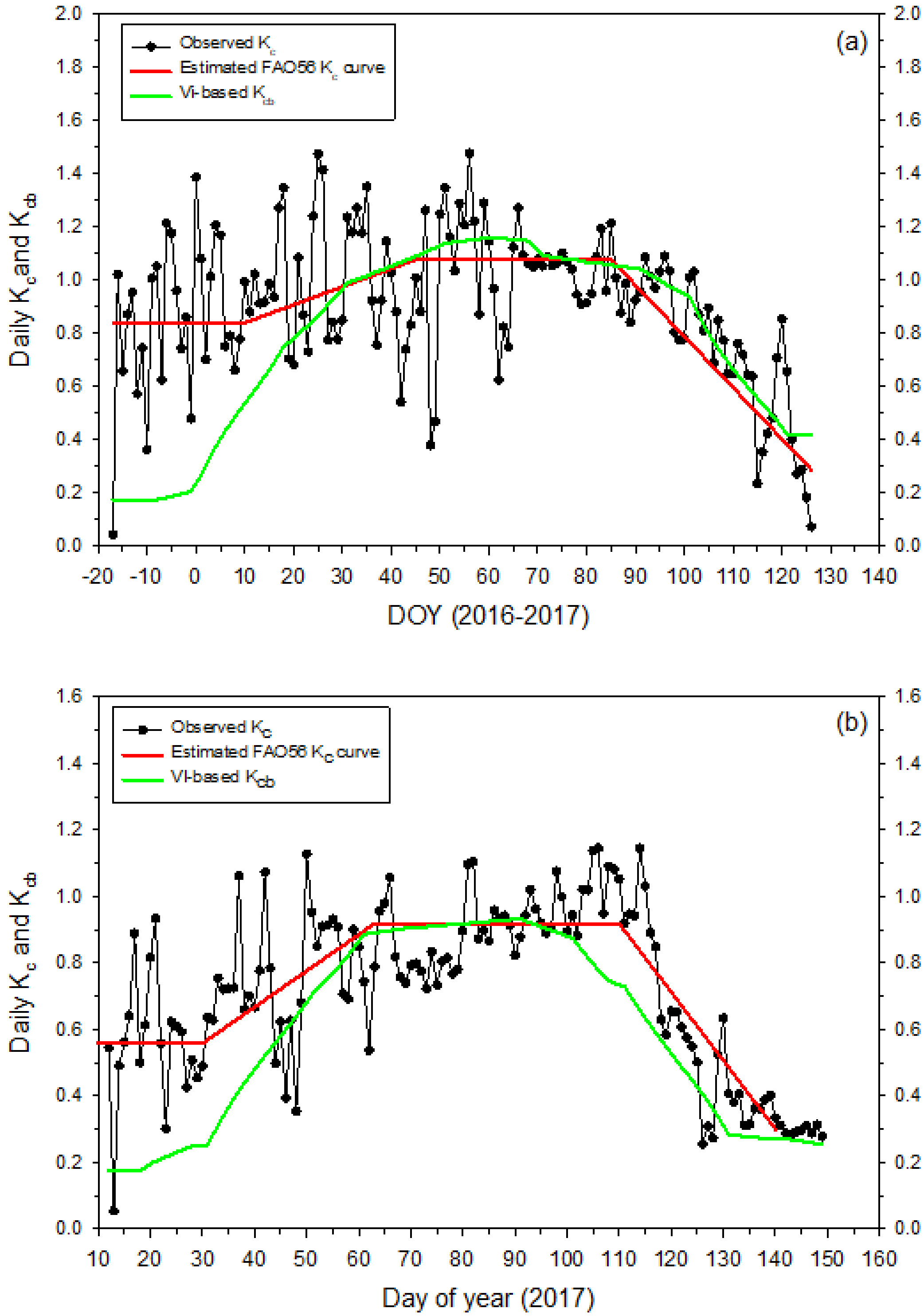
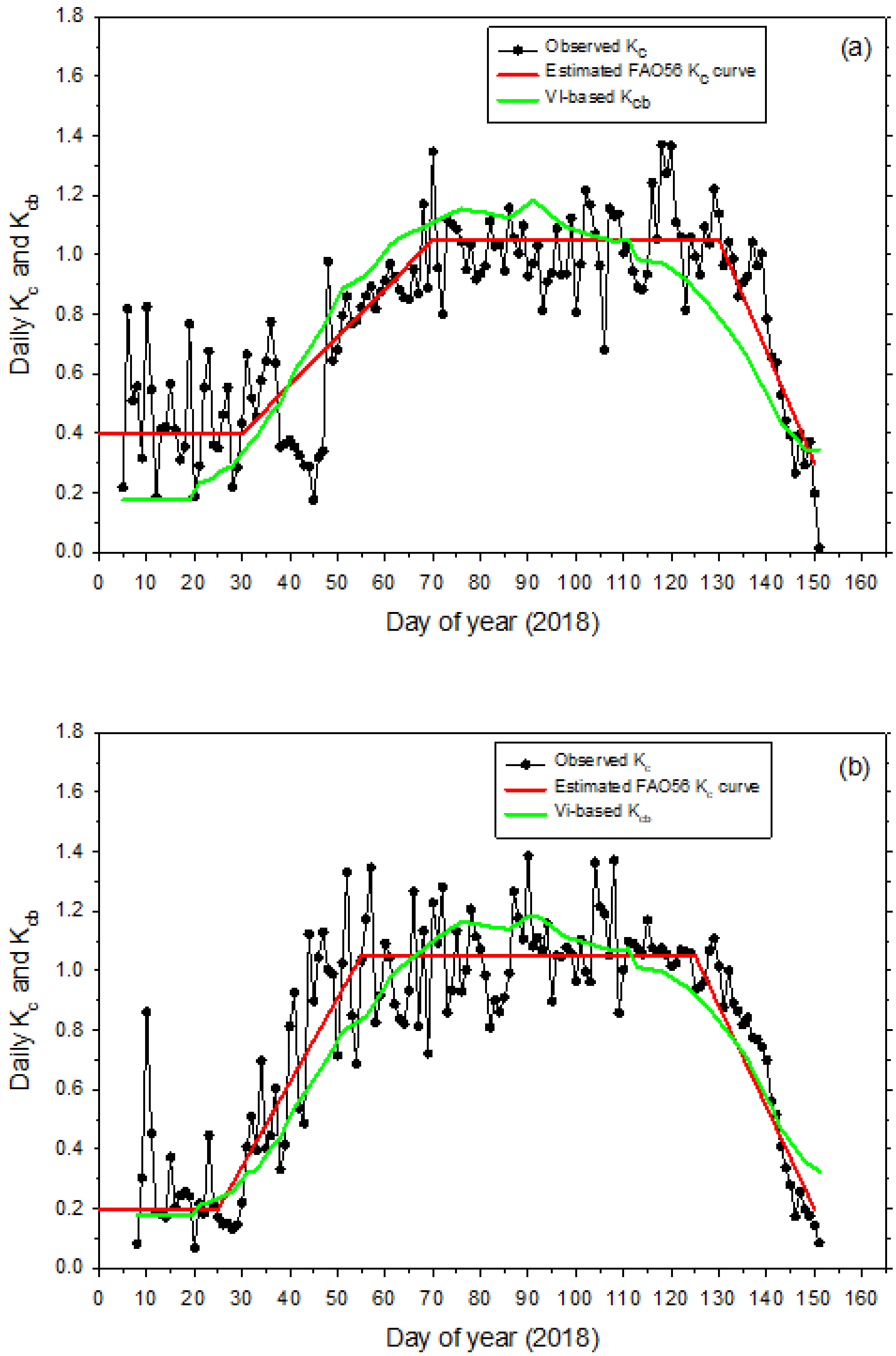


Figure 21. Daily observed wheat evapotranspiration (ET_c) and daily estimated wheat crop transpiration (T_c) modeled as daily basal crop coefficient (K_{cb}), derived by normalized satellite NDVI, times the daily reference evapotranspiration (ET_o) at YID 16-17-2 (a) YCWUA 16-1b(b).


(a)
Observed K_c
Estimated FAO56 K_c curve
VI-based K_{cb}
Daily K_c and K_{cb}
Day of year (2018)
(b)
Observed K_c
Estimated FAO56 K_c curve
VI-based K_{cb}
Daily K_c and K_{cb}
Day of year (2018)

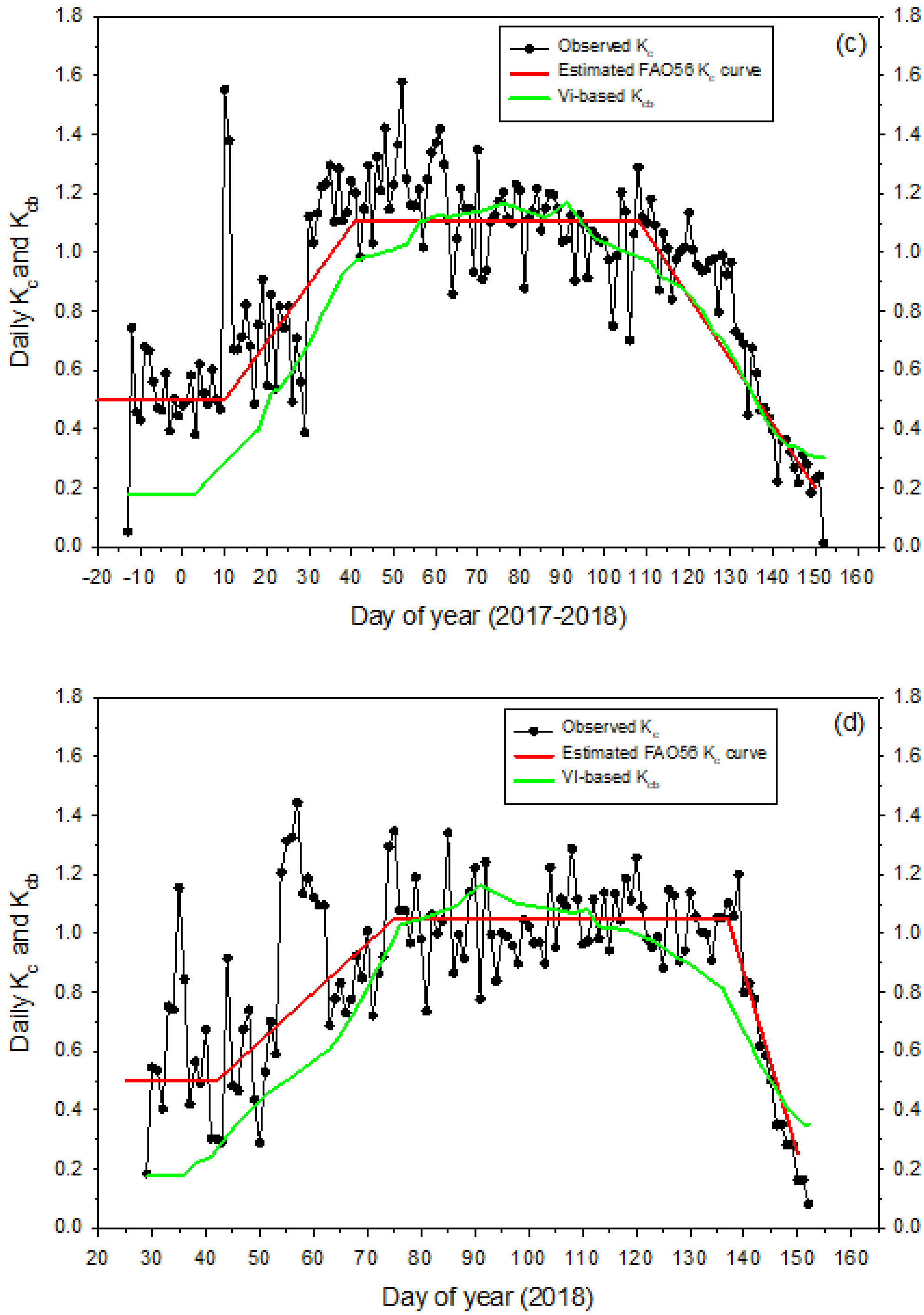


Figure 22. Daily observed wheat single crop coefficient (K_c), FAO56 K_c curve visually fitted to observed data, and daily estimated basal crop coefficient (K_{cb}) derived from normalized satellite NDVI, assuming no water stress, for Yuma fields YID18a (a), YID 18b (b), YID 18c (c) and YID 18d (d)