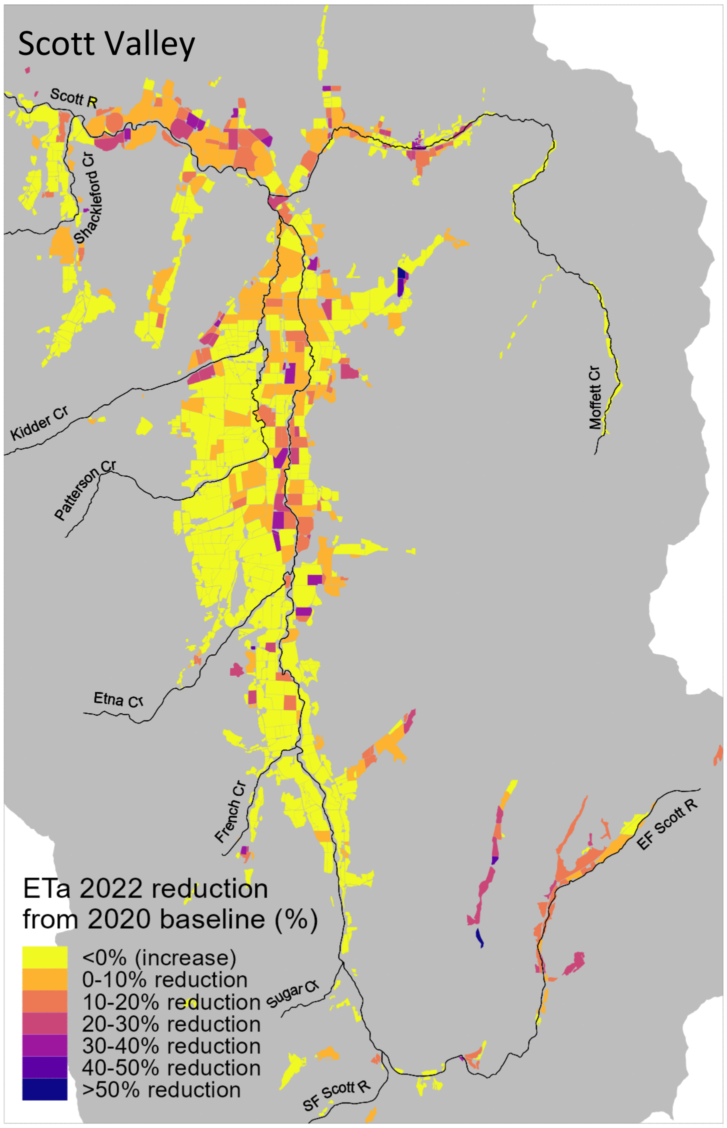
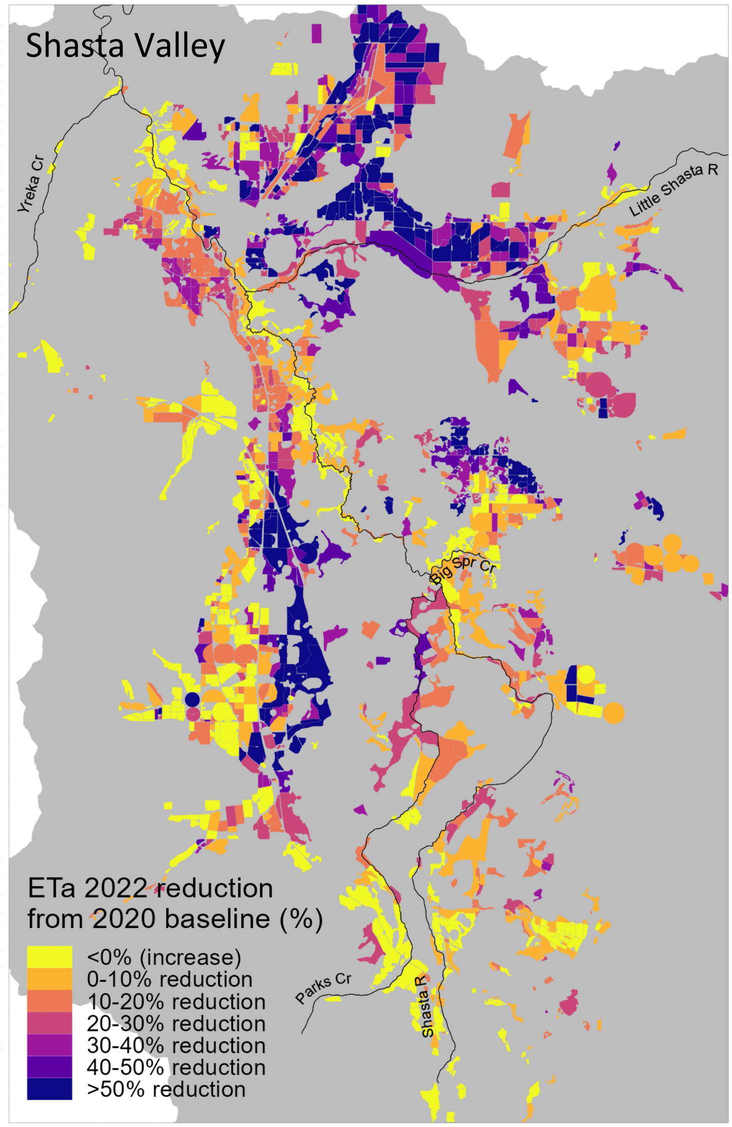
Evaluating the hydrologic effects of the 2021–2022 Scott and Shasta irrigation curtailments using remote sensing and streamflow gages





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Prepared for:
Klamath Tribal Water Quality Consortium
July 12, 2023

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EXECUTIVE SUMMARY

Key Points

- Satellite remote sensing data indicated that curtailment orders in 2022 reduced consumptive water use (evapotranspiration, ET_a) on agricultural lands in Shasta Valley, but not Scott Valley.
- Streamflow gage data indicate that flows in the Shasta River and some Scott River tributaries (Shackleford and French creeks) were substantially higher in summer 2022 than 2020 or 2021, but similar increases did not occur in the mainstem Scott River.
- A likely major reason for the lack of Scott River flow increases was that groundwater use was allowed to continue under Local Cooperative Solutions (LCS) agreements in which water users agreed to reduce pumping by 30% from a prior year baseline. Despite abundant worldwide evidence that reducing consumptive use (i.e., evapotranspiration) is key to increasing environmental water, all LCS cropping and irrigation practices were given equal weight toward the 30% reduction, regardless of the effects on consumptive use. Pumping was not measured and compliance was primarily self-reported, with limited independent verification.

Background

To protect fish populations in the Scott and Shasta rivers, California's State Water Board issued emergency regulations that curtailed agricultural surface water diversions and groundwater pumping beginning in early September 2021 (when irrigation season was nearly over) whenever instream flows dropped below minimum thresholds. Prior to curtailments, in exchange for payments, three Scott Valley ranches voluntarily agreed not to pump groundwater in 2021 from August through November.

In 2022, junior water users in the Shasta River were progressively curtailed by a watermaster when instream flows were below thresholds. Except for properties with LCS agreements, all Scott Valley surface water irrigation was curtailed on July 1, 2022, followed by groundwater curtailments on July 14. As an alternative to curtailment, Scott Valley regulations allowed LCS agreements in which groundwater users agreed to reduce groundwater "use" (not defined) from a 2020 (or 2021) baseline by 30% during the 2022 irrigation season through a collection of user-specified practices. Despite abundant worldwide evidence that reducing consumptive use (evapotranspiration, ET_a) is the key to increasing environmental water, all LCS practices were given equal weight toward the 30% reduction, regardless of how an irrigation or cropping practice affected ET_a. As a result, it is likely that some LCS practices reduced ET_a (i.e., switching to less thirsty crops, fallowing fields or corners, early cessation of irrigation, or upgrading to large-droplet sprinkler nozzles [LESA Low Elevation Spray Application, or LEPA Low Energy Precision Application]), others were not verified (i.e., without water meters or electric bills it is impossible to verify irrigation frequency or duration), and other LCS practices likely increased ET_a (e.g., smaller sprinkler nozzles enhance wind drift losses). Compliance was primarily self-reported, with limited independent verification.

Study objectives were to: 1) explore no-cost remote sensing methods for assessing agricultural water use and explain them in an accessible way, and 2) use remote sensing and streamflow gage data to evaluate the hydrologic effects of the 2021 and 2022 irrigation curtailments in the Scott and Shasta valleys. Results are intended to be repeatable and inform water resource management including future LCS agreements.

Methods

I used satellite remote sensing data to assess ET_a and the greenness (Normalized Difference Vegetation Index, NDVI) of fields in the Scott and Shasta valleys for 2017–2022, with a focus on 2020–2022. For most analyses I used OpenET, a collaborative project that develops high-resolution (30-meter pixels) time series maps of ET_a across the Western U.S. largely based on the thermal infrared sensors aboard NASA/USGS Landsat satellites. These sensors can detect temperature reductions of actively transpiring plants that evaporatively cool as they transpire water, an effect similar to a human body cooling while sweating. For the Scott Valley, I quantitatively summarized these ET_a data by sub-watershed, irrigation source type (e.g.,

groundwater or surface water), and land management units (i.e., LCS boundaries) while making qualitative comparisons for similar categories in the Shasta Valley. I also analyzed streamflow gage data for nine sites from the U.S. Geological Survey and California Department of Water Resources.

Results

<u>Daily gaged streamflow</u>

During April–August, flows in the mainstem Shasta River gage at Yreka were much higher in 2022 than 2020 or 2021, except during late August 2022 when the Shasta River Water Association publicly violated curtailment orders. Inter-year patterns in summer 2020–2022 at the gage in the mainstem Scott River largely track the Salmon River gage used as a hydrologic reference (i.e., 2022 flows close to median, 2020 lower than median, and 2021 lowest), consistent with other years in 2002–2022, suggesting that the 2022 irrigation curtailments did not strongly affect flows at the Scott Valley outlet. In contrast, late August flows in Shackleford and French creeks were higher in 2022 than in any other year 2002–2022, despite being close to median flows earlier in the year. The high late August flows in Shackleford and French creeks, appear to be due to a combination of diversion curtailments and summer precipitation events. Gaged Scott River tributaries besides Shackleford Creek and French Creek do not show evidence of curtailment-driven increases in 2022.

<u>Basinwide evapotranspiration (ET_a) and comparisons to river flow</u>

Monthly and annual OpenET summaries indicated that ET_a was substantially lower in Shasta Valley in 2022 than previous years. Lower ET_a in 2022 occurred throughout the entire April–September irrigation season. In contrast to Shasta results, ET_a was stable in Scott Valley from 2020–2022. Most individual fields in Scott Valley showed no reduction in ET_a from 2020 to 2022 whereas many fields in Shasta Valley did show reductions (see maps on cover page).

Comparison of Shasta River gaged flow and ET_a from Shasta Valley agricultural fields in 2020 and 2022 indicated that for July–October, the increase in flow between 2022 and 2020 was similar in magnitude to the decrease in ET_a between 2022 and 2020 (Figure ES-1). In Scott Valley, ET_a was similar in 2020 and 2022, corresponding with the lack of increase in river flow between 2020 and 2022 (Figure ES-1).

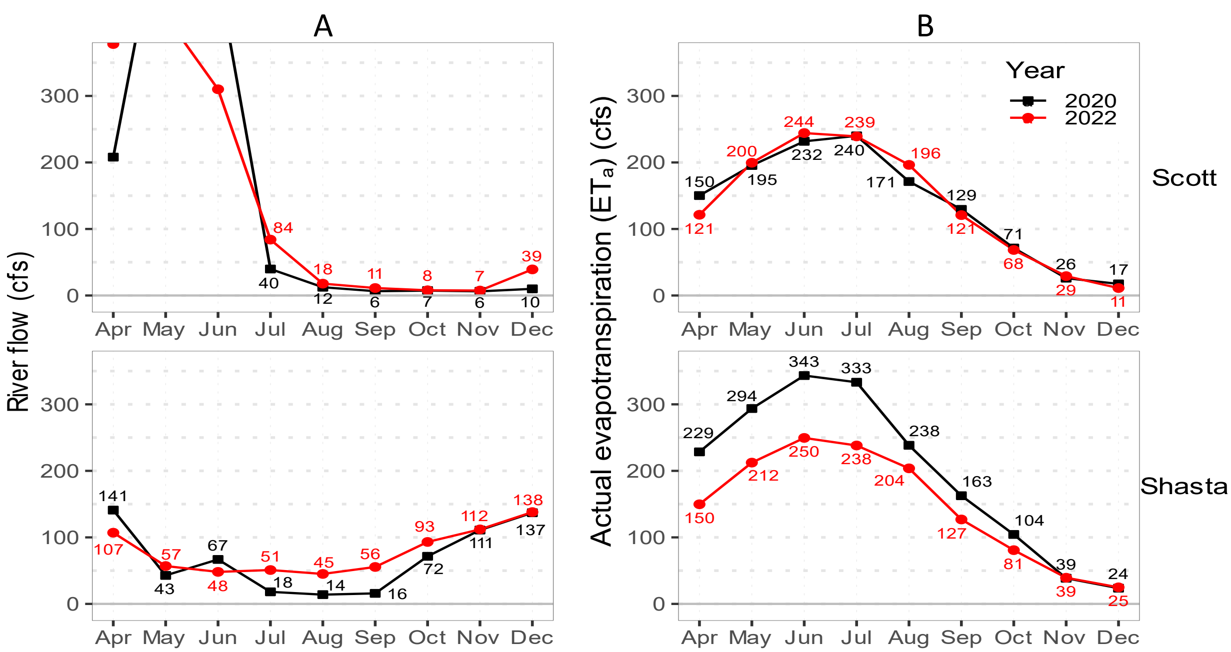


Figure ES-1. Comparison of monthly (a) river flows at USGS gages, and (b) actual evapotranspiration (ET_a) rate of agricultural fields in Shasta and Scott valleys for the months of April–December in 2020 and 2022. Y-axis is truncated to highlight the low-flow period.

ET_a by Irrigation Source and Sub-watershed

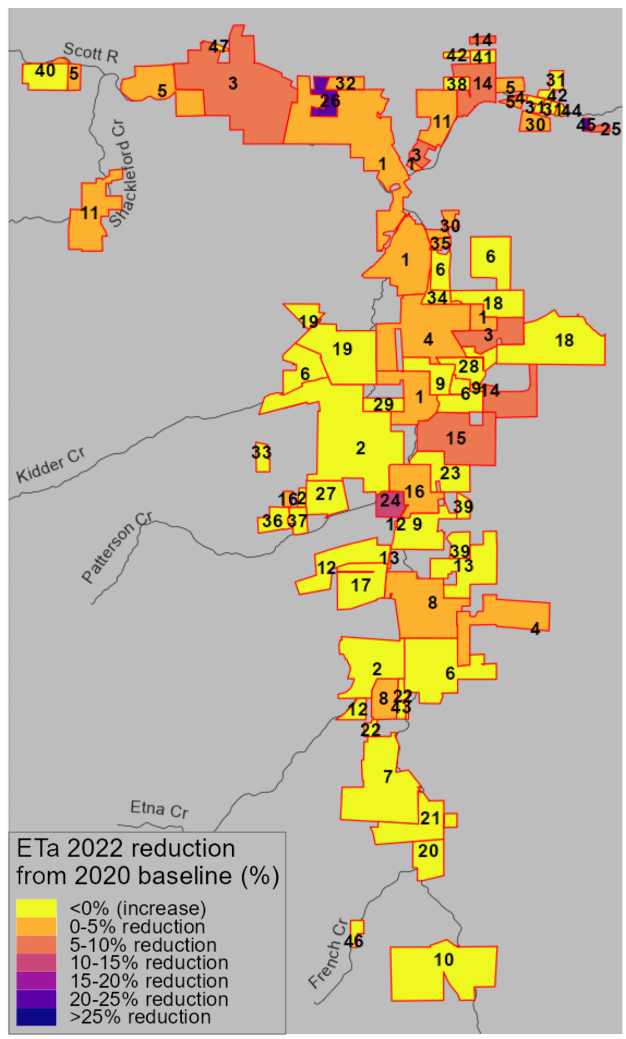
In Scott Valley, the monthly timing and magnitude of ET_a and greenness (NDVI) were relatively consistent among years for most irrigation water sources. The largest differences occurred for sub-irrigated fields (areas in the Etna, Patterson, and Kidder Creek watersheds where irrigation is not required due to groundwater near the soil surface), where ET_a and NDVI were higher in 2022 than 2020 and 2021. In addition, in 2022 fields irrigated with surface water also had higher NDVI in April–September, and higher ET_a in July and August, than in 2020 and 2021.

In the Shasta Valley, I did not calculate ET_a summaries by irrigation water source, but side-by-side maps indicate that ET_a reductions from 2020 to 2022 were greater in surface water-irrigated fields than groundwater-irrigated fields, except in the groundwater-irrigated Unit #9 (Big Springs Irrigation District). Surface-water irrigated fields in Unit #1 (Montague Water Conservation District) had especially large ET_a reductions.

ET_a by Local Cooperative Solutions (LCS)

In the Scott River, 47 ranches totaling 15,449 irrigated acres developed LCS agreements for the 2022 irrigation season. None of the ranches achieved a 30% ET_a reduction from 2020 to 2022 (Figure ES-2). LCS practices for the three ranches with the greatest reductions in ET_a (21%, 20%, and 14%, respectively) included: #45 (no irrigation after June 30), #26 (no irrigation on 30% of typical irrigated acreage), and #24 (grain hay irrigated through June only, no alfalfa irrigated after mid-August, and reduced nozzle size). Of the ten largest ranches that comprise 65% of the total area irrigated under LCS agreements, only two had reductions of at least 4%. Despite lacking legal access to irrigation after July 14, many fields in Scott Valley without LCS agreements showed no reductions in ET_a in 2022, likely due to a combination of reasons: availability of summer surface water is limited even in years without curtailment, some fields are naturally sub-irrigated by high water tables, and many fields appear likely to have been irrigated with groundwater in violation of curtailment orders (e.g., 971 acres with 2022 ETa >35 inches).

Figure ES-2. Scott Valley map showing the percent reduction in actual evapotranspiration (ET_a) for each LCS between 2022 and the 2020 baseline. See Table B3 in Appendix B for a key to LCS ranch numbers.



ET_a effects of 2021 Pumping Forbearance

Monthly time series of ET_a at three 2021 pumping forbearance fields, where irrigators were paid to not pump after August 1, indicated that ET_a was 17% lower in August 2021 than the August mean of 2017–2020 and lower than in other groundwater-irrigated fields in Scott Valley. Converting units of ET_a to cfs, this 17% reduction equates to 3.4 cfs for the duration of August. Effects were smaller in September 2021, with a 12% (1.4 cfs) reduction in ET_a. Interestingly, NDVI and ET_a in the 2021 pumping forbearance fields were higher in April–May 2021 than in April–May 2017–2020, which on an annual basis may have partially offset some of the ET_a reductions observed in August–September.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1 INTRODUCTION

1.1 STUDY AREA

The study area is the agricultural lands in the Scott and Shasta valleys, located in Siskiyou County, California, USA (Figure 1). In the Shasta Valley, irrigation water is sourced primarily from surface water diversions that are subject to regulation by a watermaster. When demand for irrigation water in Shasta Valley exceeds supply, which occurs most summers, junior-priority water rights are regulated off to ensure water delivery to users with senior-priority water rights. The only major surface water storage is Dwinnell Reservoir where Montague Water Conservation District captures winter and spring runoff to irrigate lands in northern Shasta Valley. Some irrigation water in Shasta Valley is derived from groundwater wells (Figure 21).

In Scott Valley, most irrigation water is from groundwater wells but there are also substantial diversions of surface water from the Scott River and its tributaries (Figure 19). When surface water supplies are insufficient, typically beginning in July, many growers switch to groundwater (Tolley et al. 2019). Watermaster service in Scott Valley is currently provided only in Wildcat Creek (a tributary south of Sugar Creek) and French Creek (SCFCWDGSA 2022a).

Figure 1. Location of the Scott and Shasta valleys. Map adapted from SSCSRT (2003).

1.2 2021 AND 2022 IRRIGATION CURTAILMENTS AND 2021 FORBEARANCE CONTRACTS

On May 10, 2021, California Governor Newsom declared a drought emergency for 41 counties including Siskiyou County. To protect fish populations in the Scott and Shasta rivers, California's State Water Resources Control Board (SWRCB) issued emergency regulations establishing minimum instream flows. Minimum flows vary by month and day, ranging from 30 to 200 cfs in Scott River and 50 to 125 cfs in the Shasta River. Under these regulations, diversions of surface water and pumping of groundwater were to be curtailed once river flows dropped below specified minimum levels. These regulations went into effect on August 30, 2021. On September 9 and 10, 2021, SWRCB issued curtailment orders in the Scott River and Shasta River watersheds to protect minimum instream flows (SWRCB 2022), but irrigation season was nearly over by those dates. Irrigation season typically ends on July 10, Sept. 1, and Oct. 15 for grain, alfalfa, and pasture, respectively in Scott Valley (Foglia et al. 2018) and Oct. 1 in Shasta Valley (SCFCWDGSA 2022b). The emergency regulations were modified and extended for an additional year on July 29, 2022[1]. Except for properties with Local Cooperative Solutions (LCS) agreements, discussed below, all groundwater irrigation in Scott Valley was curtailed on July 14, 2022, preceded by surface water irrigation curtailments on July 1 (Ragazzi 2022) near the time when most surface water diversions typically cease in most years due to lack of available water regardless of curtailments.

As an alternative to curtailment, the emergency regulations allowed water users to develop Local Cooperative Solutions (LCS). Fifty LCS agreements were approved for the 2022 irrigation season, 47 of which were in Scott Valley[2] and were primarily groundwater users (Figure 2). Under these LCS agreements, water users agreed to reduce "groundwater use" (not defined) from a 2020 (or 2021) baseline by 30% during the irrigation season. The specific actions intended to result in these reductions were specified in plans developed by each water user. Practices included:

- Upgrades to efficiency of irrigation equipment (i.e., changes to sprinkler nozzles)
- Reducing irrigation rates or frequencies
- Switching crops (e.g., alfalfa to grain)
- Fallowing of fields or corners of fields
- Reducing the number of cuttings of alfalfa (i.e., early cessation of irrigation)

SWRCB's (2022) stated justification for the 30% threshold was that the Scott Valley Integrated Hydrologic Model (SVIHM) indicated that ceasing groundwater pumping for alfalfa irrigation by July or August in dry years would increase river flows during October–December. SWRCB did not state the magnitude of these anticipated flow increases, but based on model results presented in Appendix 4-A of the Scott Valley Groundwater Sustainability Plan (SCFCWDGSA 2022a) presumably would not be sufficient to meet the minimum instream flows. Since August–December typically comprises approximately 30% of annual groundwater pumping, the LCS guidelines allowed the 30% reduction to be stretched over the entire irrigation season instead of a no-pumping period confined to August–December (SWRCB's 2022). A cessation of pumping of August 1 would have guaranteed some reduction in consumptive use whereas LCS agreements may or may not reduce consumptive use. All practices were given equal weight toward the 30% reduction in groundwater pumping, regardless of whether a practice ultimately reduced or increased consumptive water use, or merely reduced the amount pumped (see Section 1.3 below). Some LCS practices may have increased consumptive use (e.g., smaller sprinkler nozzles enhance wind drift losses). Pumping was not measured and compliance was primarily self-reported with limited independent verification. Nearly all wells use electric pumps, so for users who did not substantially alter the energy efficiency of their irrigation equipment (e.g., install motors with variable frequency drives) it would be possible to use electric utility bills to evaluate differences in pumping between years, but this was not required and was rarely done. Each LCS agreement specified a coordinating entity, either the California Department of Fish and Wildlife (CDFW) or Siskiyou Resource Conservation District (SRCD), that was supposed to verify implementation in 2022, including periodic on-site inspections with 24-hours advanced

[1] https://www.waterboards.ca.gov/drought/scott_shasta_rivers/
[2] https://www.waterboards.ca.gov/waterrights/water_issues/programs/drought/scott_shasta_rivers/ilcs.html#theListCooperative

notice, but there was no verification of the reported 2020 or 2021 baseline. More than 90 percent of groundwater-irrigated acres in Scott Valley enrolled in an LCS (Ragazzi 2022).

Prior to the 2021 curtailments, three large Scott Valley ranches downstream of Fort Jones signed forbearance contracts with the California Department of Fish and Wildlife, agreeing to accept cash payments in exchange for not pumping groundwater from August 1 to December 1, 2021 (Figure 3) (Croteau 2022).

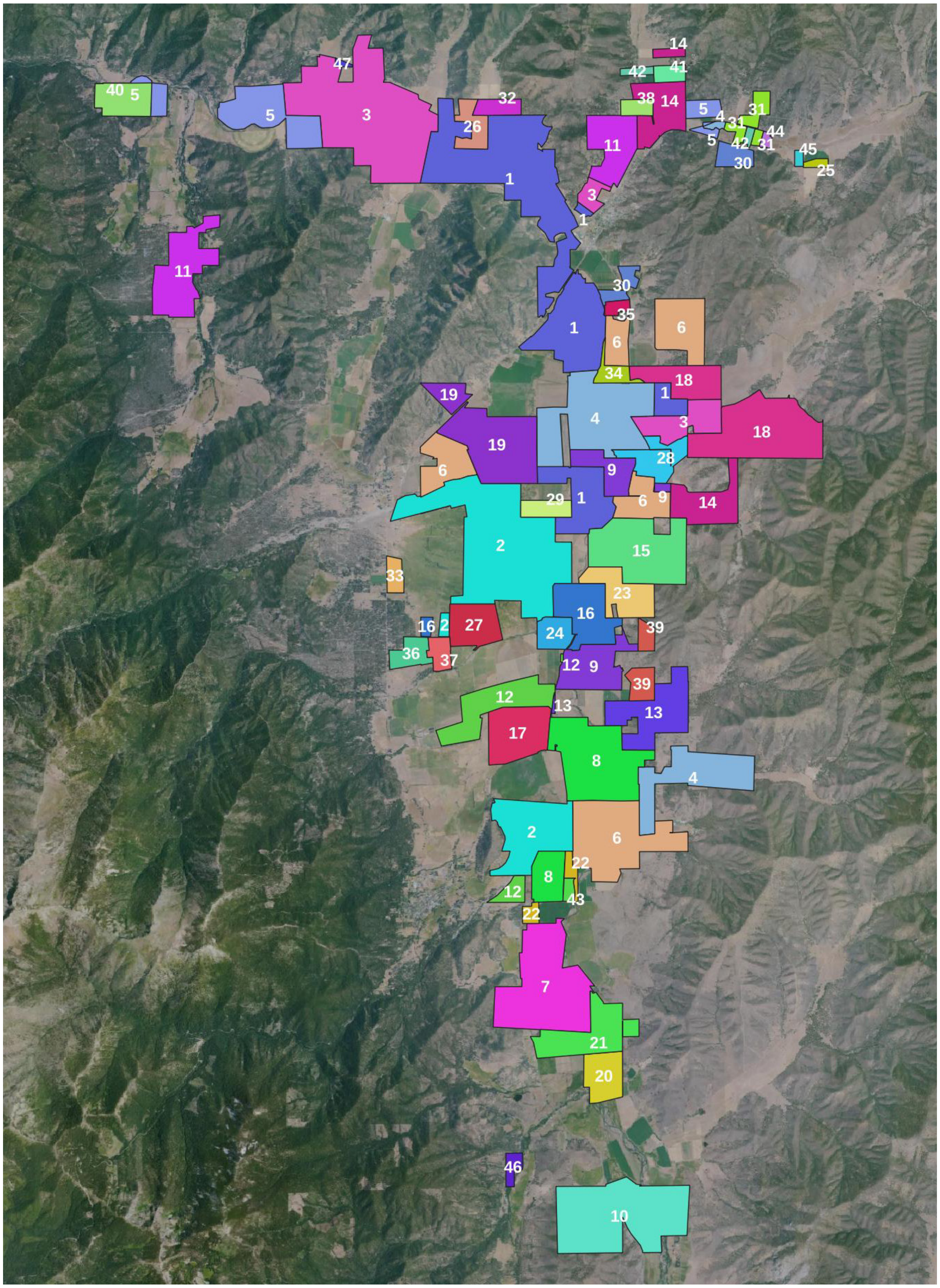


Figure 2. Map of Scott Valley properties with 2022 Local Cooperative Solutions (LCS) agreements, adapted from SWRCB grouping of parcel data. Table B3 in Appendix B has a key to LCS ranch numbers.

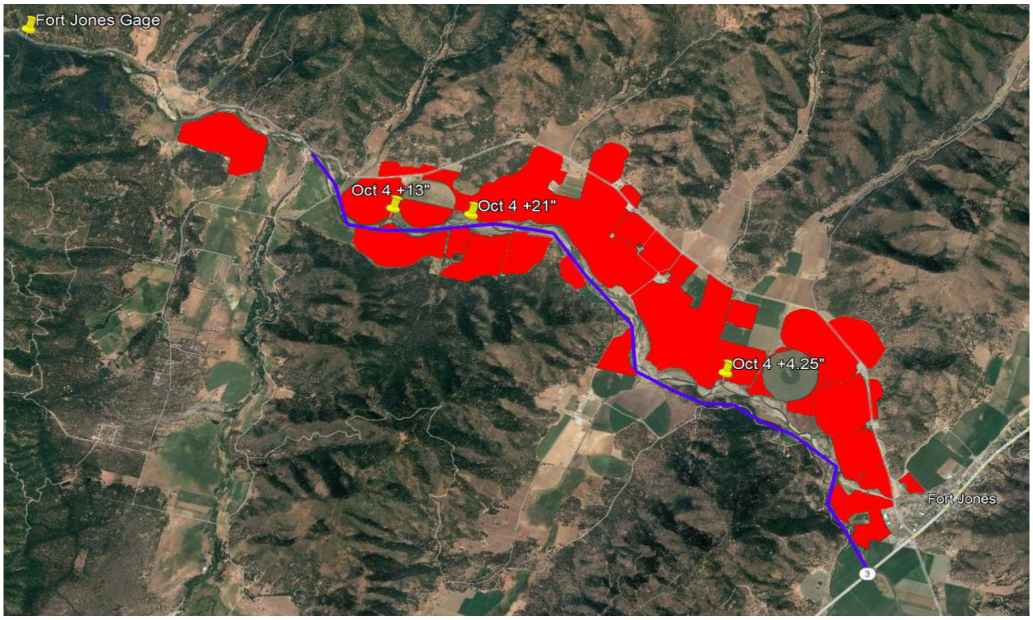


Figure 3. Map of Scott Valley 2021 pumping forbearance fields where three ranches downstream of Fort Jones were paid not to pump groundwater from August–November of 2021. Map adapted from Croteau (2022). "Oct" labels refer to CDFW river elevation monitoring, not relevant for purposes of this report.

1.3 WHAT ARE CONSUMPTIVE USE (EVAPOTRANSPIRATION) AND IRRIGATION EFFICIENCY, AND HOW DO THEY AFFECT WATER BUDGETS?

To understand the mechanisms by which irrigation curtailments and the LCS agreements might affect instream flows in the Shasta and Scott rivers, it is necessary to understand some important concepts including consumptive water use and irrigation efficiency (IE). Consumptive water use is water that is lost from the land into the air through conversion to water vapor, such as transpiration by crops or evaporation from soil (Perry and Steduto 2017). IE is typically defined as "the ratio of water consumed by the crop to total water withdrawals" (Israelsen 1950). Techniques for increasing IE include sprinkler or drip irrigation systems, laser leveling of fields, conversion of canals to pipes, and lining canals to reduce seepage (Pérez-Blanco et al. 2020). These concepts, and their implications, are explored in the following sections.

1.3.1 IRRIGATION EFFICIENCY DOES NOT REDUCE CONSUMPTIVE USE UNLESS ACCOMPANIED BY OTHER POLICIES

Across the globe, governments and water managers have promoted increased IE as a solution to reducing water scarcity and increasing water for environmental uses including instream flows; however, there is widespread evidence that this approach has failed (Contor and Taylor 2013; Grafton et al. 2018; Pérez-Blanco et al. 2020, 2021; Perry and Steduto 2017). Increased farm-scale IE fails to increase water availability at larger spatial scales (watersheds and basins), a phenomenon known as the paradox of irrigation efficiency (Grafton et al. 2018). A primary reason for this paradox is that in inefficient irrigation systems, a large percent of water withdrawals is non-consumptive (i.e., recharge or runoff from surface flood irrigation), water that is "lost" from a farm but returns to streams or groundwater and becomes a "source" for downstream users. Increasing IE, such as conversion of surface flood to sprinklers or drip irrigation, reduces these non-consumptive "losses" (Figure 4). A second reason that increased IE fails to increase water availability at larger spatial scales is that it enables increases in consumptive use though expansion of irrigated area, switching to more water-intensive crops, or more thorough irrigation of existing crops (i.e., portions of fields that were not adequately irrigated previously then become well-watered after IE) (Grafton et al. 2018; Pérez-Blanco et al. 2020, 2021; Perry and Steduto 2017).

A global review showed that irrigation efficiency alone does not reduce consumptive use; instead, water consumption increased in 83% of case studies (Pérez -Blanco 2020). Reductions in consumptive use occurred only where policies were implemented to constrain water availability and consumption (e.g., charges and quotas). Pérez -Blanco (2020) concluded: "*The true strength of WCTs [Water Conservation Technologies] is that within a context of constrained water availability, they facilitate increased agricultural production and income on-site and provide the basis to minimize the potential negative impacts of reduced water consumption.*"

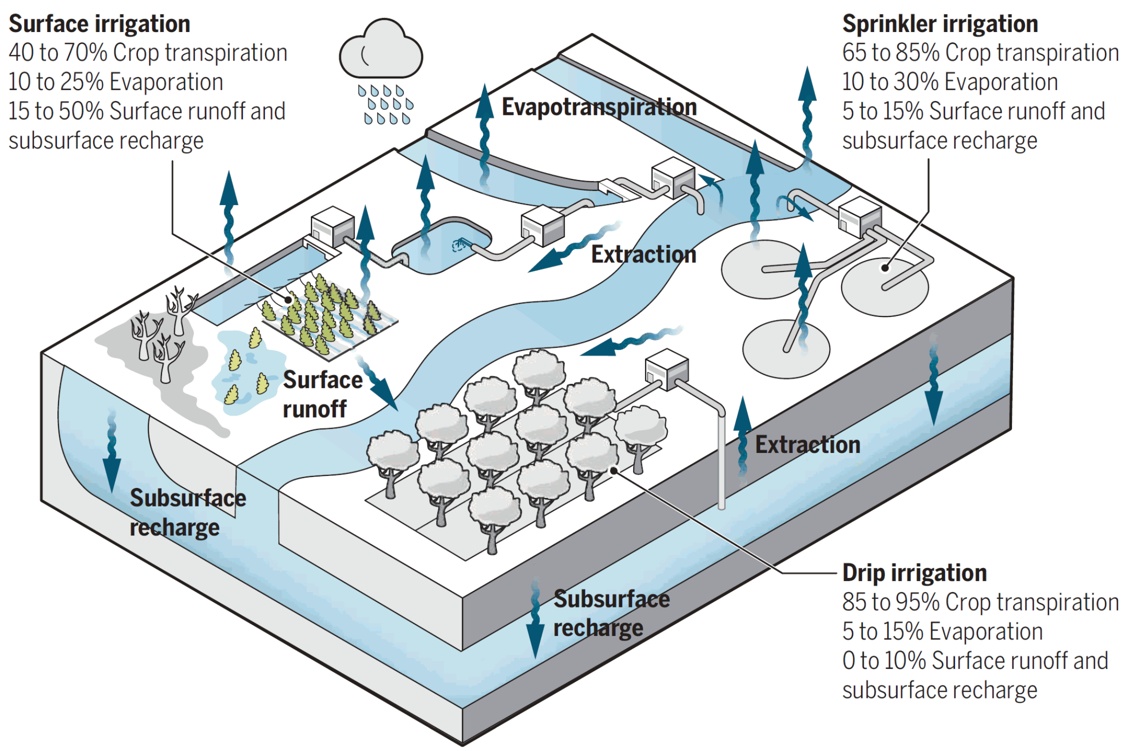


Figure 4. Diagram comparing inflows and outflows of water applied to agricultural fields through surface (i.e., flood), sprinkler, and drip irrigation. Figure cropped from Grafton et al. (2018) *Science* article *The Paradox of Irrigation Efficiency: Higher Efficiencies Rarely Reduce Water Consumption*. Values shown are general global ranges from Grafton et al. (2018), not specific to Scott/Shasta and will depend on crop and soil types, weather, and other factors.

1.3.2 ACCOUNTING FOR CONSUMPTIVE AND NON-CONSUMPTIVE USES OF WATER

Irrigation technology has evolved over time to be more efficient using the classical definition that counts non-consumptive seepage as losses; however, the change from surface flood irrigation to sprinkler irrigation can increase consumptive use through increased exposure to air and wind. Surface flood irrigation was one of the earliest and least efficient irrigation systems developed, with a large percentage of water applied becoming runoff or recharge (Figure 4, Figure 5a). Moveable wheel lines with high-pressure impact sprinklers were an early pressurized irrigation technology (Hill 2000). Introduced in the 1950s, center pivot irrigation systems initially used high-pressure impact sprinklers (New and Fipps 2000) but have since evolved to MESA (mid-elevation spray application), LESA (low elevation spray application), LEPA (low energy precision applicator), and MDI (mobile drip irrigation) (Peters et al. 2016, Yost et al. 2020) (Figure 5). LESA and LEPA are becoming more widely used in Scott Valley. MDI has been tested in alfalfa (Gull 2021, Molaei et al. 2022) but to my knowledge is not used on Scott or Shasta valleys. In *The More You Expose, the More You Lose: Limiting Center Pivot Irrigation Water Losses*, Sarwar and Peters (no date) explain that spray losses can be reduced by:

- Moving sprinklers as close to the ground as possible
- Decreasing pressure
- Increasing nozzle sizes
- Choosing sprinklers that throw large droplets without compromising irrigation water distribution uniformity and runoff

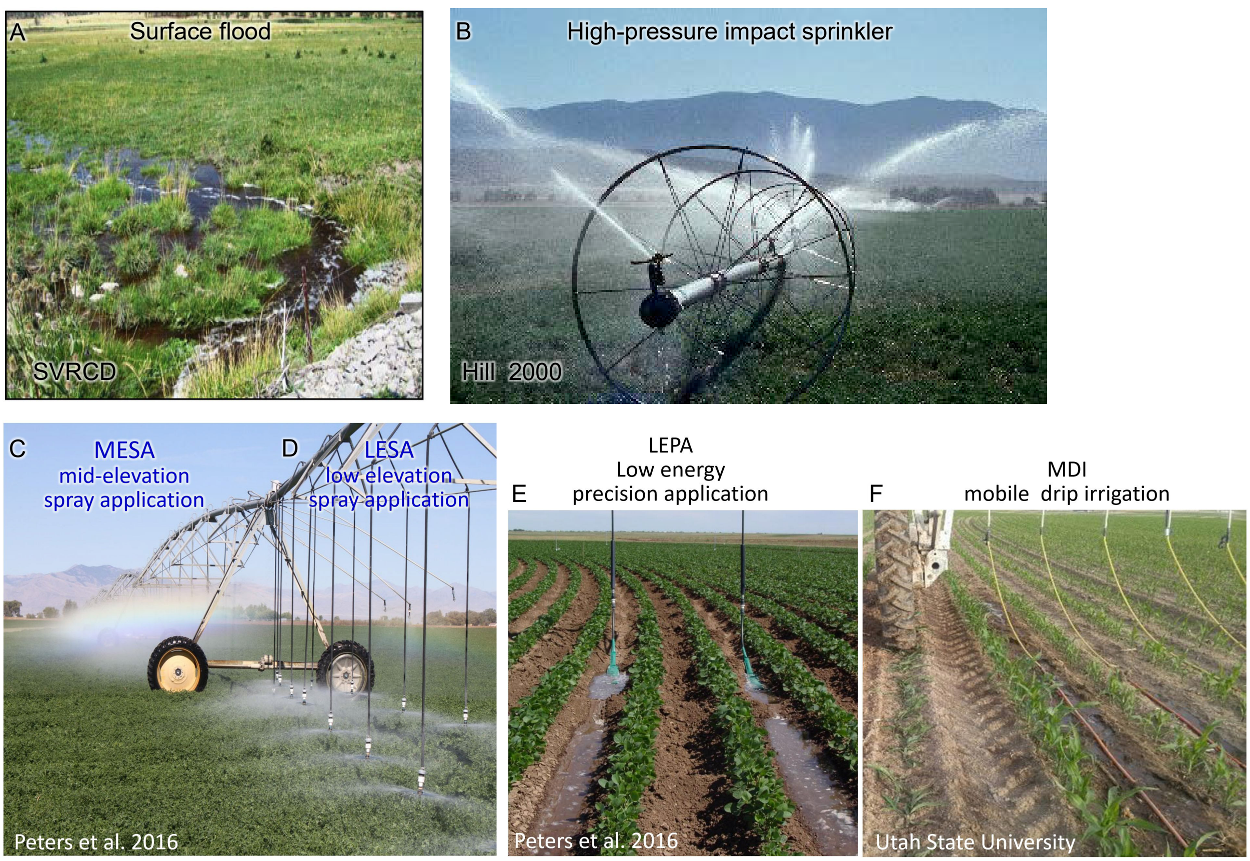


Figure 5. Photographs of irrigation technologies: (a) surface flood (b) high-pressure impact sprinkler, (c) MESA mid-elevation spray application, (d) LESA low elevation spray application, (e) LEPA low energy precision application, and (f) MDI mobile drip irrigation. Images modified from Peters et al. (2016), Utah State University (Yost et al. 2021), Hill (2000), and SVRCD[3].

[3] https://www.waterboards.ca.gov/northcoast/water_issues/programs/tmdls/shasta_river/110726/110726_tailwatrpub_pamphlet3.pdf

To understand how a particular irrigation technology will affect water budgets, it is instructive to consider the components of irrigation water budgets and their relative magnitudes (Figure 6). Water applied to a field is either consumed (evapotranspiration) or becomes a return flow (runoff or deep percolation). In the Scott and Shasta valleys all return flows are potentially re-usable for irrigation, because there are no unusable sinks (i.e., saline waterbodies) although water quality of return flows can be degraded by increased water temperatures and nutrients. Of the consumed fraction, some is productive (i.e., crop transpiration) while some is an unproductive waste (i.e., sprinkler water lost to wind and evaporation before reaching the soil). Definitions and details of these components are provided in the following bullets:

- *Sprinkler evaporation losses (SEL) is the sum of wind drift and evaporation losses (WDEL) and canopy interception losses (IL).* Some of the water leaving sprinkler nozzles is lost to the air before reaching the soil. These sprinkler evaporation losses (SEL) are due to the sum of wind drift and evaporation losses (WDEL) and canopy interception losses (IL) (Stambouli et al. 2013). Despite 15% lower irrigation rates in LESA and LEPA fields than in MESA fields, equal crop yields were achieved in an Eastern Washington peppermint/spearmint study, attributed to lower SEL in the LESA and LEPA fields (Molaei et al. 2021b).

    - *Wind Drift and Evaporation Losses (WDEL) is water that evaporates into the air or is carried away by the wind before reaching the crop or soil*. While increased humidity from WDEL slightly suppresses ET in downwind fields, the suppression equates to only a tiny fraction of the WDEL from the source field (Molaei 2021a). WDEL increases when droplets are smaller, sprinklers height is taller, wind speeds are higher, and relative humidity is lower (Molaei 2021c, Sarwar et al. 2019, Stambouli et al. 2013). A three-year study in Eastern Washington found WDEL of about 19% for MESA but only 4% for LESA (Sarwar et al. 2019). WDEL was 8.5% in an impact sprinkler-irrigated alfalfa field in Spain (Stambouli et al. 2013). WDEL is typically lower for irrigation at night than during the day (Stambouli et al. 2013).

    - *Interception Loss (IL) is water that lands on the surface of plants (leaves, etc.), including crops and weeds, but does not reach the soil surface*. This water then evaporates and returns to the air as water vapor. IL has a short-term suppressive effect on crop ET during and immediately after irrigation events, until the leaf surfaces dry out, but this suppression equates to only a small fraction of the total applied water (Molaei 2021c). IL increases total ET because high evaporation rates of intercepted water outweigh the short-term suppression of crop transpiration (Uddin et al. 2015, Marek et al. 2023); therefore, IL is considered non-beneficial. IL varies with application height (above, within, or below canopy), crop type (alfalfa or grass, etc.), crop growth stage (sparse or full canopy, etc.), and the depth of water applied per irrigation event (Lamm et al. 2019, Lin et al. 2020, Wang et al. 2020). IL was 2.9% in an impact sprinkler-irrigated alfalfa field in Spain (Stambouli et al. 2013). A study of low-pressure sprinkler-irrigated alfalfa in China found that canopy interception varied with growth stage and increased with plant height (Wang et al. 2020). During each irrigation event, 0.46–1.49 mm. of water was intercepted in the canopy, equating to 5.3–17.6% of the total irrigation water applied (Wang et al. 2020). Non-linear regressions to predict interception based on alfalfa plant height were developed by Jiao et al. (2016) and Wang et al. (2020).

- *Soil evaporation is the evaporation of water from wet soil or ponded water.* Soil evaporation rates vary with weather conditions (air temperature, wind speed, humidity, etc.), crop growth stage (sparse or full canopy, etc.), and sprinkler method (Lamm et al. 2019). Evaporation is minimized with drip irrigation. For example, soil evaporation in a Kansas cornfield was 35% lower with MDI than LESA (Kisekka et al. 2017).

- *Crop transpiration is water beneficially transpired and results in crop growth.* For most crops, the relationship between crop transpiration and crop production is essentially linear, meaning any reduction in crop transpiration results in economically undesirable decreases in crop yield (Perry and Steduto 2017).

- *Runoff is water that runs off a field into surface water* (e.g., a stream or river). This occurs when water is applied faster than can be infiltrated into the soil, such as during surface flood irrigation. Runoff can also occur with LESA or LEPA irrigation on soils with low infiltration capacity (Peters et al. 2016, Lamm et al., 2019).

- *Deep percolation is water that infiltrates into groundwater.* In surface flood irrigation, a large percent of water can percolate and become groundwater recharge (Figure 4).

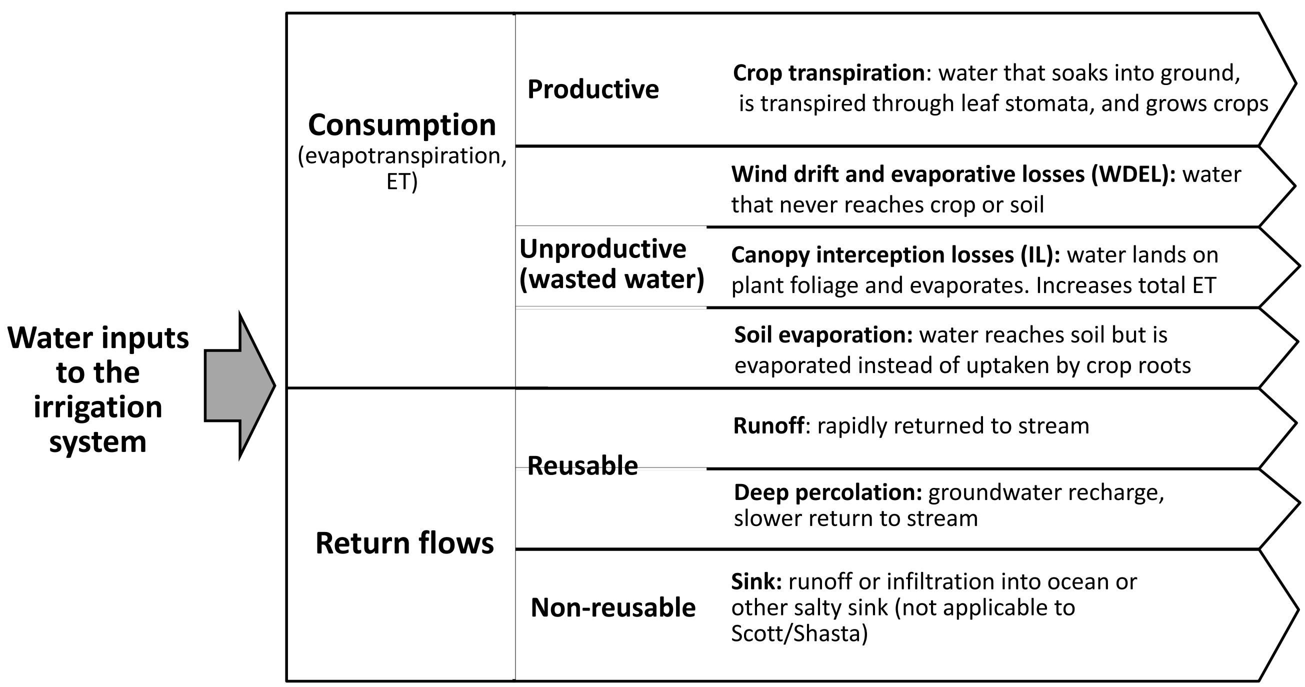


Figure 6. Water accounting schematic, showing the potential fates for water extracted for agricultural irrigation. Layout, concepts, and terminology adapted from Pérez-Blanco et al. (2020 and 2021) and Perry and Steduto (2017), with added detail.

1.4 WHICH AGRICULTURAL PRACTICES ARE MOST LIKELY TO REDUCE CONSUMPTIVE USE AND INCREASE RIVER FLOWS?

Given the discussion of irrigation efficiency and consumptive use in Section 1.3, which agricultural practices are most likely to reduce consumptive use and increase river flows?

The logical first choice would be to reduce unproductive consumptive uses (wind drift and evaporative losses, canopy interception losses, and soil evaporation) because these losses serve no purpose in crop growth, and reducing them would reduce consumptive use without detrimentally affecting agricultural production. This could be accomplished by: 1) upgrading wheel line impact sprinklers to center pivots with LESA, LEPA, or MDI, and 2) upgrading MESA center pivots to LESA, LEPA, or MDI. Reductions in consumptive use that could be achieved with these technologies would vary based on conditions (e.g., average wind speeds for a field), but based on the literature reviewed in Section 1.3 are likely in the range of 5-20%. Quantifying the maximum feasible reduction in unproductive consumptive use in the Scott and Shasta valleys would require a detailed assessment that is beyond the scope of this report. However, assuming a 10% reduction in total consumptive may be a reasonable, albeit aggressive, back-of-the-envelope estimate for the sake of exploration. Multiplying the monthly valley-wide June 2020 evapotranspiration values in Figure 26b by 10% yields 34 cfs for Shasta Valley and 24 cfs for Scott Valley. For September 2020, 10% of evapotranspiration equates to 16 cfs for Shasta Valley and 13 cfs for Scott Valley. In comparison, the emergency minimum instream flows for Shasta River are 50 cfs for June, 50 cfs for September 1–15, and 75 cfs for September 16–30. Emergency minimum instream flows for Scott River are 125 cfs for June 1–23, 90 cfs for June 24–30, and 33 cfs for September. The months of June and October were selected here for comparison because they are the months during the irrigation season with the maximum and minimum evapotranspiration, respectively.

The ballpark estimates above suggest that solely reducing unproductive consumptive use would likely not be sufficient to achieve the desired instream flows. Meeting instream flows would likely also require some level of reduction to crop transpiration and agricultural production. Reduced crop transpiration could occur through early cessation of irrigation or fallowing of fields.

Conversion of surface flood irrigation to wheel-line sprinklers would likely increase consumptive use, as would conversion to center pivots unless pivots were equipped with a technology with near-zero wind drift and evaporative losses (i.e., LEPA or MDI). Similarly, converting sprinkler heads to smaller nozzles, as was done in some Scott Valley LCS agreements, would likely increase consumptive use by enhancing wind drift losses.

1.5 MEASURING AND ESTIMATING ACTUAL EVAPOTRANSPIRATION

Actual evapotranspiration (ET_a) is the total quantity of water that is removed from a surface (i.e., the land) due to a combination of evaporation and transpiration. There are several methods available for measuring and estimating ET_a:

- ET_a can be directly measured in the field using specialized equipment known as eddy flux towers (Volk et al. 2023).
- Since direct field measurements of ET_a are difficult and expensive, the most common method for estimating ET for irrigated crops is to multiply a reference ET (derived from weather data) by a crop coefficient. Reference ET assumes a well-watered reference crop

(ET_0 for grass or ET_r for alfalfa) with no drought stress and is typically calculated with the physical Penman-Monteith equation (Monteith 1965) using the following data inputs: solar radiation, air temperature, humidity, and wind speed (Blankenau 2020). The crop coefficient, abbreviated K_c, is the assumed ET of the crop relative to the reference ET. For example, the surface water balance model in the Scott Valley Integrated Hydrologic Model used a K_c value of 0.9 for alfalfa (Foglia et al. 2018).

- ET_a can also be estimated using satellite remote sensing, as explained in Section 1.6.1 below. Remote sensing approaches do not rely on the assumption that the vegetation is well-watered.

1.6 REMOTE SENSING OF AGRICULTURAL WATER USE AND CROP DYNAMICS

1.6.1 SATELLITES AND VEGETATION INDICES

Many no-cost satellite-based remote sensing datasets are available to inform assessments of agricultural water use and vegetation dynamics (Dauwalter et al. 2017, García-Santos et al. 2022, Zeng et al. 2022). The highest resolution free images available are aerial photos from the U.S. Department of Agriculture's (USDA) National Agricultural Inventory Program[4] (NAIP), but these are only available every 1–3 years (Figure 7a). The European Space Agency's Sentinel 2 satellites have a return interval of 5 days and spatial resolution of 10 meters (Claverie et al. 2018) (Figure 7b). The National Aeronautics and Space Administration (NASA) and U.S. Geological Survey (USGS) Landsat satellites have a return interval of approximately 8 days (Figure 7) (Hemati et al. 2021, Wulder et al. 2022).

Each satellite has sensors that record various bands of wavelengths. Indices of vegetation greenness can be calculated from combinations of bands (Zeng et al. 2022). Two of the most popular vegetation indices are Normalized Difference Vegetation Index (NDVI) (Figure 7e) and Enhanced Vegetation Index (EVI) (Figure 7d). EVI has a higher dynamic range than NDVI, allowing better differentiation between forests and deep green well-watered agricultural fields, as shown in Figure 7.

The Landsat satellites have a thermal infrared (TIR) sensor that measures the temperature of the Earth's surface, also known as skin temperature (Figure 7f). The native spatial resolution of the Landsat thermal infrared sensors is 60–120 meters, sufficient to characterize the dynamics of agricultural fields including corners around center pivots, and data are downscaled to 30 meters using visible and near-infrared sensors (García-Santos et al. 2022). The skin temperature is different from the air temperature as it is the temperature of the surface of the Earth. Just as human skin is evaporatively cooled by sweat, transpiration of water from a plant's stomata cools the leaf surface. As a result, the Landsat thermal infrared sensors can detect temperature differences between a dry field and field with actively transpiring plants (Figure 7f). These thermal infrared sensors are a key driver of most algorithms for remotely sensing of evapotranspiration, including those used in OpenET (García-Santos et al. 2022, Melton et al., 2021).

[4] https://naip-usdaonline.hub.arcgis.com/

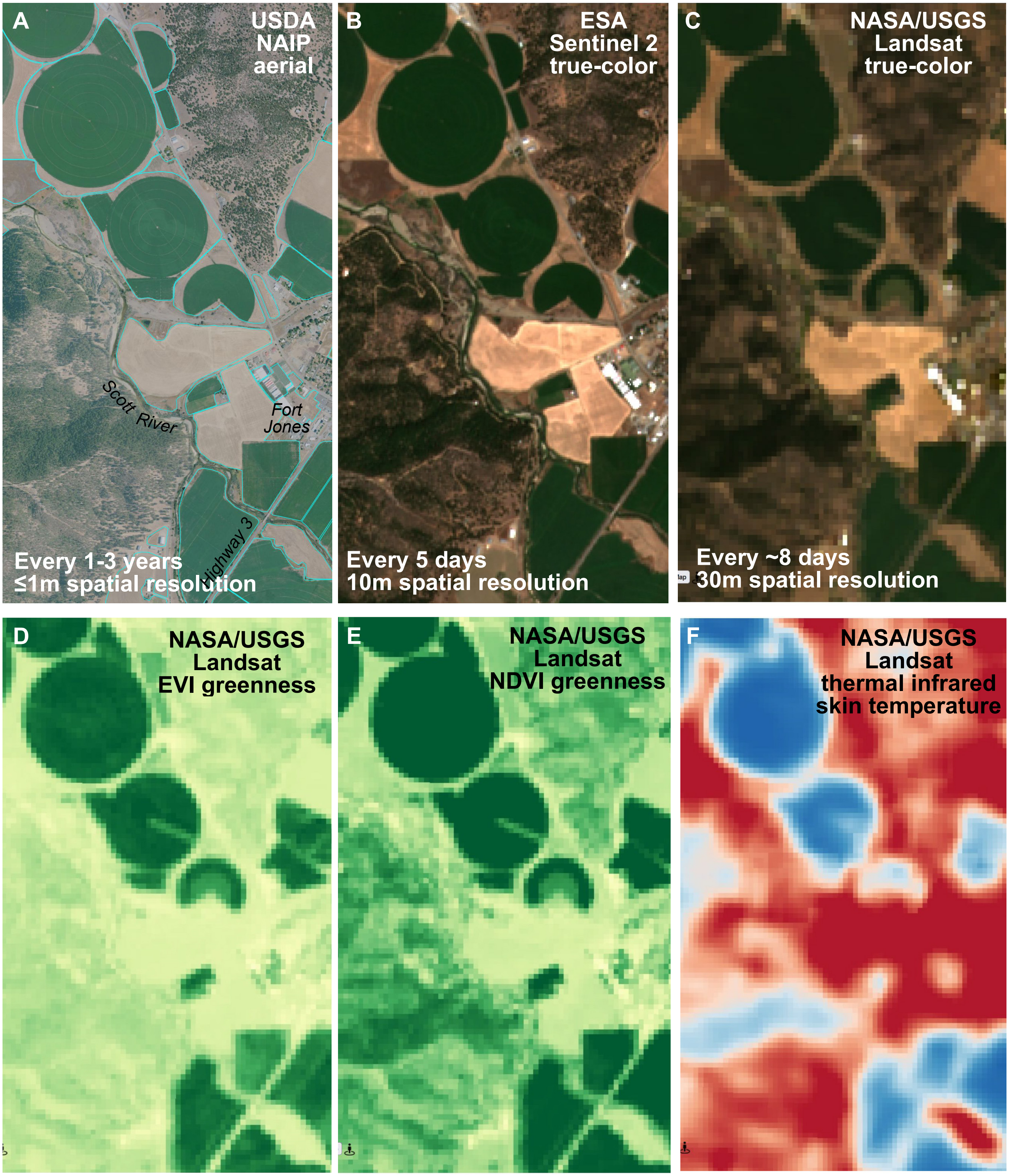


Figure 7. Examples of remote sensing products available for the same week in mid-July 2022 for the Scott Valley downstream of the Highway 3 bridge crossing near Fort Jones. Black text in (a) are labeled landmarks. Product dates: (a) 7/15/2022, (b) average of 7/15/2022-7/20/2022, and (c)(d)(e)(f) 7/20/2022. See text for key to abbreviations. All panels were created using ClimateEngine.org except (a).

1.6.2 EVAPOTRANSPIRATION AND OPENET

1.6.2.1 METHODS SUMMARY

OpenET is a collaborative project using remote sensing to develop detailed time series maps of actual evapotranspiration (ET_a) in the western United States (Melton et al., 2021). Participants include the federal government, universities, non-governmental organizations, and for-profit corporations. Readers interested in in-depth technical details should read Melton et al. (2021). The following paragraph provides a brief explanation of OpenET methods, making generalizations and omitting many details (Figure 7).

OpenET uses data from satellites (primarily Landsat skin temperatures but also other Landsat sensors and other satellites) to generate a time series of the percent of reference ET detected for each 30-meter pixel for each available day, similar to a crop coefficient that varies in time and space. After filling gaps on days when satellite data are not available, the percent of reference ET is then multiplied by a reference ET derived from gridded weather data (in California, primarily spatial CIMIS), yielding pixel-scale ET_a. OpenET uses six different algorithms for calculating pixel-scale ET_a, and a final ensemble average is created by combining the six estimates with outliers excluded. The resulting final ET_a time series for each pixel is then aggregated to agricultural field boundaries.

1.6.2.2 ACCURACY AND SOURCES OF ERROR

OpenET has been validated with detailed field measurements from eddy flux tower sites for a range of ecosystems, crops, and climates across the Western U.S. In the Phase 1 intercomparison at 24 crop sites, average errors for the OpenET ensemble means were 16.4% at a monthly timestep and 21.8% at a daily timestep (Melton et al. 2021). The Phase 2 intercomparison is in progress, with preliminary results at 45 crop sites indicating average errors of 16.6% for monthly time scales and 13.2% for the agricultural growing season which spans several months[5].

There are multiple potential sources of error in the OpenET data, including: inherent limits of satellite sensor instruments, atmospheric conditions (e.g., smoke and clouds), gap-filling of missing satellite data, and gridded meteorological data. The effects of wildfire smoke on OpenET results have not been specifically evaluated. Cloud and aerosol screens exclude Landsat pixels (and a buffer surrounding them) when smoke is detected, but extended periods of smoke would cause long periods of missing satellite data that need to be filled, potentially degrading accuracy. Alfalfa is harvested multiple times during the growing season and these cutting cycles presumably affect ET_a. The linear interpolation used to fill temporal gaps in satellite data does not account for these cutting-driven cycles, so individual alfalfa fields might have artificially higher or lower ET_a depending on when cuttings happened relative to the satellite overpasses, particularly if clouds or smoke cause long gaps (Landsat satellites return approximately every eight days). These errors could be important for individual fields, but are unlikely to substantively affect larger-scale (i.e., sub-basin) averages because the timing of cuttings varies among fields. If local weather data are available, such as from the California Department of Water Resources' California Irrigation Management Information System (CIMIS) stations, these data could be used in place of the gridded meteorological data and may result in a more accurate calculation of ET_a.

[5] https://d197for5662m48.cloudfront.net/documents/publicationstatus/113056/preprint_pdf/550add2c4cbbd9281b66b5c3533c17e3.pdf

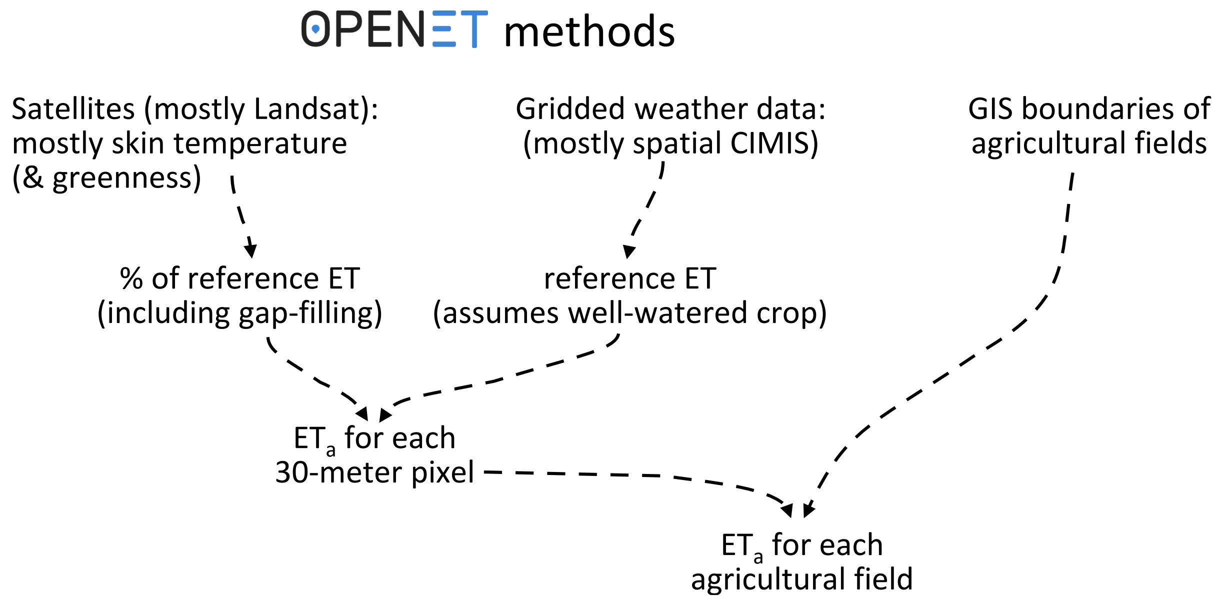


Figure 8. Simplified version of OpenET methods for calculating actual evapotranspiration (ET_a). See Melton et al. (2021) for technical explanation and details.

1.7 STUDY OBJECTIVES

The objectives of this study were to: 1) explore no-cost publicly available remote sensing methods for assessing agricultural water use, 2) explain those remote sensing methods in an accessible way to facilitate understanding by people who are not remote sensing practitioners, and 3) apply remote sensing and streamflow gage data to evaluate the effects of the 2021 and 2022 irrigation curtailments in the Scott and Shasta valleys. Results are intended to be repeatable and inform water resource management.

2 METHODS

2.1 DATA SOURCES

2.1.1 GIS MAP DATA

2.1.1.1 AGRICULTURAL FIELD BOUNDARIES AND IRRIGATION WATER SOURCES

GIS boundaries of Scott Valley land use, including irrigation sources (i.e., groundwater, surface water, etc.) for agricultural fields, were obtained from the Scott Valley Integrated Hydrologic Model (SVIHM) (Kouba and Harter 2023)[6]. Similar data for Shasta Valley generated in 2010 were obtained from CDWR. A separate set of agricultural field boundaries in the Klamath Basin, including Shasta and Scott, were obtained by request from OpenET (Melton et al. 2021).

[6] Data downloaded from https://github.com/cmkouba/EoDS_MS_HESS/tree/main/Data/SVIHM%20Reference%20Data. There were multiple versions of sub-watershed and irrigation source in land use GIS file. I used the *WTRSRCE_11* and *Trib_2011* columns.

2.1.1.2 MANAGEMENT UNITS

Several categories of land management units were assembled to enable comparative analyses: LCS agreements, irrigation districts, and Safe Harbor Agreements (SHAs). GIS boundaries of the 2022 Scott River LCS agreements, derived from parcel boundaries, were obtained from the SWRCB Division of Water Rights along with a spreadsheet summarizing water use estimates for each LCS (Figure 2). The LCS datasets contained a few errors that I corrected and informed SWRCB about. Minor remaining issues include overlap between LCS polygons (e.g., #5 and #40), apparently due to the leasing of portions of parcels. GIS boundaries of irrigation districts in the Shasta Valley from the California Special Districts Association were downloaded from koordinates.com[7]. Friends of the Shasta River provided a GIS boundary for the Shasta Water Users Association (for convenience, it is categorized in this report as in irrigation district even though it is not a special district) and the boundaries of properties enrolled in the Shasta River SHAs[8], derived from parcel boundaries.

2.1.2 REMOTE SENSING PRODUCTS AND TOOLS

Two easy-to-use online tools were used for accessing and summarizing satellite data: OpenET (Section 1.6.2) (Melton et al. 2021) and Sentinel Hub EO Browser[9]. Specific methods are discussed below in Section 2.2.3. In addition, Figure 7 in the Introduction above presents examples images from another online tool, Climate Engine[10] (Huntington et al. 2017). When possible, URLs are provided in figure captions so readers can browse the original data online. While many of the detailed data summaries presented in the Results section of this report were created with custom scripts in R desktop software (R Core Team 2022), the online tools are surprisingly easy to use for browsing satellite imagery or generating time series for single polygons of interest. Brief introductory tutorials to those tools are available in Appendix D.

The field greenness (NDVI) data were only evaluated for the months of April–September because it is the core irrigation season. In addition, NDVI values during the winter are affected by the presence of snow which is not relevant to objectives of this study.

2.1.3 STREAMFLOW GAGES

Streamflow gage data for nine sites were obtained from the U.S. Geological Survey (USGS) and California Department of Water Resources (CDWR) (Table 1). Approved daily USGS data were downloaded using the R dataRetrieval package (De Cicco et al. 2022). Approved daily CDWR data were downloaded from the California Water Data Library[11]. At the Sugar Creek gage (site code F25890), approved records ended 3/21/2022 so 15-minute provisional data through 9/30/2022 were downloaded from the California Data Exchange Center (CDEC[12]). Due to lack of high-flow measurements, CDWR data are only available during low and moderate flows. For simplicity, an additional USGS flow gage on the mainstem Shasta River near Montague was not used because flows appear to be relatively similar to the Shasta River at Yreka gage. An additional CDWR flow gage on the Little Shasta River was not used because it is only available on CDEC (station LSR) as provisional data with apparent outliers.

[7] https://koordinates.com/layer/96028-california-special-districts/
[8] https://www.fisheries.noaa.gov/resource/document/shasta-river-template-safe-harbor-agreement-and-site-plans
[9] https://apps.sentinel-hub.com/eo-browser/
[10] https://www.climateengine.org/
[11] https://wdl.water.ca.gov/waterdatalibrary
[12] https://cdec.water.ca.gov/dynamicapp/QueryF?s=SGN

Table 1. Streamflow data sites utilized in this study.

Site Code	Site Name	Source	Period of Record Utilized	Purpose and/or Notes
11522500	Salmon R a Somes Bar CA	USGS	2002-01-01 to 2022-12-31	Diversions upstream have minimal influence on low flows. Can be used as a hydrologic reference.
11523200	Trinity R AB Coffee C NR Trinity Center CA	USGS	2002-01-01 to 2022-12-31	Diversions upstream have minimal influence on low flows, except during severe droughts (Asarian et al. 2023). Can be used as a hydrologic reference.
11517500	Shasta R NR Yreka CA	USGS	2002-01-01 to 2022-12-31	Outlet of Shasta Valley
11519500	Scott R NR Fort Jones CA	USGS	2002-01-01 to 2022-12-31	Outlet of Scott Valley
F25650	French Creek at Highway 3 near Callahan	CDWR	2004-10-01 to 2022-08-30	Diversions upstream affect low flows. Can be used to assess effects of surface water curtailments on tributary flow.
F25890	Sugar Creek near Callahan	CDWR	2009-10-01 to 2022-12-31	
F25484	Shackleford Creek near Mugginsville	CDWR	2004-10-01 to 2022-09-30	
F26050	Scott River, East Fork, at Callahan	CDWR	2002-06-28 to 2022-08-30	
F28100	Scott River, South Fork, near Callahan	CDWR	2002-06-29 to 2022-08-30	

2.2 ANALYSES

2.2.1 DAILY GAGED STREAMFLOW

I plotted daily flow data from nine USGS and CDWR streamflow gages for the years 2002–2022 to qualitatively assess differences between years that might be attributable to irrigation curtailments (Table 1). I calculated the median flow for each Julian day and gage for the common period 2010–2022 when all gages were operating most years (Sugar Creek gage was the last to start, 9/10/2009), and then compared daily flows for each year to Julian day medians.

I also used gages from the Salmon River and upper Trinity River with flows relatively unaffected by human water diversions as hydrologic references to compare with gages in the mainstem Scott River and its tributaries (Table 1). The watersheds of the Salmon and upper Trinity rivers are located to the west and southeast of the Scott River watershed, respectively, and have similar snowmelt-driven mountain hydrology although they lack the Scott River's large alluvial valley (Van Kirk and Naman 2008). The Shasta River has unique volcanic geology with stable year-round spring-derived flows and lacks a nearby hydrologic reference gage.

2.2.2 REVIEW OF SATELLITE IMAGERY FROM 2020 AND 2022

As a qualitative illustration to support this report's quantitative analyses, I present imagery from the Landsat and Sentinel 2 satellites showing conditions in the Scott and Shasta valleys in mid-August 2020 and 2022, obtained from the Sentinel Hub EO Browser. The images presented are Sentinel 2 true color, Sentinel 2 EVI greenness, and Landsat skin temperature. Dates were chosen to avoid wildfire smoke that limited the availability of high-quality satellite images in late summer 2020 (Figure 9).

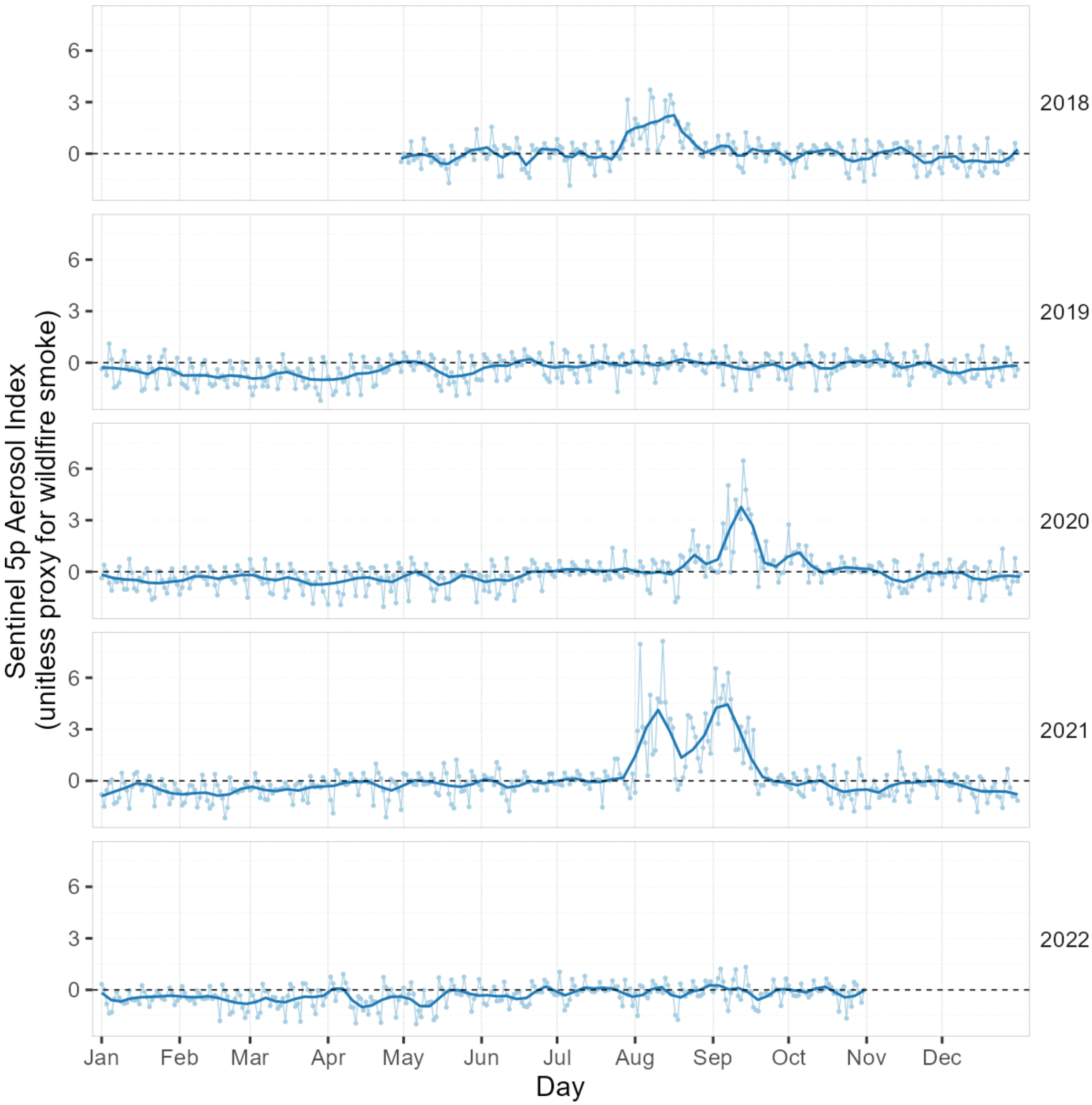


Figure 9. Daily time series of the Sentinel 5p Aerosol Index (Stein Zweers 2022) for Scott Valley agricultural lands for 4/30/2018–10/31/2022, used here as a proxy for wildfire smoke. Light blue lines are values for individual days. Dark blue lines are LOESS (locally estimated scatterplot smoothing) smoothers. Data were summarized using the Sentinel Hub EO browser (https://sentinelshare.page.link/uw2Z).

2.2.3 EVAPOTRANSPIRATION AND GREENNESS IN AGRICULTURAL FIELDS

The OpenET website allows easy access to time series for individual fields. However, the OpenET Application Programming Interface (API) is not yet publicly available, so summarizing OpenET data across large geographic areas is currently difficult[13]. I contacted OpenET support, and Will Carrara of Ames Research Center Co-operative for Research in Earth Science and Technology (ARC-CREST) responded with an offer to generate a time series for my area of interest. I then requested and received a monthly time series for ET_a and NDVI for each OpenET agricultural field in the Klamath Basin. Only data for the Scott, Shasta, and Butte valleys are presented in this report. ET_a units presented in this report differ based on context but can include:

- *ET_a volume* in units of acre-feet per month or year. Volume is used to emphasize relative contributions to ET_a in a geographic unit (e.g., in which sub-watershed does most ET_a occur?)
- *ET_a depth* in units of inches per month or year, calculated by dividing ET_a volume by area. Rate is used for area-normalized comparisons (i.e., did irrigation source affect the amount of water consumed per acre?). Units are similar to precipitation.
- *ET_a rate* in units of cubic feet per second (cfs), calculated by dividing ET_a volume by the number of seconds in a month. Rate is used to compare ET_a to streamflow.

As a supplement to the Landsat-based OpenET NDVI, I also reviewed true color, EVI, and NDVI from the Sentinel 2 satellites and Harmonized Landsat Sentinel (HLS). Relative to Landsat, Sentinel 2 has a higher spatial resolution (10 meters vs. 30 meters) and temporal resolution (once every five days vs. approximately every eight days). HLS combines Sentinel 2 and Landsat so is available more frequently than either dataset in isolation. Animated movies of these results are provided in Appendix C.

2.2.3.1 SUB-BASIN RESULTS

Using the R terra package (Hijmans 2023), I intersected the GIS boundaries of the OpenET agricultural fields with USGS National Hydrography Dataset (NHD) sub-basins (i.e., 8-digit Hydrologic Units). I then joined the OpenET monthly time series to the field boundaries, and aggregated ET_a and NDVI to the sub-basin scale. I present two sets of results for Shasta Valley, one for the entire valley and another that excludes fields within the Montague Water Conservation District (MCWA) because those fields are irrigated with water stored in Dwinnell Reservoir and thus were not directly affected by the 2021–2022 curtailments.

2.2.3.2 STRATIFICATION BY IRRIGATION SOURCE AND SUB-WATERSHEDS

I used the R terra package to intersect the OpenET agricultural fields with the SVIHM agricultural fields in Scott Valley (Figure 10), enabling the OpenET time series data to be aggregated using the attributes of the SVIHM fields including sub-watershed and irrigation source (see Section 3.3.2 for maps).

There are differences in the geographic extent of these two datasets. SVIHM polygons cover the entire floor of Scott Valley but do not include the upper reaches of tributaries (i.e., Moffett Creek and East Fork Scott River) (Figure 10). OpenET fields include upper reaches of tributaries but do not include many un-irrigated areas around the edges of the valley that are included in SVIHM (Figure 10). In addition, the polygon boundaries do not match exactly and there is not a one-to-

[13] The 2016–2021 pixel-scale OpenET data are available through the Google Earth Engine catalog, but summarize these data by field requires writing code and the 2022 are not yet available.

one relationship between the datasets (i.e., one OpenET polygon may be represented by multiple polygons in SVIHM, or vice-versa).

A similar analysis would be possible for Shasta Valley using the irrigation water source data from CDWR, but was not conducted due to time and budget constraints.

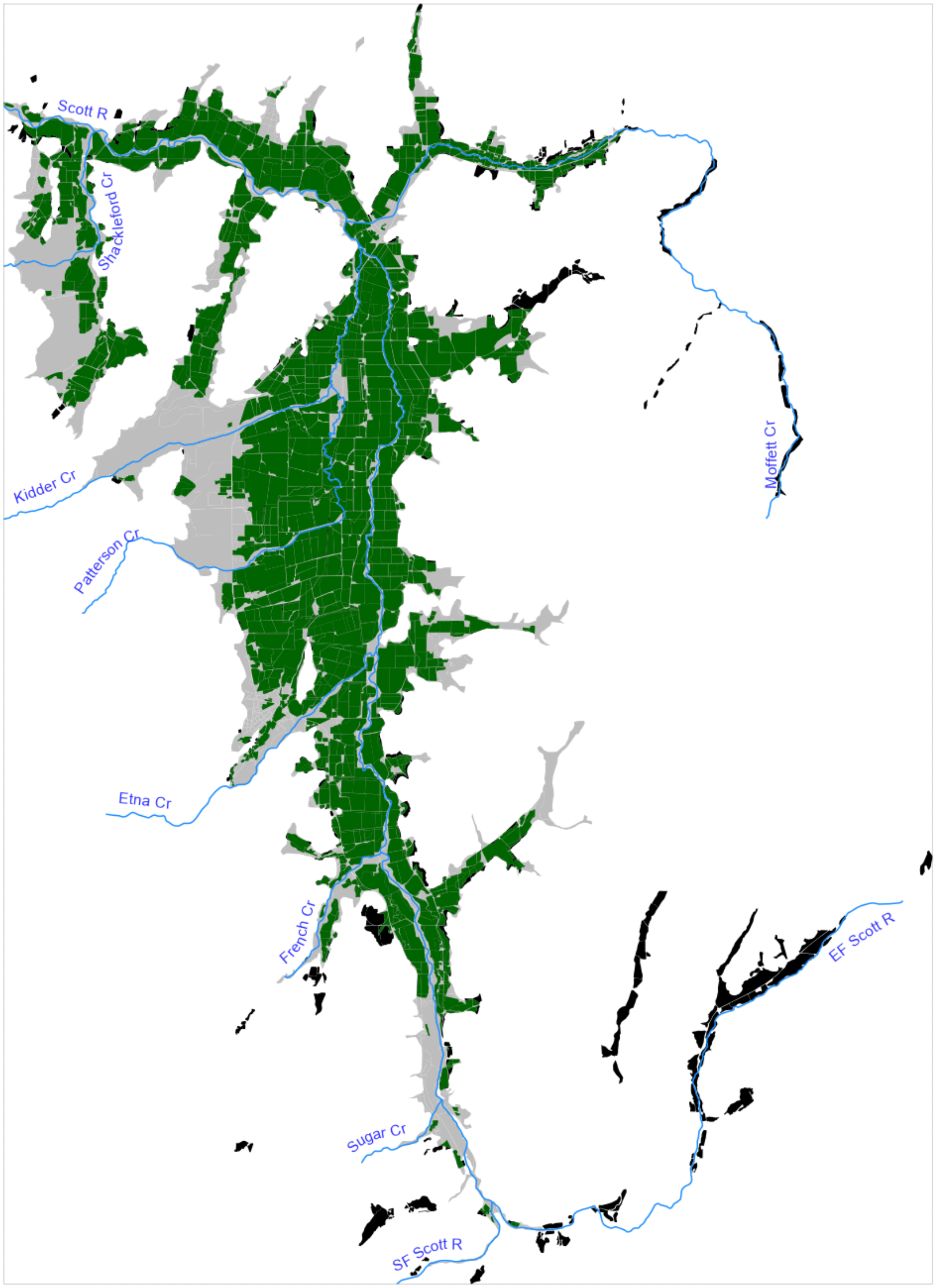


Figure 10. Extents of the Scott Valley Integrated Hydrologic Model (SVIHM) land use polygons and OpenET agricultural fields. Legend: green = overlap of SVHIM land use polygons and OpenET fields, gray = SVHIM land use polygons that are not also OpenET fields, black = OpenET fields that are not also SVHIM land use polygons.

2.2.3.3 *STRATIFICATION BY LOCAL COOPERATIVE SOLUTIONS (LCS) AND MANAGEMENT UNITS*

For Scott River, I used the R terra package to intersect the OpenET agricultural fields with the LCS polygons, enabling the OpenET time series data to be aggregated for each LCS. A similar analysis would be possible for management units (i.e., irrigation districts and SHAs) in Shasta Valley, but was not conducted due to time and budget constraints.

2.2.3.4 *EVALUATING EFFECTS OF 2021 PUMPING FORBEARANCE CONTRACTS*

As discussed in Section 1.2 above, three ranches in the northern portion of Scott Valley signed forbearance contracts in which they agreed not to pump groundwater in August-October 2021 in exchange for cash payments. I manually selected the OpenET fields that best matched those shown in CDFW's map of the fields included in the 2021 groundwater forbearance contracts (Figure 3). Polygons did not match exactly, but were close enough as to provide a high-quality representation when fields were aggregated. Using the intersection of OpenET fields and SVIHM land use (Section 2.1.1.1), I excluded fields not designated as groundwater-irrigated in SVIHM. I then generated a monthly 2017–2022 time series of ET_a and NDVI data for the aggregated 2021 groundwater forbearance fields and compared them to other groundwater-irrigated fields in the Scott Valley to evaluate whether ET_a and NDVI were reduced during the 2021 forbearance period.

2.2.4 COMPARISON OF EVAPOTRANSPIRATION AND STREAMFLOW

To place the monthly sub-basin-wide ET_a estimates in context, I compared them to monthly average river flows from the USGS gages located at the outlet of Scott and Shasta valleys.

3 RESULTS AND DISCUSSION

3.1 DAILY GAGED STREAMFLOW

At the Salmon River and Trinity River hydrologic reference gages, flows in the months of June–August were lowest in 2021; however, these gages show differing trends for these months in 2022, with Salmon flows near the median in 2022 and below-median in 2020, and Trinity flows below median in 2020 and 2022 (Figure 11). These contrasting signals in 2022 were uncommon in the 2002–2022 period of record evaluated, with Salmon and Trinity flows typically having consistent inter-year patterns (Figure A28). These contrasting signals also complicate interpretation of 2022 flows at the Scott River sub-basin gages.

Inter-year patterns in the years 2020–2022 in the mainstem Scott River gage largely track the Salmon River gage (i.e., 2022 flows close to median, 2020 lower than median, and 2021 lowest) (Figure 11). This is consistent with other years in 2002–2022 (Figure A28), suggesting that the 2022 irrigation curtailments did not strongly affect flows at the Scott Valley outlet. In contrast, late August flows in Shackleford and French creeks were higher in 2022 than in any other year 2002–2022, despite being close to median flows earlier in the year (Figure 11). While it is difficult to conclusively ascertain the cause of these high late August flows at Shackleford and French creeks, they are likely due to a combination of diversion curtailments and summer precipitation events. Storms in early July 2022 appear to have caused a doubling of flows in Shackleford Creek and a more subtle flow increase in French Creek and other gages. A second round of thunderstorms in early August, which also caused massive debris torrents within the McKinney Fire footprint, appears to have briefly but substantially increased flow in French Creek and South Fork Scott River. Scott River tributaries besides Shackleford Creek and French Creek do not show evidence of curtailment-driven increases in 2022. For example, by late August 2022, flows at Sugar Creek and East Fork Scott River reached their lowest levels in the 2002–2022 record (Figure 11). The South Fork Scott River has consistently higher late summer baseflow per unit of watershed area than other gaged Scott River tributaries (Figure 11b) and maintained flows close to medians in 2022.

During April–August, flows in the Shasta River were much higher in 2022 than 2020 or 2021, except during late August 2022 when the Shasta River Water Association publicly violated curtailment orders (Figure 11).

3.2 REVIEW OF SATELLITE IMAGERY FROM 2020 AND 2022

Satellite imagery showing conditions in the Scott and Shasta valleys in mid-August 2020 and 2022 is provided in Figure 12 (Sentinel 2 true color), Figure 13 (Sentinel 2 Enhanced Vegetation Index [EVI] greenness), and Figure 14 (Landsat skin temperature). The true color and EVI images indicate that large portions of the Shasta Valley were less green in 2022 than in 2020, presumably as a result of the irrigation curtailments (Figure 12 and Figure 13). The areas in Shasta Valley with reduced greenness in 2022 also have corresponding increases in Landsat skin temperatures (Figure 14), presumably due to less evaporative cooling because of less irrigation. Contrary to the observations in Shasta Valley, at the valley-wide scale the overall greenness and skin temperatures in Scott Valley appear to be similar in 2020 and 2022. Individual fields in Scott Valley vary as to whether they were greener in 2020 or 2022, likely due the timing of the mid-August satellite images relative to alfalfa cutting cycles, as well as crop rotations. A common Scott Valley management practice is an alfalfa/grain rotation with one year of a grain followed by seven years of alfalfa (Foglia et al. 2018).

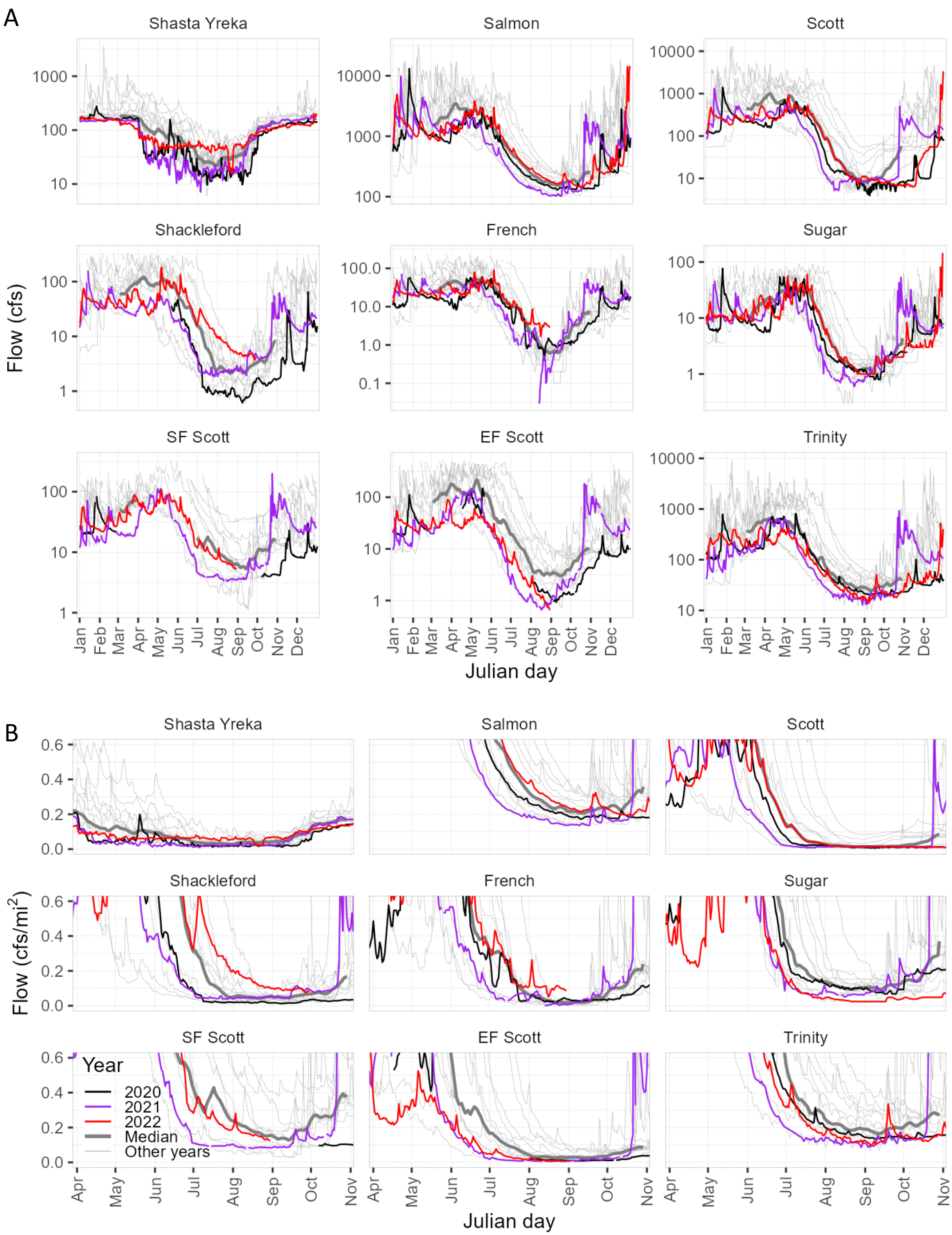


Figure 11. Daily streamflow at gages in the Scott, Shasta, Salmon, and Trinity sub-basins for the years 2010–2022, highlighting the years 2020–2022: (a) in units of cfs with log10 y-axis for Jan–Dec, and (b) in units of cfs/mi^2 for Apr–Oct, with y-axis truncated to highlight low flows. Medians were calculated from 2010–2022 data.

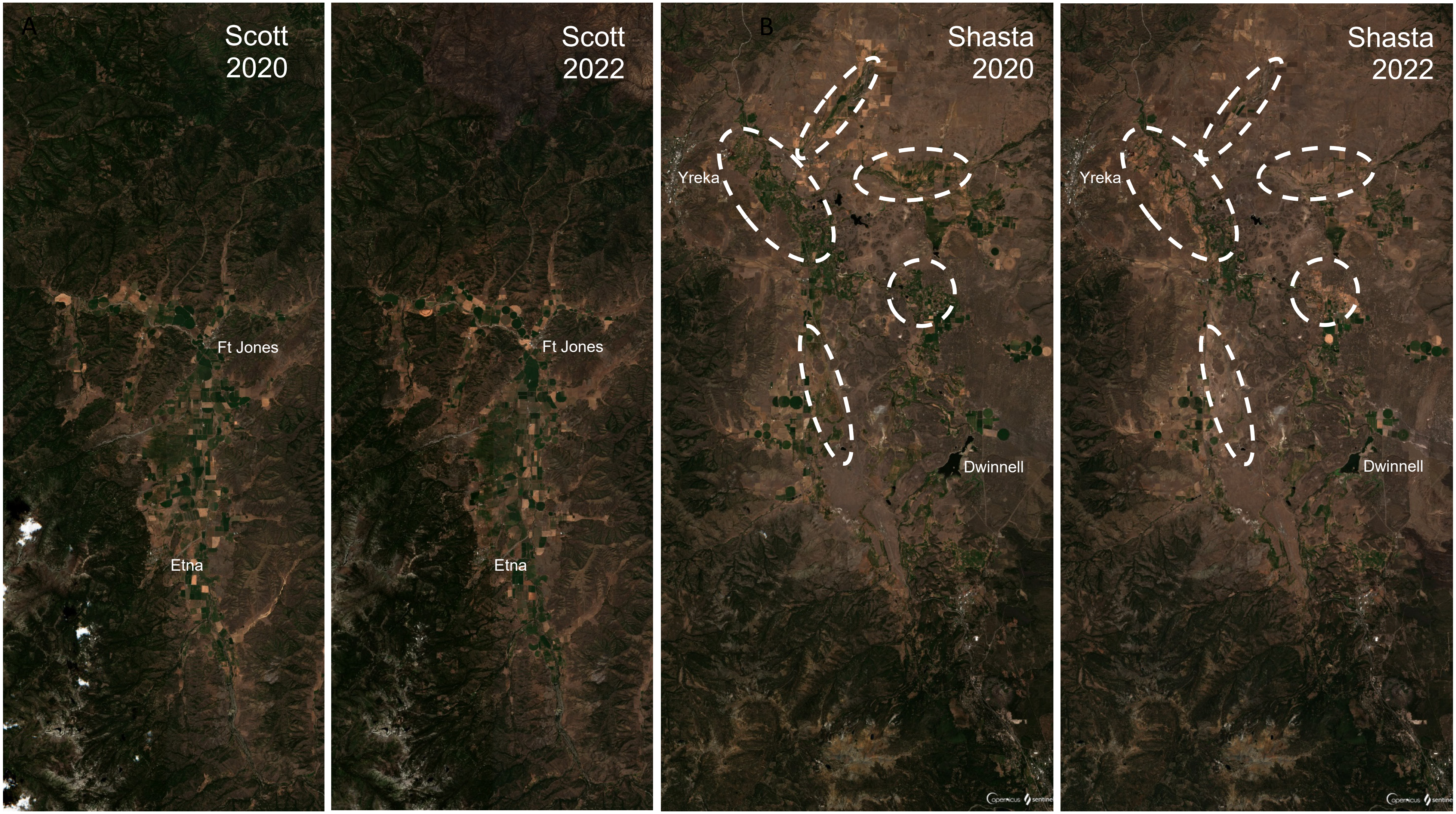


Figure 12. True color images from Sentinel 2 comparing the Shasta and Scott valleys on August 15 in 2020 and 2022. White ovals in Shasta are areas with visually apparent differences between years. To browse and compare these images in high resolution with the Sentinel Hub EO Browser, use the following link: https://sentinelshare.page.link/mwGH.

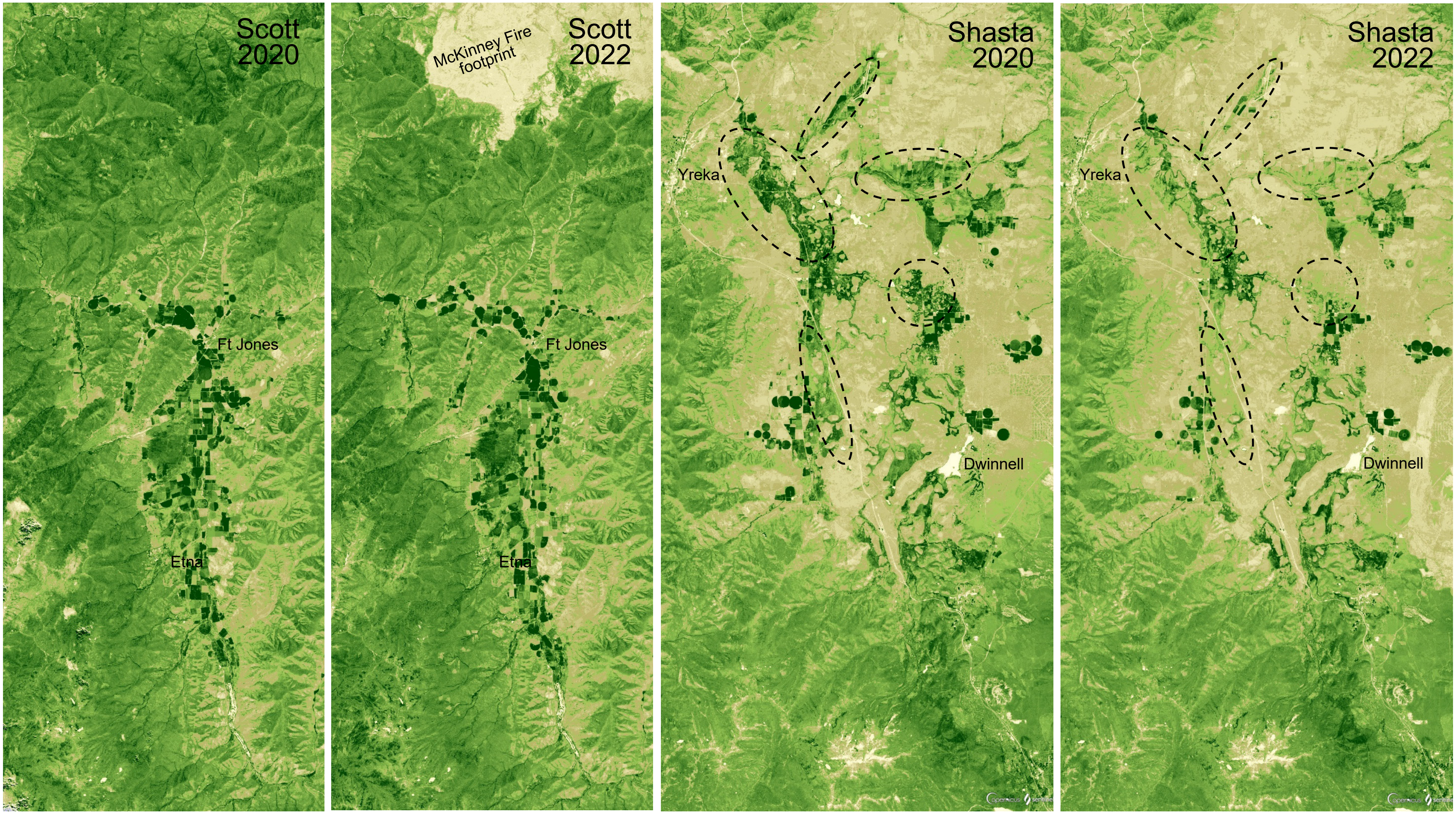


Figure 13. Enhanced Vegetation Index (EVI) greenness from Sentinel 2 comparing the Shasta and Scott valleys on August 15 in 2020 and 2022. Black ovals in Shasta are areas with visually apparent differences between years. To browse and compare these images in high resolution with the Sentinel Hub EO Browser, use the following link: https://sentinelshare.page.link/mwGH.

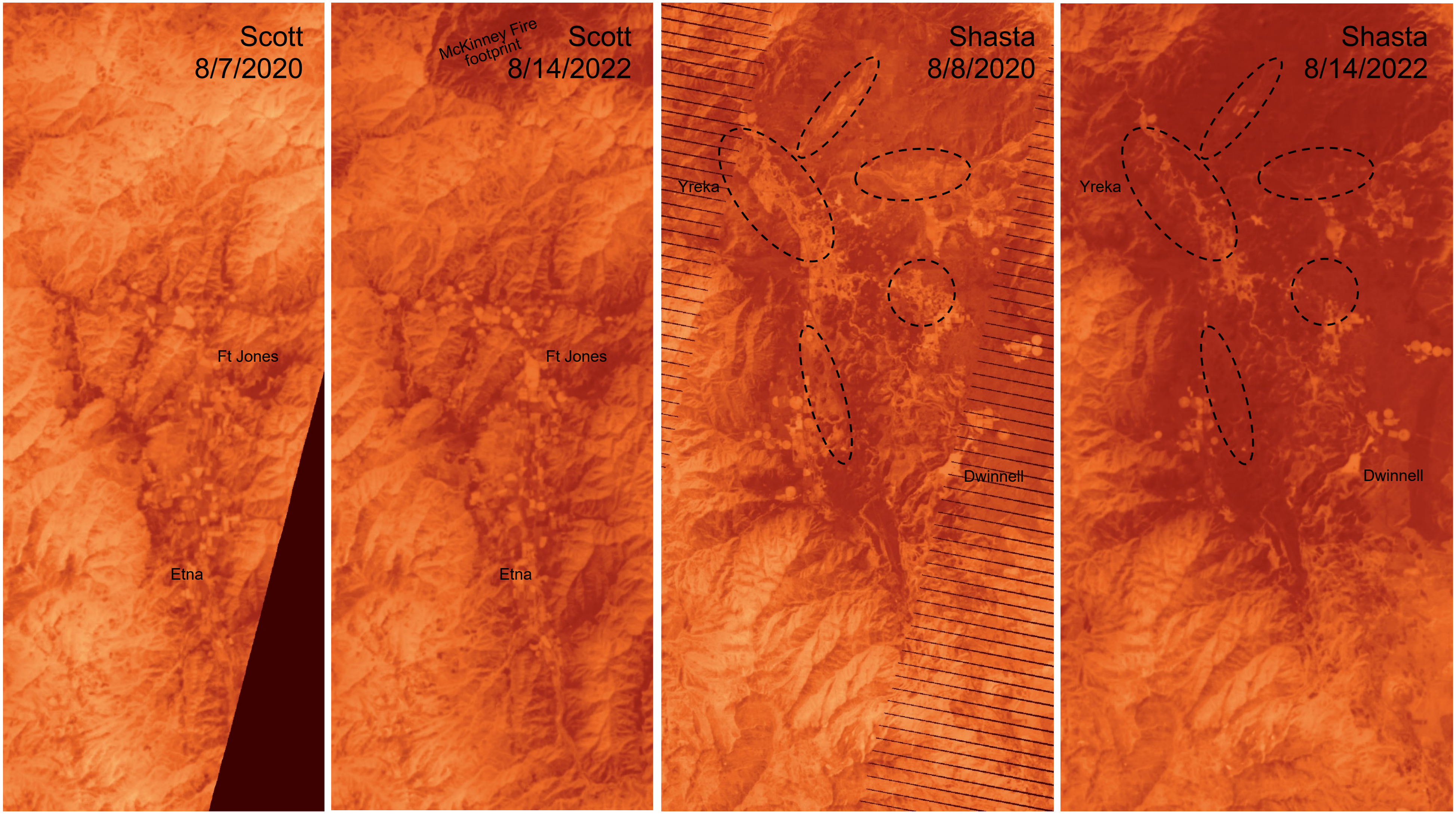


Figure 14. Landsat skin temperature comparing the Shasta and Scott valleys in mid-August of 2020 and 2022. To browse and compare these images in high resolution with the Sentinel Hub EO Browser, use the following link: https://sentinelshare.page.link/e4Zv.

3.3 EVAPOTRANSPIRATION AND GREENNESS IN AGRICULTURAL FIELDS

3.3.1 BASINWIDE RESULTS

Monthly and annual OpenET summaries indicated that ET_a depths were substantially lower in the Shasta sub-basin in 2022 than previous years (Figure 15). Including or excluding fields irrigated with water stored in Dwinnell Reservoir by the Montague Water Conservation District (MCWA) does not substantially change ET_a depth. Lower ET_a in 2022 occurred throughout the entire April–September irrigation season and were similar to inter-year patterns of field greenness (NDVI) (Figure 16). ET_a reached a seasonal peak in June 2021 similar to June 2020 levels, but then declined in July and August more rapidly than previous years. In contrast to Shasta results, ET_a depths were stable in the Scott and Butte sub-basins from 2020–2022 (Figure 15, Figure 16). In all three sub-basins, the greatest ET_a depths occurred in 2017, for unknown reasons.

Most individual fields in the Scott showed no reduction in ET_a from 2020 to 2022 whereas many fields in the Shasta did show reductions (Figure 17). Maps of annual ET_a for individual fields in the Scott and Shasta for each year are provided in Appendix B in Figure A29, Figure A30, Figure A31, and Figure A32.

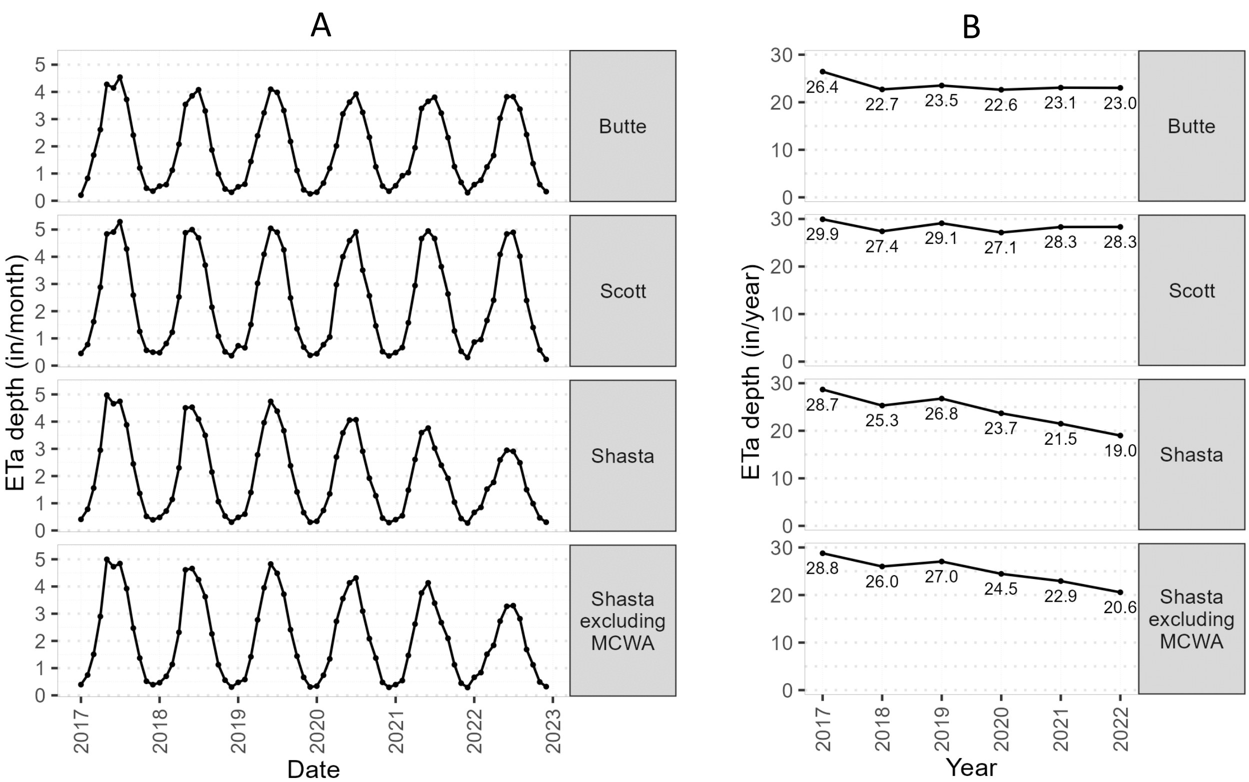


Figure 15. (a) Monthly and (b) annual time series of actual evapotranspiration (ET_a) depth for all agricultural fields on the Scott, Shasta, and Butte sub-basins for 2017–2022. Data summarized from OpenET. MCWA = Montague Water Conservation District.

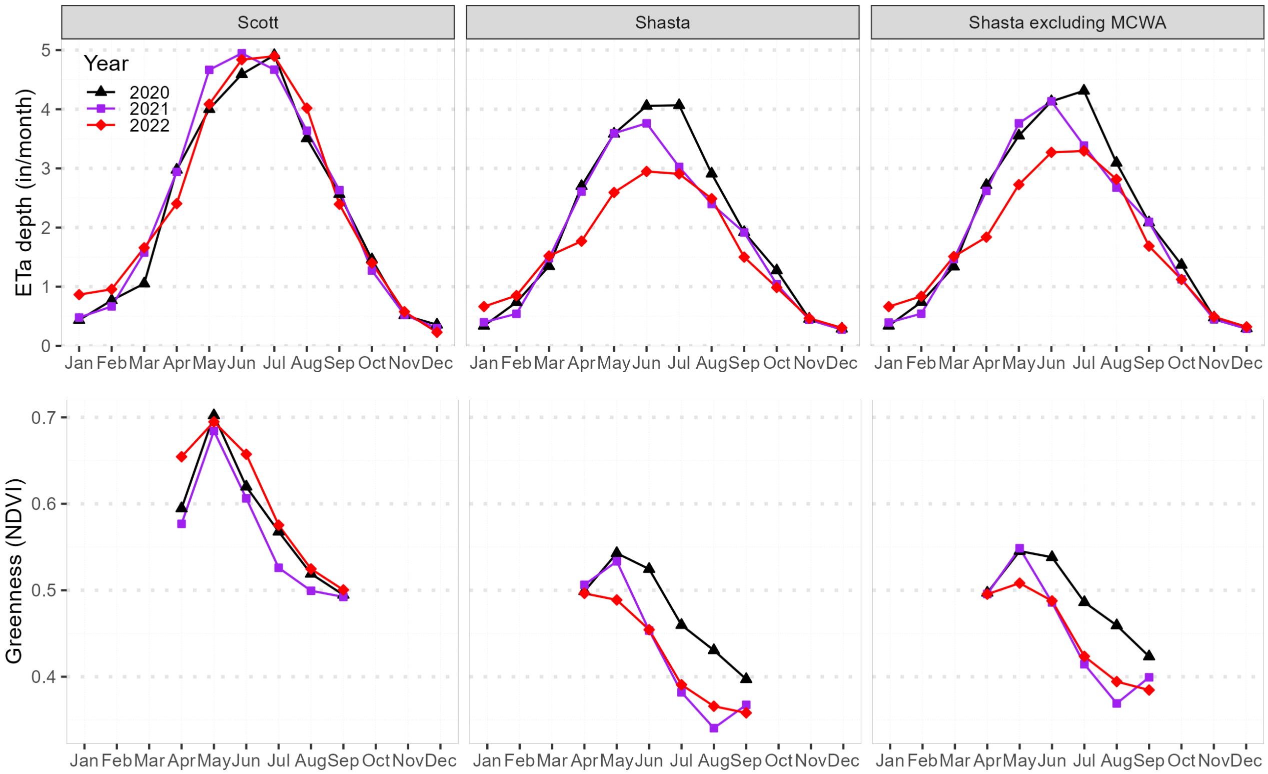


Figure 16. Monthly time series of actual evapotranspiration (ET_a) and greenness (NDVI, normalized difference vegetation index) for all agricultural fields in the (a) Scott, and (b) Shasta sub-basins for 2020–2022. Data summarized from OpenET.

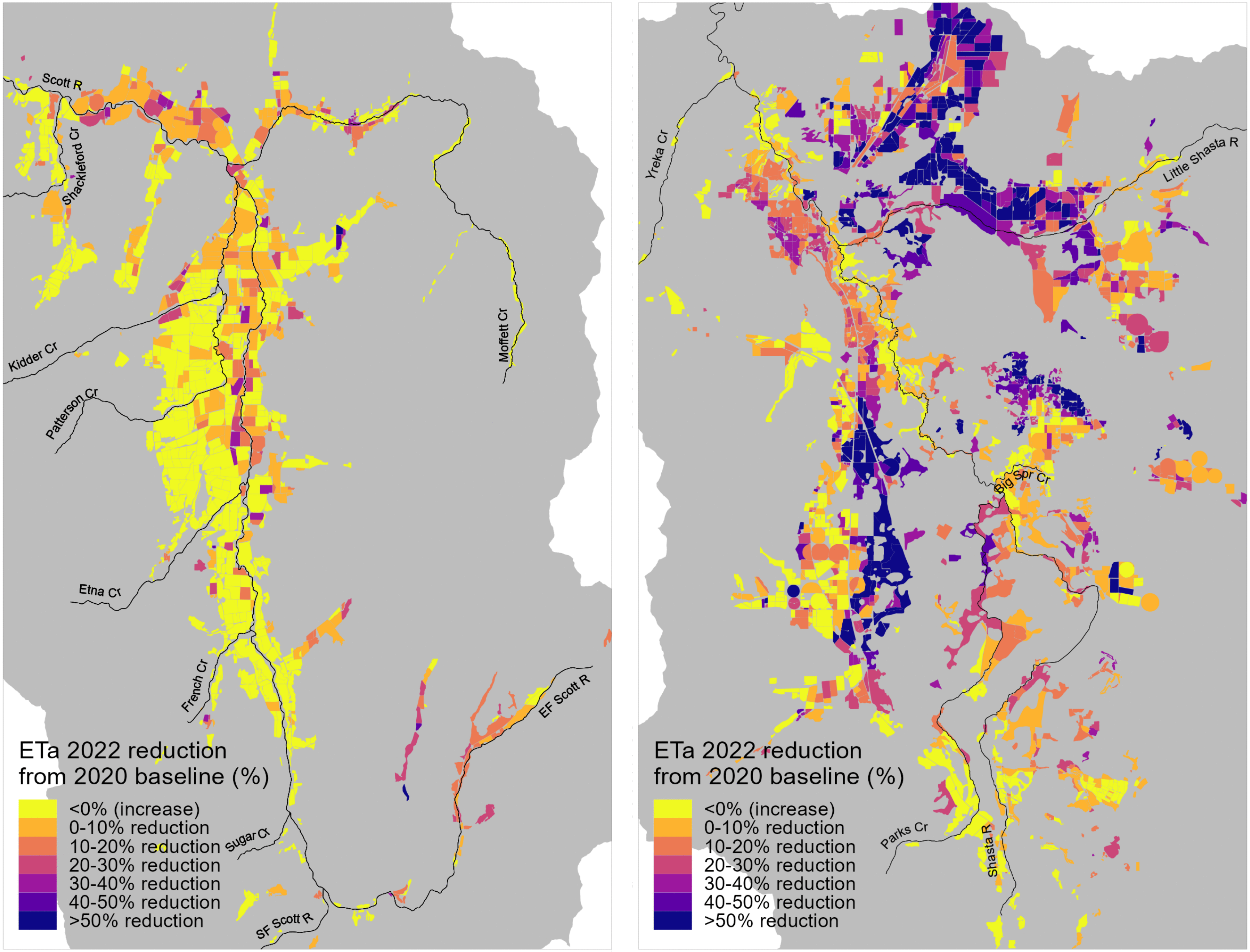


Figure 17. Maps showing the percent reduction in actual evapotranspiration (ET_a) for each agricultural field in the Scott and Shasta valleys between 2022 and the 2020 baseline. Data summarized from OpenET.

3.3.2 STRATIFICATION BY IRRIGATION SOURCE AND SUB-WATERSHEDS

In Scott Valley, monthly timing and magnitude of ET_a and NDVI were relatively consistent among years for most irrigation water sources (Figure 18, Figure 19). The largest differences occurred for sub-irrigated land, where ET_a and NDVI were higher in 2022 than 2020 and 2021 (Figure 18, Figure 19). These sub-irrigated lands are in areas with high water tables in the Etna, Patterson, and Kidder Creek watersheds (Figure 19, Figure 20). In addition, in 2022 fields irrigated with surface water also had higher NDVI in April–September, and higher ET_a in July and August, than in 2020 and 2021 (Figure 18, Figure 19).

In the Shasta Valley, I did not calculate ET_a summaries by irrigation water source, but side-by-side map comparisons suggest that ET_a reductions from 2020 to 2022 were generally greater in surface water-irrigated fields than groundwater-irrigated fields, except for large reductions in the groundwater-irrigated Big Springs Irrigation District (Figure 21).

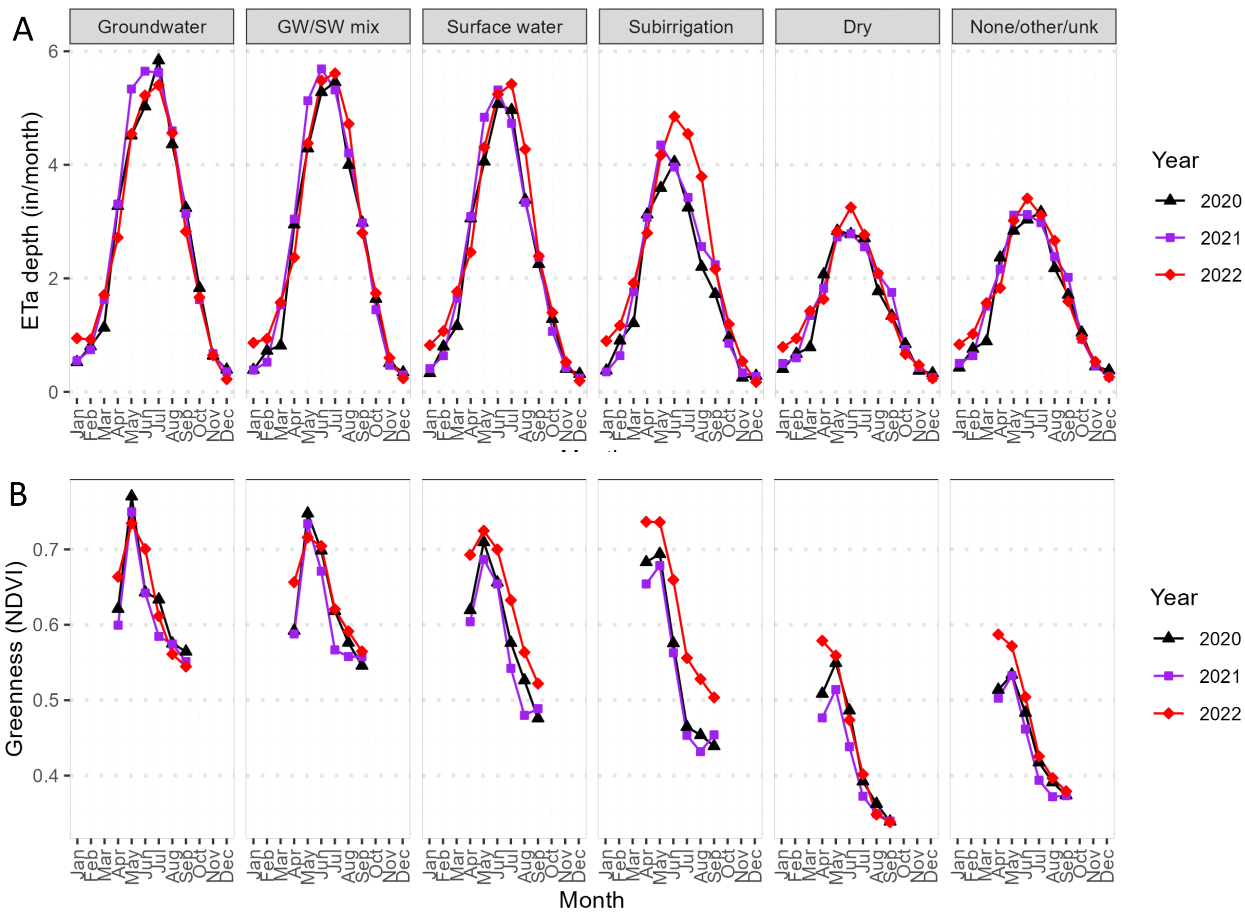


Figure 18. Monthly time series of (a) actual evapotranspiration (ET_a) and (b) greenness (NDVI, normalized difference vegetation index) for agricultural fields in Scott Valley for 2020–2022. Data summarized from OpenET using irrigation sources from SVIHM.

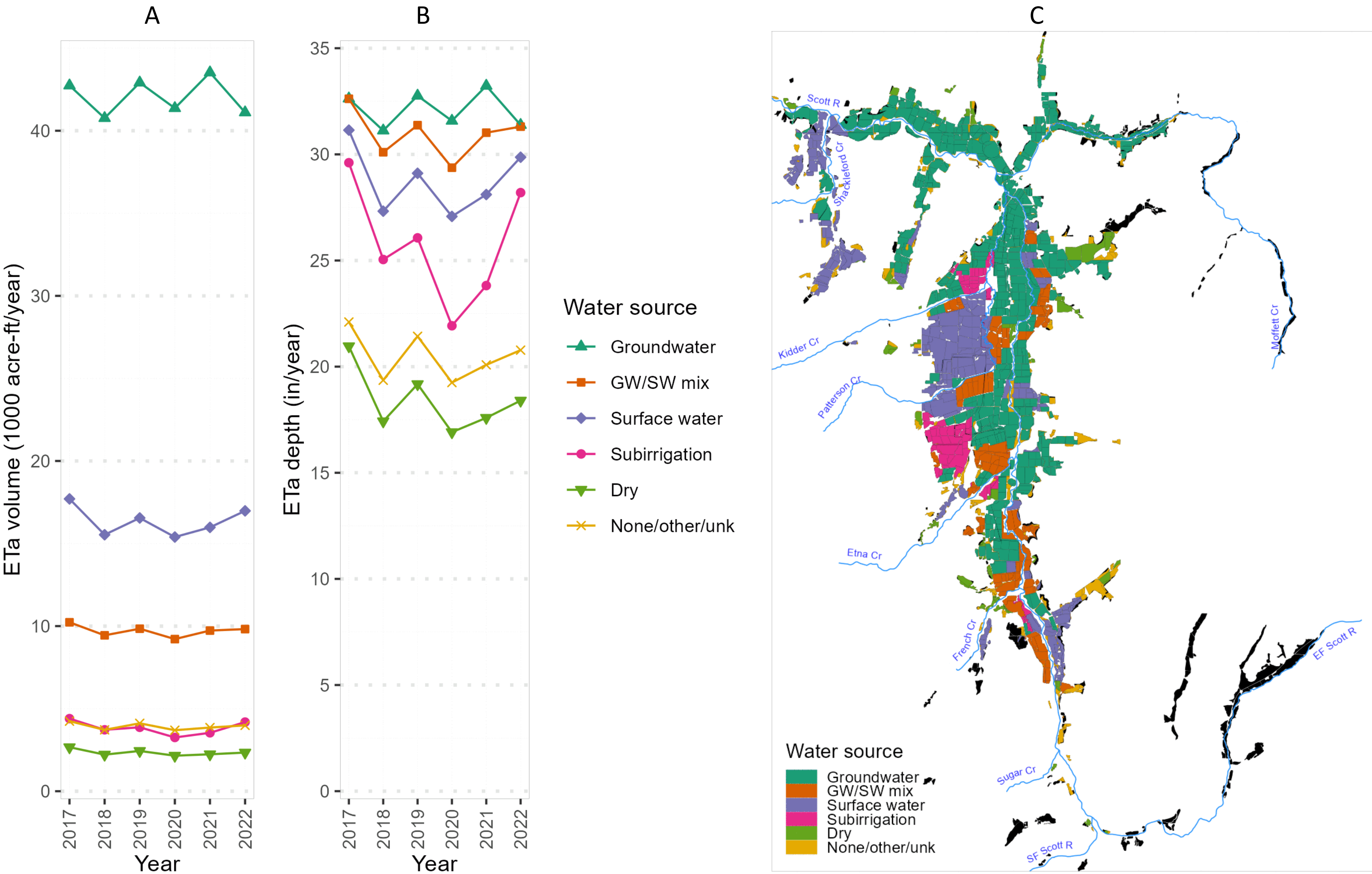


Figure 19. Annual time series of actual evapotranspiration (ET_a) (a) volume and (b) depth for agricultural fields in Scott Valley for 2017–2022, color-coded by irrigation source. Data summarized from OpenET using irrigation sources from SVIHM, shown in map (c). Black polygons indicate areas that are OpenET fields but are not also SVHIM land use polygons.

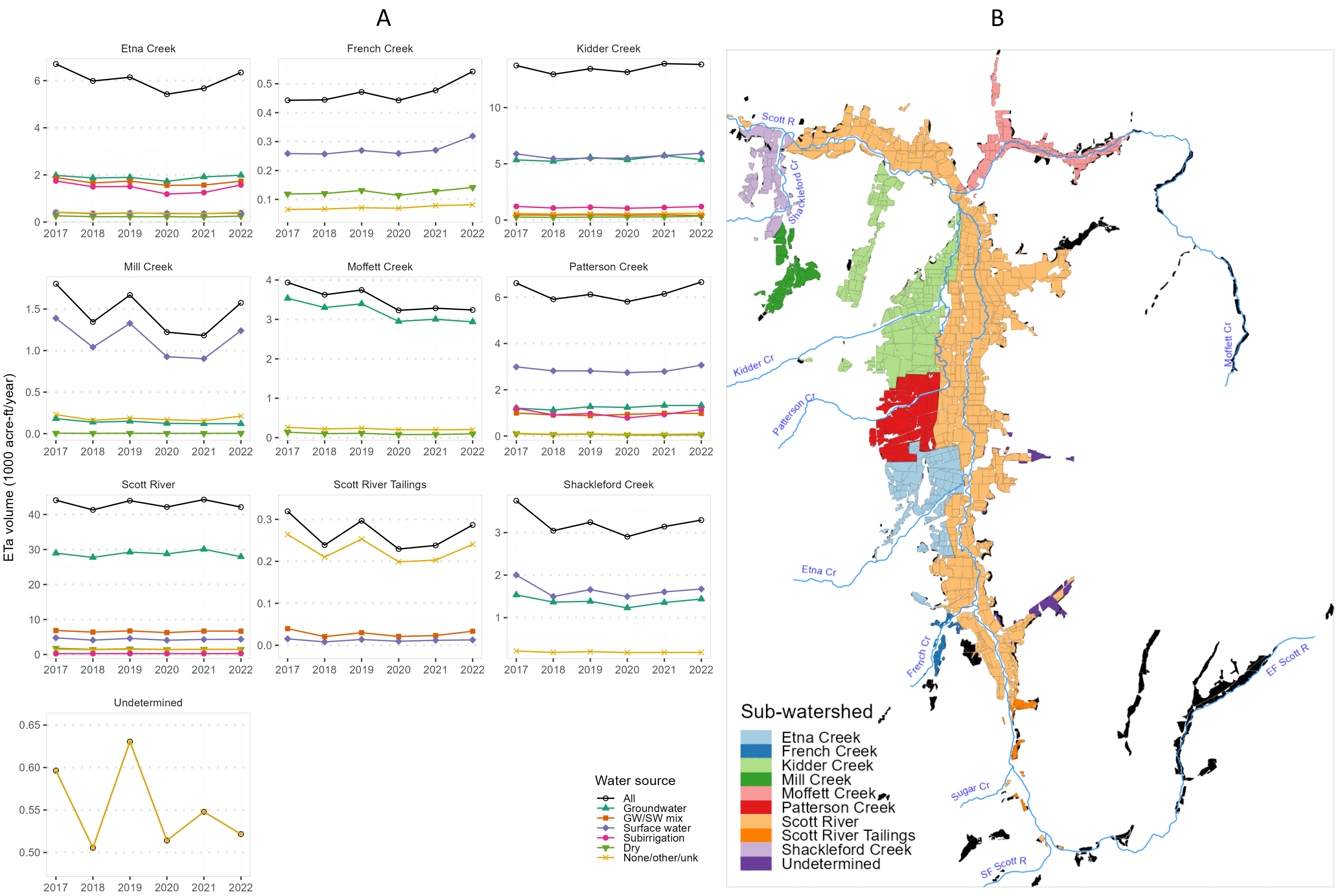


Figure 20. Annual time series of actual evapotranspiration (ET_a) (a) volume for agricultural fields in each Scott Valley sub-watershed for 2017–2022, color-coded by irrigation source. Data summarized from OpenET using irrigation sources and (b) sub-watersheds from SVIHM. Black polygons indicate areas that are OpenET fields but are not also SVHIM land use polygons. An alternative version of this figure with ET_a depths is available as Figure A33.

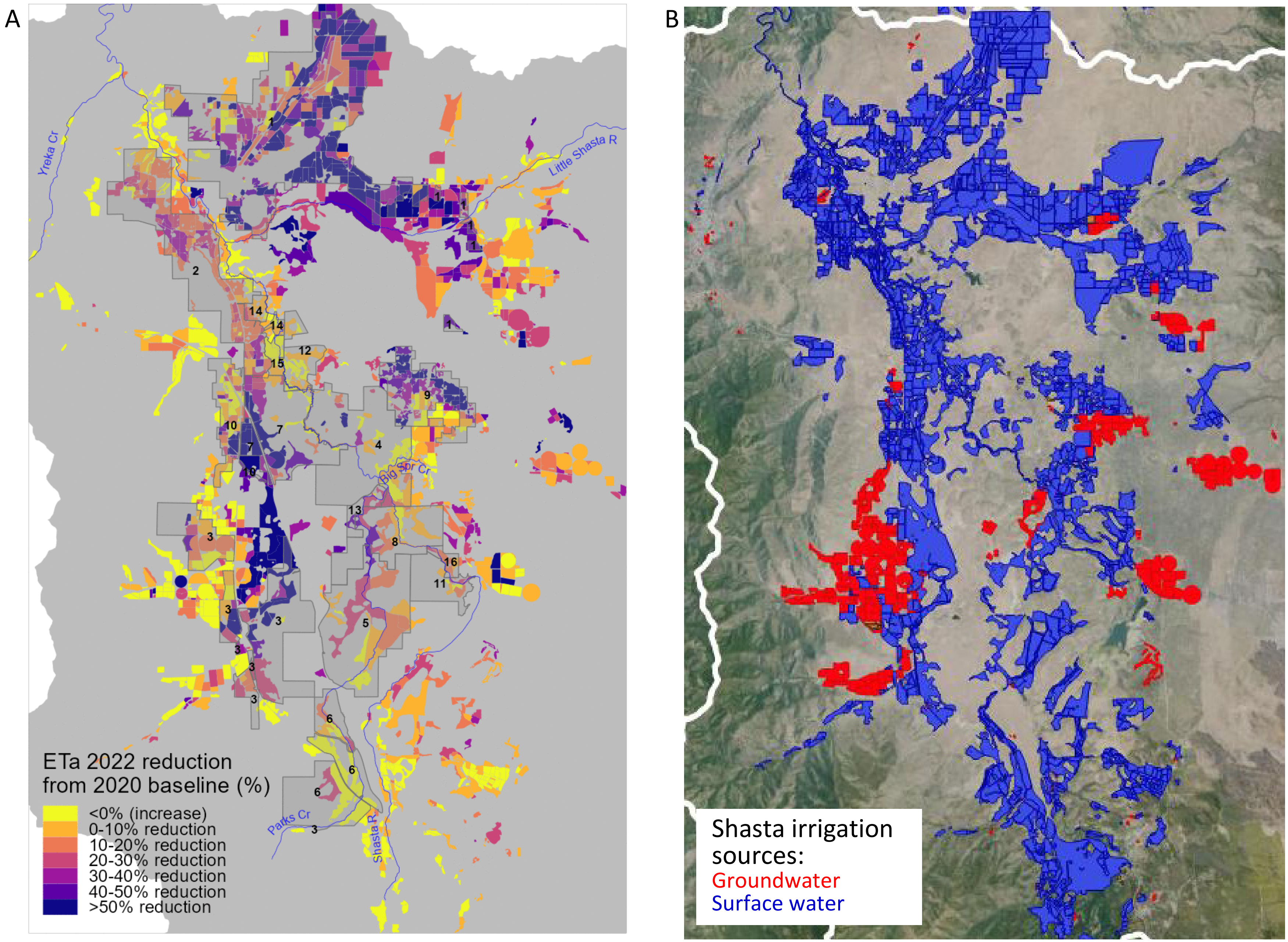


Figure 21. (a) Shasta Valley map showing the percent reduction in actual evapotranspiration (ET_a) for each OpenET agricultural field between 2022 and the 2020 baseline, with management units (irrigation districts and Safe Harbor Agreements) overlaid as numbered gray polygons. (b) Irrigation sources from CDWR. See Table B4 in Appendix B for key to management unit numbers. Data summarized from OpenET.

3.3.3 STRATIFICATION BY LOCAL COOPERATIVE SOLUTIONS (LCS) AND MANAGEMENT UNITS

In the Scott River, 47 ranches developed Local Cooperative Solutions (LCS) agreements for the 2022 irrigation season (Figure A35). Figure 22 shows annual ET_a volumes and depths for each of these properties for 2020, 2021, and 2022. None of the ranches achieved a 30% ET_a reduction from 2020 to 2022 (Figure 22b, Figure 23b). The 16.8-acre Ranch #45, the 125-acre Ranch #26, and 165-acre Ranch #24 came closest, with reductions of 21%, 20%, and 14%, respectively (Table B3, Figure 23b). Practices in Ranch #45's LCS were: a) no corner cannon irrigation, and b) all irrigation would cease after the second cutting of alfalfa after June 30. Practices in Ranch #26 LCS were that 30.4% of their typical acreage would not be irrigated in 2022. Practices in Ranch #24's LCS were: a) crop rotation of 80 acres of alfalfa to grain hay, b) reduced cuttings of alfalfa/alfalfa-grass to three from typical four, c) reduced nozzle size on some sprinklers, and d) grain hay would be irrigated through June only and alfalfa/alfalfa-grass through mid-august. Of the ten largest ranches that comprise 65% of the total area irrigated under LCS agreements, only two had reductions of at least 4% (5% for #3 and 4% for #1) (Table B3, Figure 23b).

Many fields in Scott Valley on properties without LCS agreements showed no reductions in ET_a from 2020 to 2022 (Figure 23a). Potential reasons for the lack of reductions likely vary by field but can be inferred from maps of ET_a and irrigation water source:

- Some fields are not normally irrigated so have low ET_a (i.e., <20 inches/year). Examples include the upper (eastern) portions of Hamlin (southeast of Fort Jones), Heartstrand, and McConaughy (east of French Creek) gulches (Figure 19c, Figure A35).
- Many ranches lacking LCS agreements are irrigated solely with surface water (Figure 24d), and the July 1 start date of 2022 surface water curtailments was near the time when most surface water diversions would typically cease in most years anyway due to lack of available water even if not curtailed. These fields are typically only irrigated through part of the summer, so do not stay green or maintain high ET_a through the entire irrigation season. For example, except for Ranch #11 LCS that is primarily groundwater-irrigated (Figure A35), fields in the Shackleford Creek and Mill Creek watersheds (Quartz Valley) are irrigated with surface water and most had 2022 ET_a similar to other years but much lower than groundwater-irrigated fields in Scott Valley (Figure 24d, Figure A30).
- Some fields are naturally sub-irrigated by high water tables so maintain crop growth and high ET_a without applied irrigation. These sub-irrigated lands outside LCS agreements are located along Kidder Creek, between Etna Creek and Patterson Creeks, and the west side of the Scott River upstream of French Creek (Figure 24c).
- Many groundwater-irrigated fields were not covered by LCS agreements yet continued to have 2022 ET_a values indicative of full irrigation, in apparent violation of curtailments. These areas are shown as dark blue in Figure 24a (971 acres >35 inches, 864 acres 32–25 inches). Similarly, many fields irrigated with a mix of groundwater and surface water had ET_a values indicative of full irrigation despite not being covered by LCS agreements (328 acres >35 inches, 542 acres 32–25 inches) (Figure 24b).

In Shasta Valley, I did not calculate ET_a summaries by management unit (irrigation districts and Safe Harbor Agreements), but map with unit boundaries overlaid show the percent ET_a reductions from 2020 to 2022 for each field (Figure 21) and 2022 ET_a (Figure A34). Figure 21 indicates especially large ET_a reductions in many fields in Unit #1 (Montague Water Conservation District, irrigated with surface water) and Unit #9 (Big Springs Irrigation District, irrigated with groundwater).

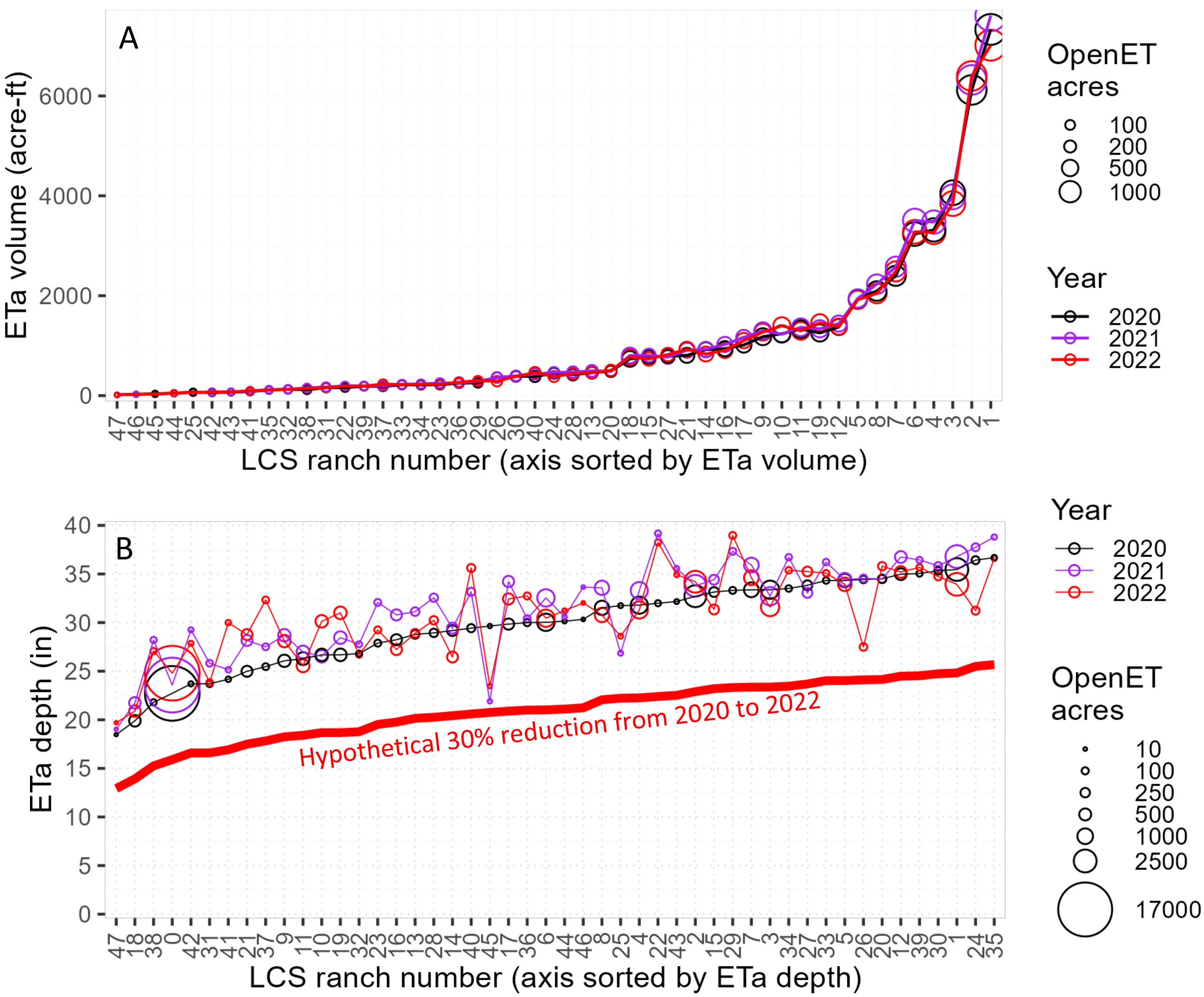


Figure 22. Actual evapotranspiration (ET_a) (a) volume and (b) depth for properties with Local Cooperative Solutions (LCS) in Scott Valley for 2020–2022. Thick red line illustrates what a 30% reduction between 2020 and 2022 would look like. See Table B3 in Appendix B for a key to LCS ranch numbers (LCS #0 is the properties without LCS). Data summarized from OpenET.

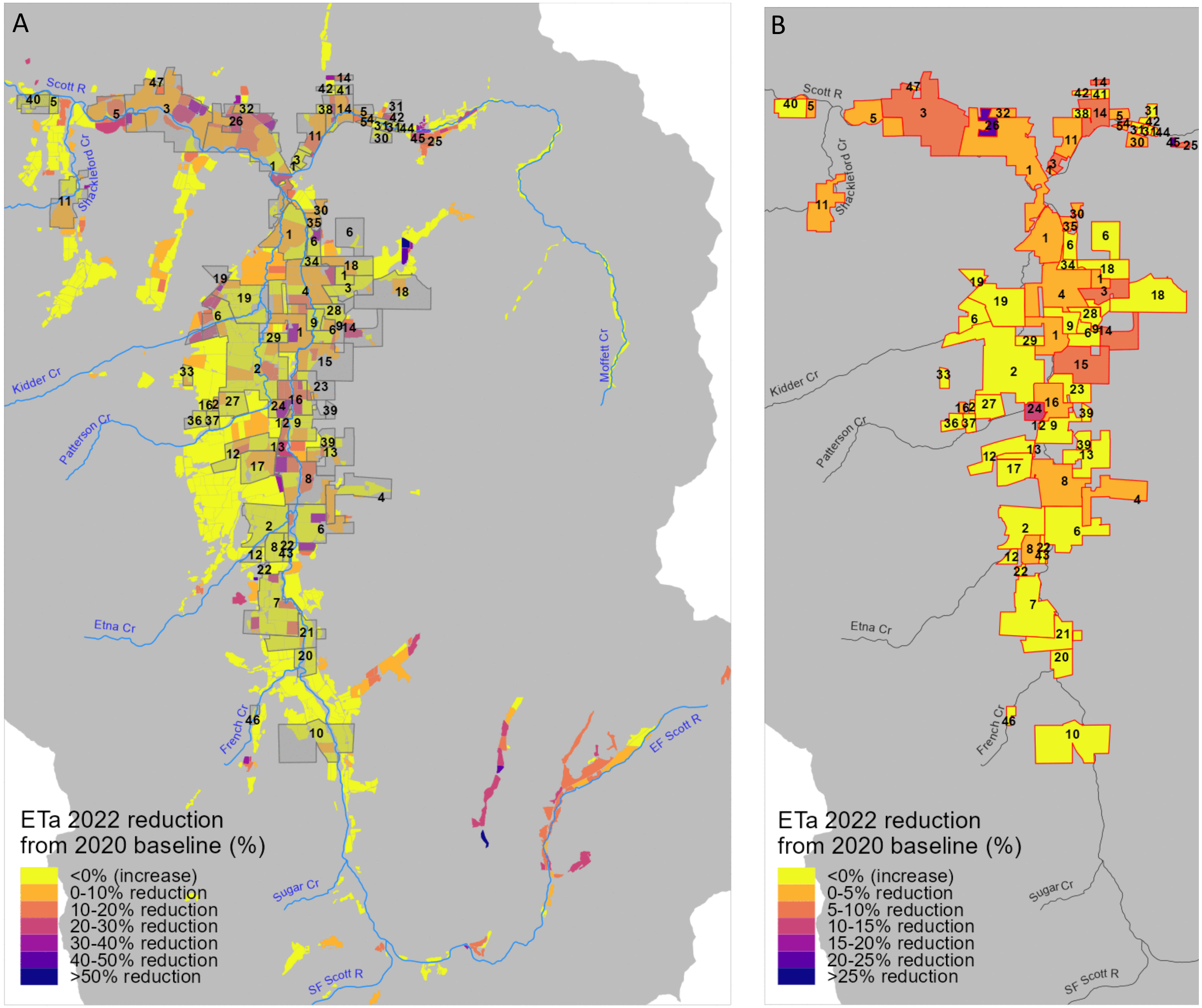


Figure 23. (a) Scott Valley map showing the percent reduction in actual evapotranspiration (ET_a) for each agricultural field between 2022 and the 2020 baseline, with Local Cooperative Solutions (LCS) overlaid as numbered gray polygons. (b) Percent ET_a reduction for each LCS. Legend scales differ. See Table B3 in Appendix B for a key to LCS ranch numbers. Data summarized from OpenET.

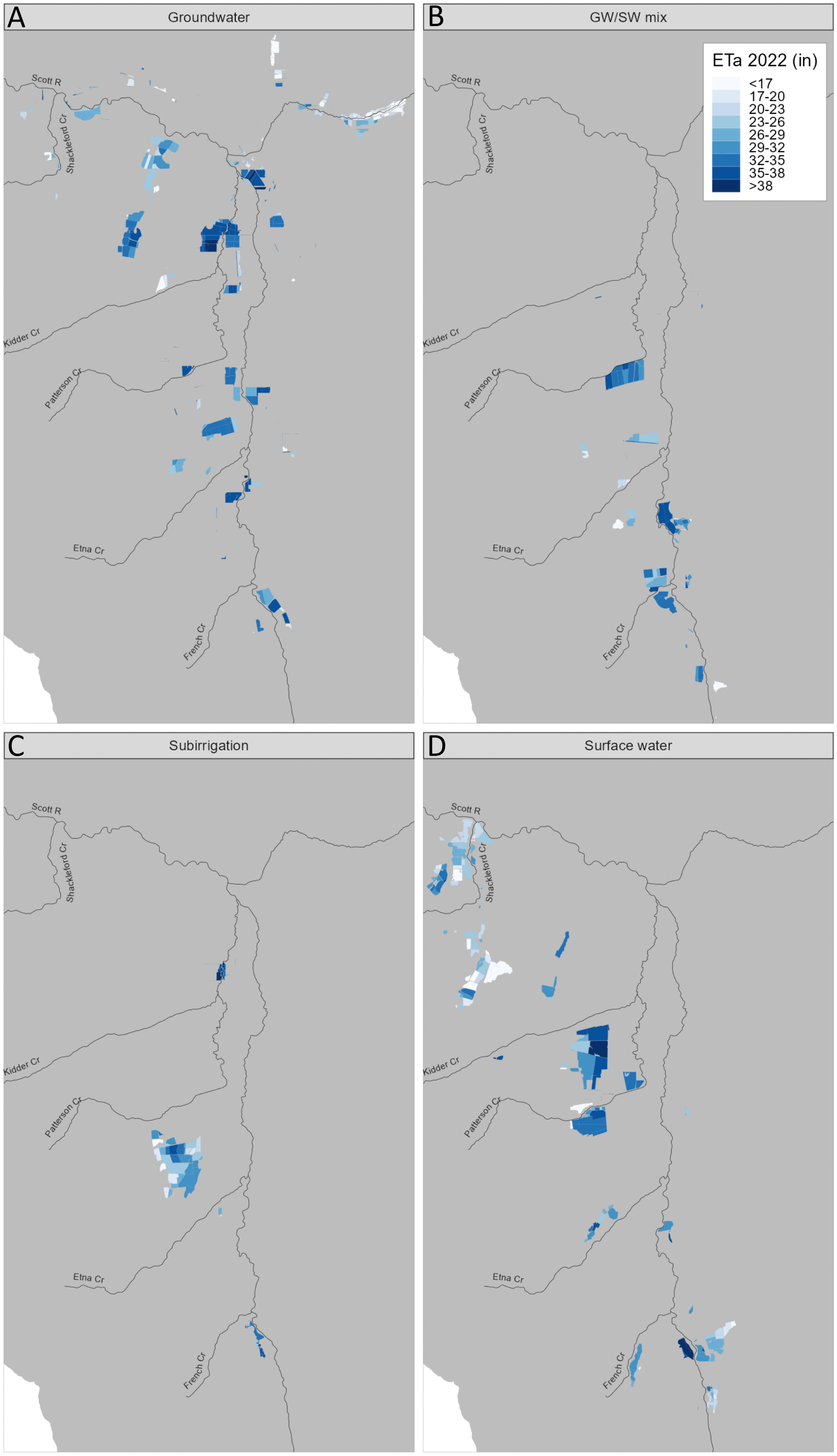


Figure 24. Actual evapotranspiration (ET_a) depth in 2022 for Scott Valley fields that lacked Local Cooperative Solutions (LCS) and were: (a) irrigated solely with groundwater, (b) irrigated with a mix of groundwater and surface water, (c) naturally sub-irrigated by high water tables, or (d) irrigated with surface water. Data summarized from OpenET using irrigation sources from SVIHM and LCS boundaries from SWRCB.

3.3.1 EVALUATING EFFECTS OF 2021 PUMPING FORBEARANCE CONTRACTS

Monthly time series of ET_a at 2021 pumping forbearance fields indicated that ET_a was 17% lower in August 2021 than the August mean of 2017–2020 (Figure 25a top panel) and lower than in other groundwater-irrigated fields in Scott Valley (Figure 25b top panel). Converting units of ET_a to cfs, this 17% reduction equates to 3.4 cfs for the duration of August (Figure 25a middle panel). Effects were smaller in September 2021, with a 12% reduction in ET_a, equating to 1.4 cfs. Greenness of the 2021 pumping forbearance fields, as measured by NDVI, was also lower in August and September than in 2017–2020. Interestingly, NDVI and ET_a in the 2021 pumping forbearance fields were higher in April and May 2021 than in April and May 2017–2020 (Figure 25a top panel), which on an annual basis may have partially offset some of the ETa reductions observed in August and September.

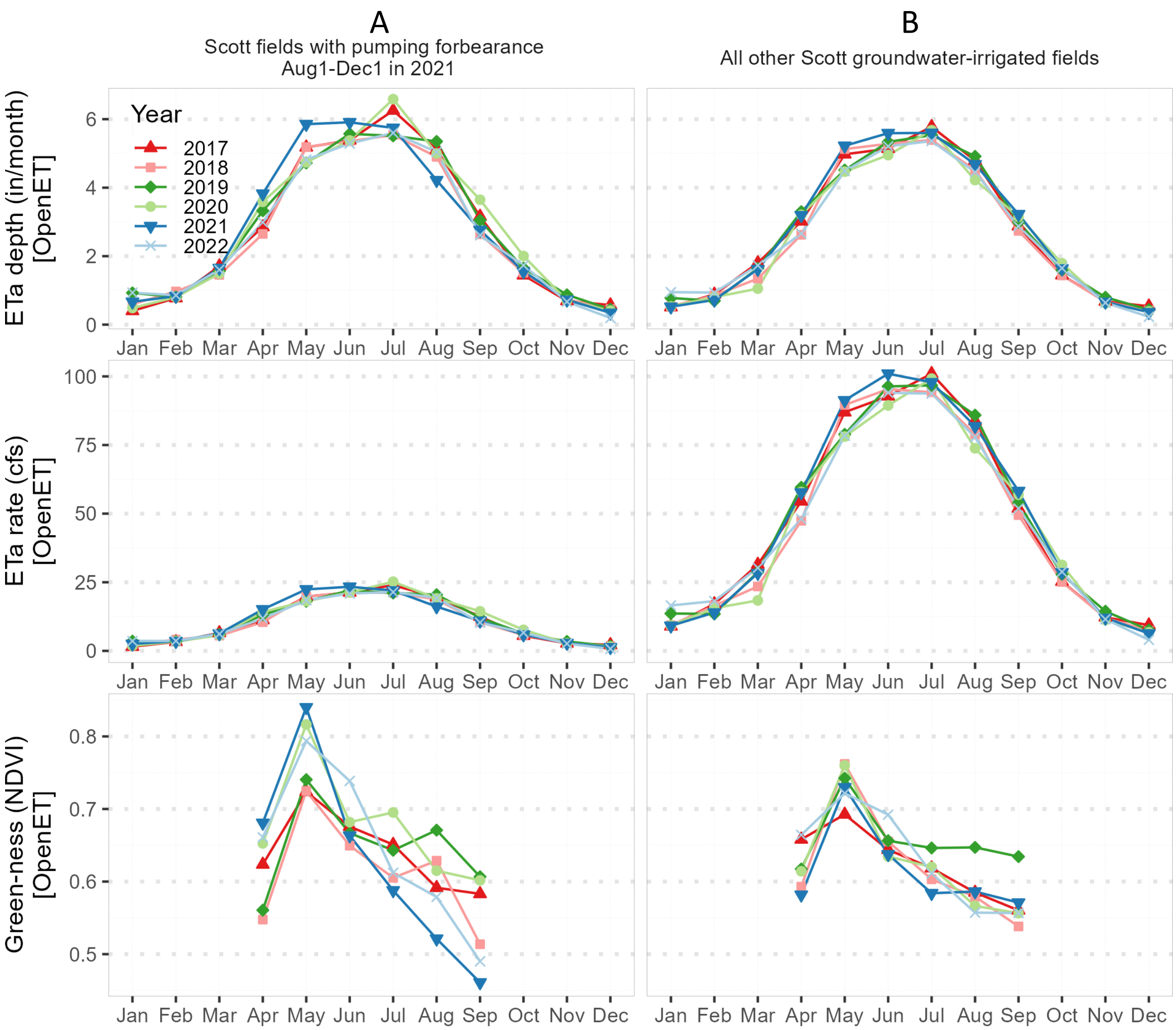


Figure 25. Comparison of actual evapotranspiration (ET_a) depth, ET_a rate, and greenness (NDVI) between (a) 2021 pumping forbearance fields, and (b) all other groundwater-irrigated fields in the Scott Valley. In 2021 pumping forbearance fields, landowners were paid not to pump groundwater from August–November of 2021. Data summarized from OpenET. See Figure 3 for a map of these fields.

3.4 COMPARISON OF EVAPOTRANSPIRATION AND STREAMFLOW

Comparison of flow at the Shasta River USGS gage and ET_a from Shasta Valley agricultural fields in 2020 and 2022 indicated that for the months of July–October, the increase in flow between 2022 and 2020 (mean 31 cfs) was similar in magnitude to the decrease in ET_a (mean 47 cfs) (Figure 26). Excluding lands inside MCWA that were irrigated with stored water from Dwinnell Reservoir and not directly affected by the curtailments, the ET_a reduction (mean 33 cfs) was nearly identical to the flow increase (Figure 26). In Scott Valley, ET_a was similar in 2020 and 2022 (Aug–Oct mean 5 cfs greater in 2022), corresponding with the lack of substantial increase in river flow between 2020 and 2022 (Aug–Oct mean 4 cfs greater in 2022) (Figure 26). ET_a rates on agricultural lands far exceed river flow rates during late summer in both Scott and Shasta, but some of the water for this ET_a is supplied by residual soil moisture, so river flow would not necessarily instantly increase by an equivalent amount if that ET_a did not occur. Similarly, there can be substantial lags in the timing of when groundwater that is pumped for irrigation would have become streamflow had it not been extracted. These lags depend on complex factors such as aquifer properties and the distance between wells and streams.

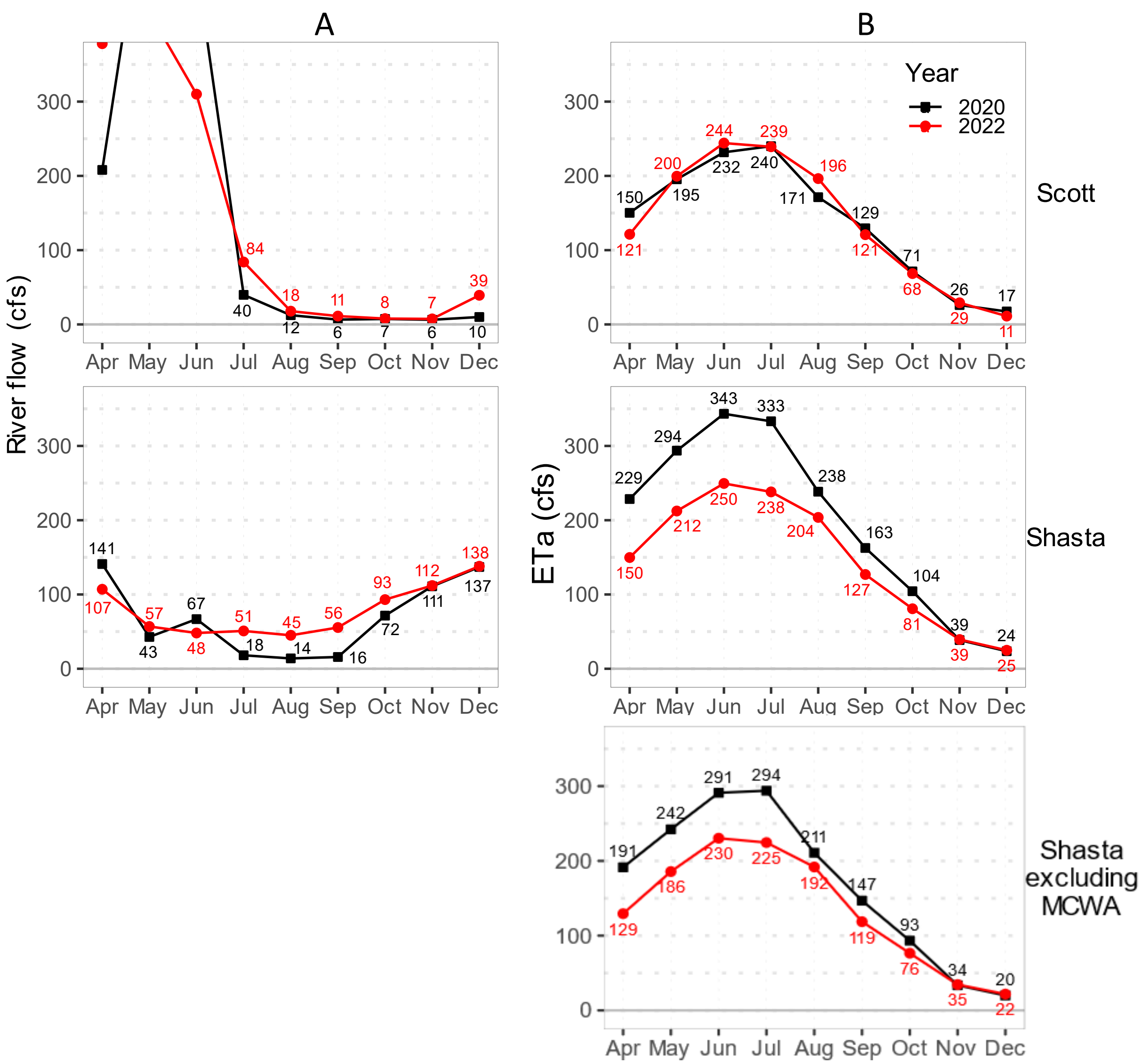


Figure 26. Comparison of monthly (a) river flows at USGS gages, and (b) actual evapotranspiration (ET_a) rates of agricultural fields in the Shasta and Scott for the months of April–December 2020 and 2022. Y-axis is truncated to highlight the low-flow period. ET_a data summarized from OpenET.

4 RECOMMENDATIONS FOR ADDITIONAL ANALYSES

4.1 NEED FOR FIELD-SPECIFIC MAPS OF LCS PRACTICES TO EVALUATE EFFECTIVENESS AND COMPLIANCE

Most of the LCS agreements included maps of the proposed management practices for each field, but these maps were sketched on paper and are not available in a GIS format. If these maps could be transferred into a GIS format, a time-intensive task, it would then be possible to use remote sensing tools to evaluate: 1) which practices effectively reduced ET_a, and 2) what compliance rates were for some practices. Compliance with some practices such as fallowed fields, early cessation of irrigation, and crop switching should be easily verifiable using measures of field greenness such as NDVI or EVI. Other practices such as the number of hours that a sprinkler operated for, or how many days per month irrigation occurred, are impossible to verify with remote sensing or periodic field inspections, but could be verified with water meters or electric utility bills. Water meters are rare in Scott and Shasta valleys but electric bills should exist nearly universally.

4.2 ELECTRIC UTILITY BILL DATA COULD BE USED TO VERIFY LCS PUMPING REPORTS

As noted above in Section 1.2 above, compliance with the LCS groundwater pumping reductions was primarily self-reported with limited independent verification. A valuable aspect of the remote-sensing approach used in this report is the ability to consistently evaluate conditions across previous and current years without the need to install or operate new monitoring equipment. Since nearly all wells use electric pumps, electric utility bills are another approach that could provide consistent information across years. For groundwater users who did not substantially alter the energy efficiency of their irrigation equipment (e.g., install motors with variable frequency drives) it should be possible to use electric consumption to evaluate relative changes in pumping between years. In the Shasta and Scott valleys, this has not yet been required and has rarely been done, but the data do exist and could be used by most water users to document their pumping history if they choose to.

4.3 NEED FOR FURTHER EVALUATION OF DIFFERENCES BETWEEN APPLIED WATER ESTIMATES IN SCOTT VALLEY

Table 2 compares the OpenET ET_a summarized in this report with ET_a from the Scott Valley groundwater model (SVIHM), irrigation applied in SVIHM, and irrigation applied as reported in the LCS agreements. This study's summaries of Open ET_a for irrigated lands in Scott Valley are approximately 10% lower than ET_a from SVHIM (Table 2). A more intriguing difference is that the LCS-reported average irrigation[14] for the baseline year (mostly 2020 but 2021 for a few LCS agreements) of 44.1 inches was 95% higher than the 22.6 inches represented in the current version of SVIHM (Table 2). Only 6 of 46 ranches reported baseline irrigation of less than 22.6 inches (Table 2). The reason for this discrepancy merits evaluation. Potential explanations include either, or a combination, of the following:

[14] The reported irrigation for each ranch was weighted according to its size. Average was calculated 1) for each ranch, calculated irrigation volume as the irrigation depth times reported baselines irrigated acres, 2) divide the sum of irrigation volumes for all ranches by the sum of the acres for all ranches, yielding area-weighted irrigation depth.

- LCS agreements may have overestimated water use for the baseline year. Each LCS had to show at least a 30% reduction in anticipated groundwater pumping between the baseline year and 2022. There was no verification of the baseline.

- The three ranches upon which the SVIHM irrigation rates were derived (Orloff 2014, Foglia 2018) may not have been representative of the overall population of ranches in Scott Valley. In the original version of SVIHM (Foglia et al. 2013), average irrigation depth for alfalfa was 33.1 inches. The Scott Valley Groundwater Advisory Committee said that value was too high, so detailed studies of three ranches were then conducted that yielded a lower irrigation value that was then used to update SVIHM (Foglia et al. 2018).

Average LCS-reported irrigation for 2022 was 29.2 inches, approximately 29% higher than the 22.6 inches from the current version of SVIHM but nearly identical to the 30.3 inches from the original version of SVIHM (Table 2).

Table 2. Comparison of irrigation applied and actual evapotranspiration in irrigated agricultural lands in the Scott Valley, derived from several information sources. Foglia et al. (2013) and Foglia et al. (2018) data are long-term averages for hydrologic years 1991–2011 and 1991–2018, respectively.

	Irrigation Applied (inches)				Actual evapotranspiration [ET_a] (inches)			
Information source	**All irrigated lands**	**Alfalfa**	**Pasture**	**Grain**	**All irrigated lands**	**Alfalfa**	**Pasture**	**Grain**
Foglia et al. (2013)	30.3	33.1	29.7	14.1	35.7	40.1	33.9	16.1
Foglia et al. (2018)	22.6	21.5	26.0	10.3	34.2	36.8	34.8	16.1
LCS agreements baseline 2020 or 2021	44.1							
LCS agreements 2022	29.2							
OpenET 2017-2022 (this study)					31.1			

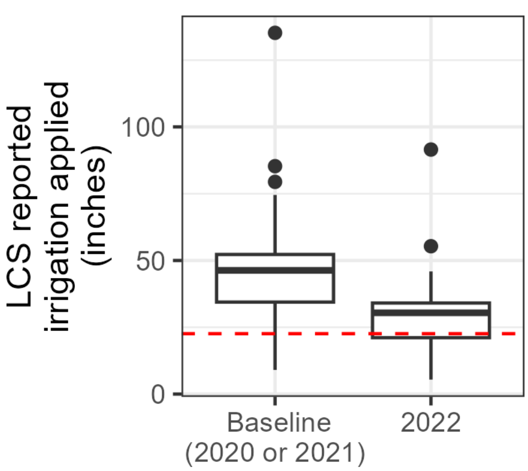


Figure 27. Boxplot of the distribution of the applied irrigation depths calculated from volumes and acres reported from 46 LCS agreements. See Table B3 Appendix B for data values. Red dashed line is 22.6-inch average irrigation depth from SVIHM (Foglia et al. 2018). The horizontal line inside the box is median, the upper and lower edges of the box are 25th and 75th percentiles, the upper whisker extends to the highest value that is within 1.5 times the interquartile range (75th minus 25th percentile) from the box's edge, and points plotted beyond the whiskers are outliers.

5 ACKNOWLEDGMENTS

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6 DATA AVAILABILITY STATEMENT

All data and code are available upon request. Code has not yet been streamlined or fully documented to facilitate use by others.

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APPENDIX A: ADDITIONAL FIGURES

This appendix provides additional figures that, for the sake of brevity, were placed here instead of in the report's main text.

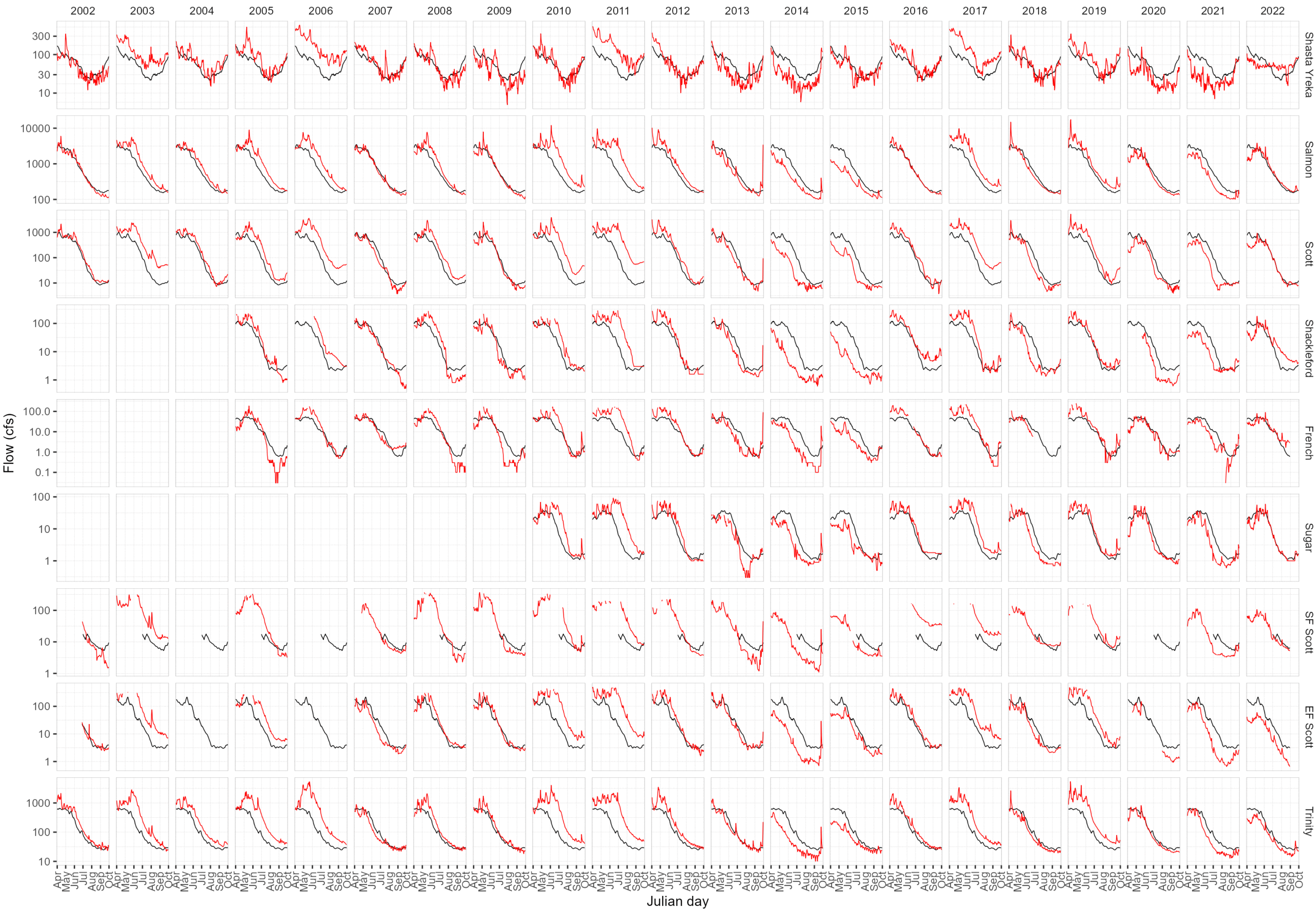


Figure A28. Daily streamflow (red lines) at gages in the Scott, Shasta, Salmon, and Trinity sub-basins for months of Apr–Sept in the years 2002–2022. Black lines are Julian day medians for the years 2010–2022. Y-axis is a log10 scale.

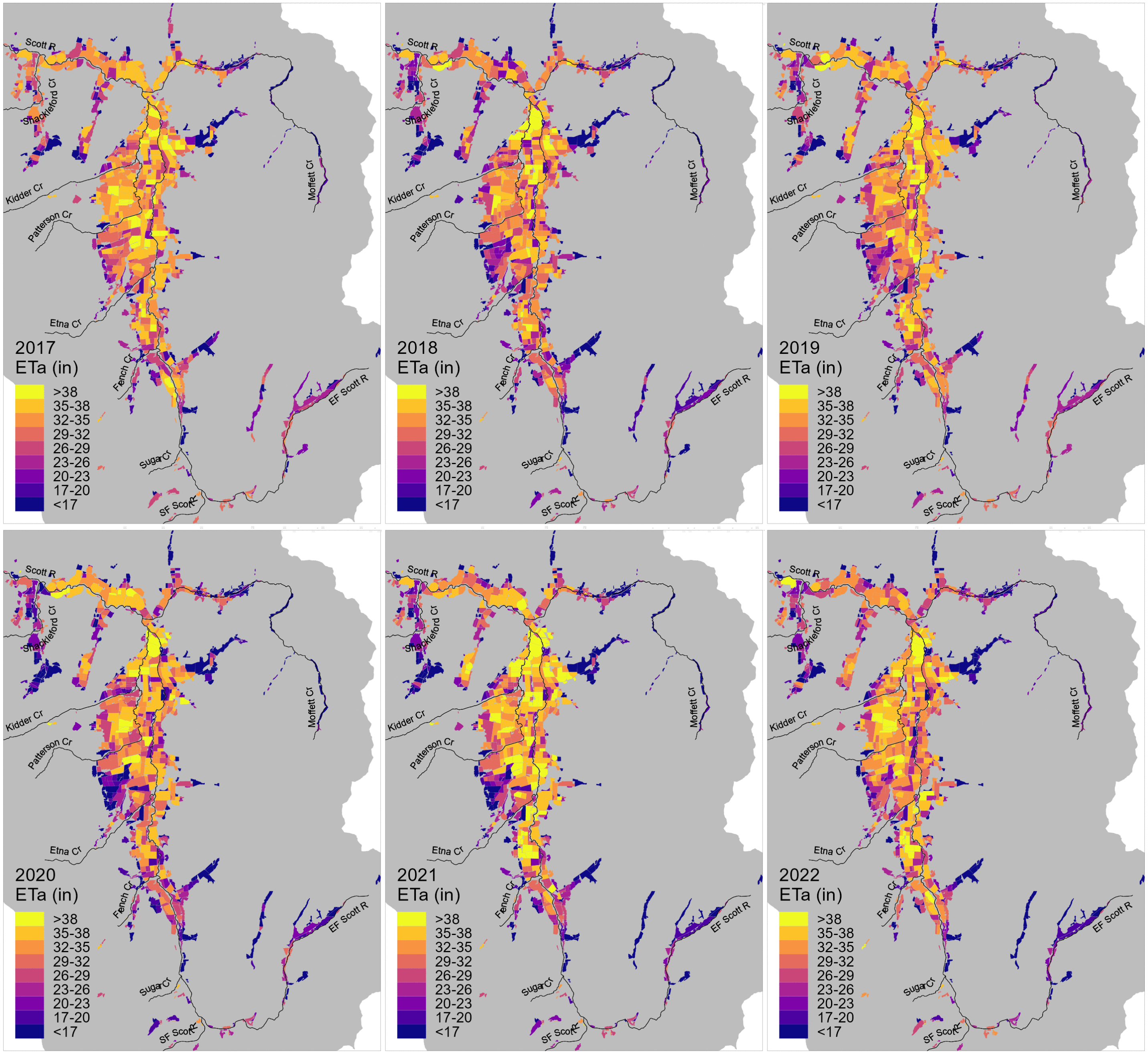


Figure A29. Maps showing annual actual evapotranspiration (ET_a) depth for each agricultural field in the Scott River sub-basin for the years 2017–2022. Data summarized from OpenET.

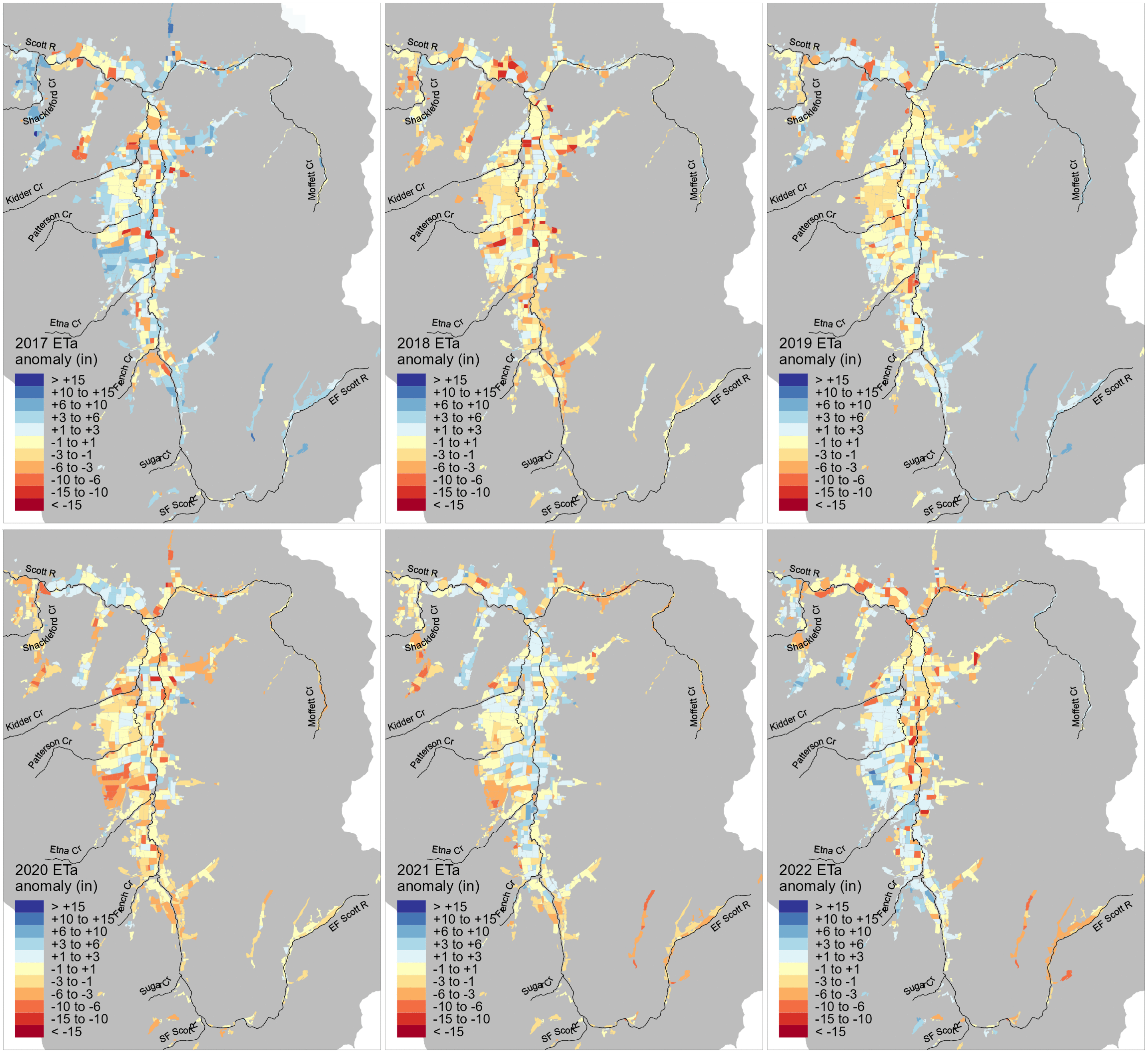


Figure A30. Maps showing annual actual evapotranspiration (ET_a) depth anomalies for each agricultural field in the Scott River sub-basin for the years 2017–2022. Anomalies calculated as a field's current year ET_a minus the field's long-term mean ET_a. Data summarized from OpenET.

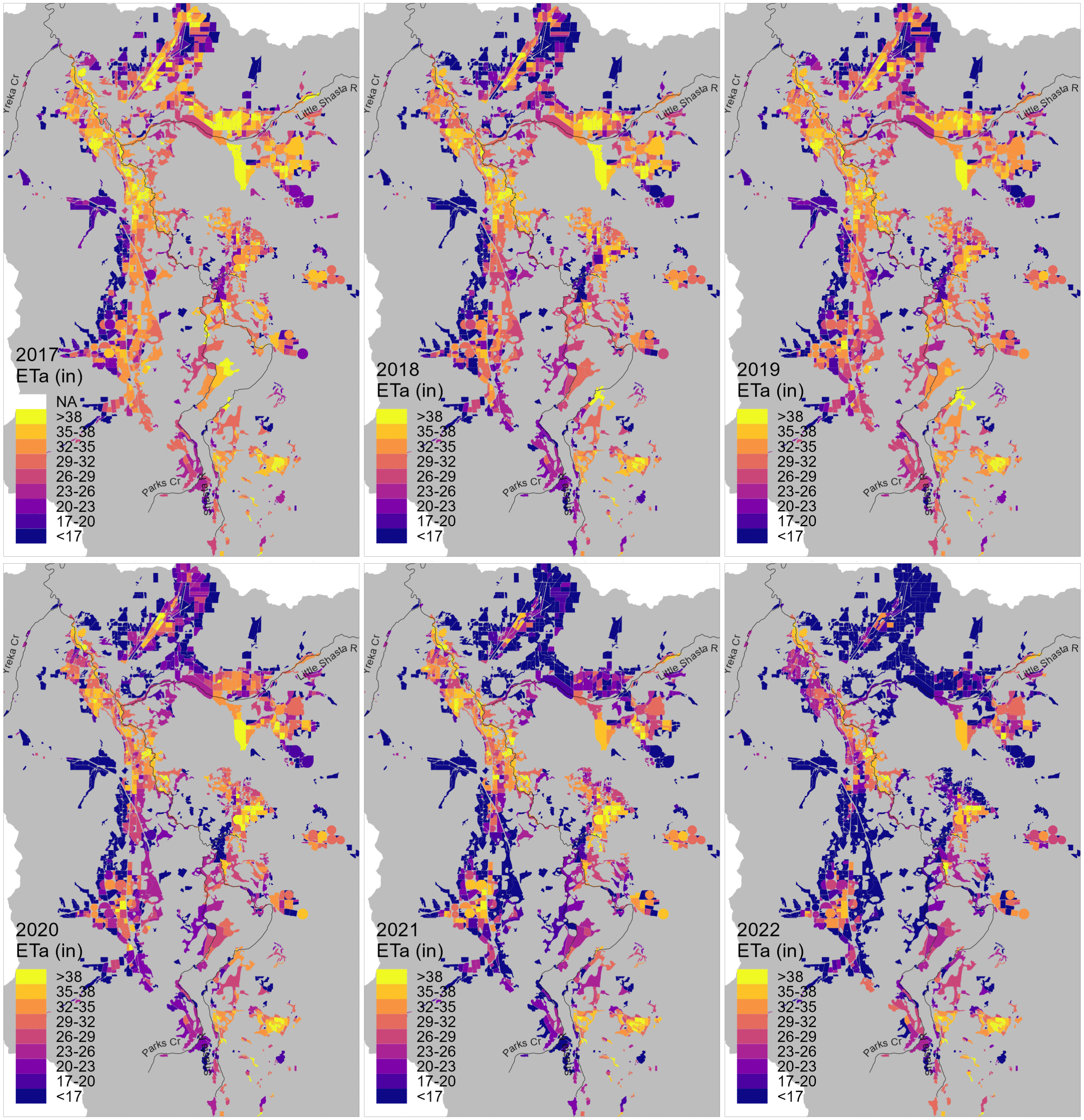


Figure A31. Maps showing annual actual evapotranspiration (ET_a) depth for each agricultural field in the Shasta River sub-basin for the years 2017–2022. Data summarized from OpenET.

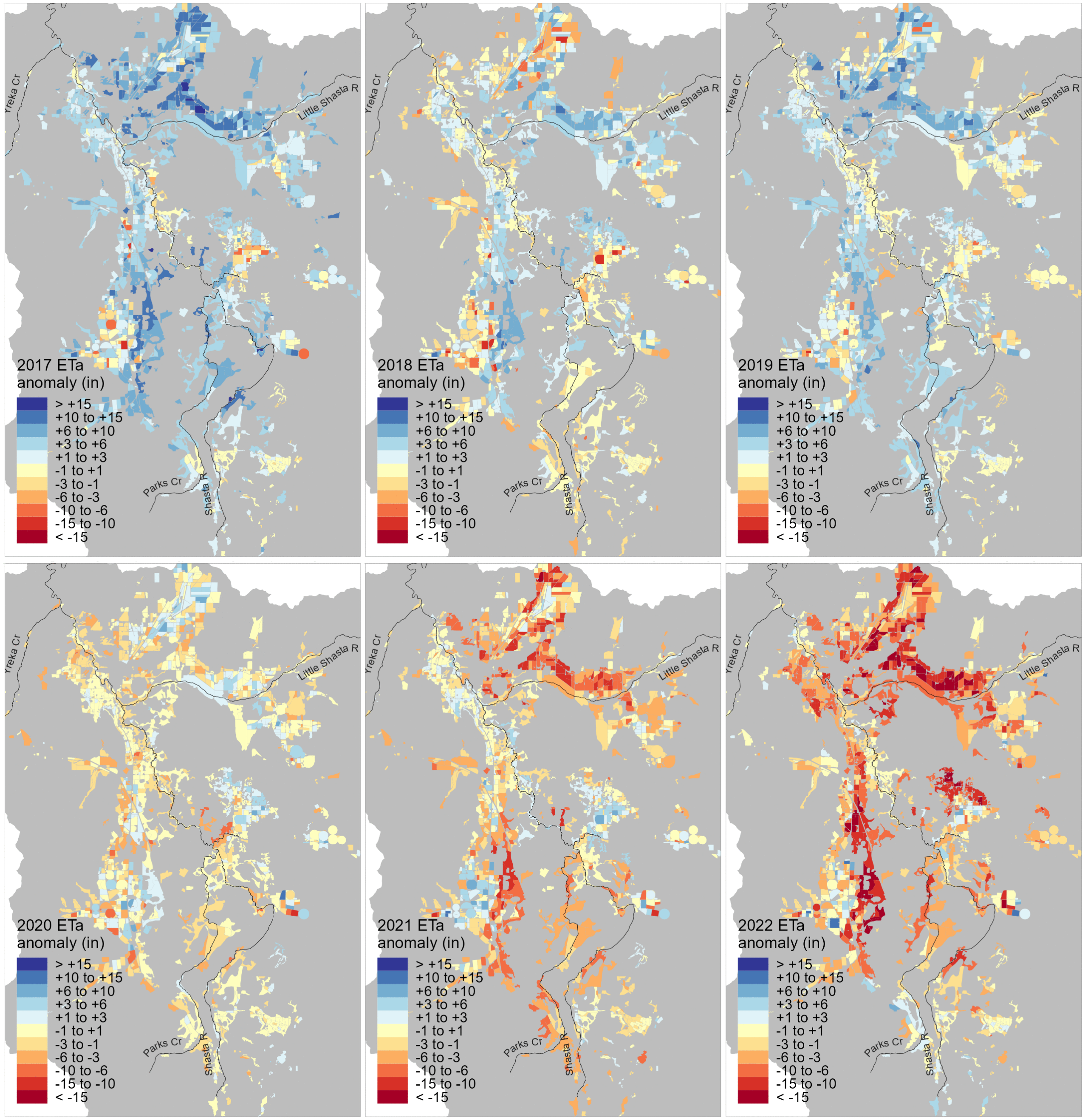


Figure A32. Maps showing annual actual evapotranspiration (ET_a) depth anomalies for each agricultural field in the Shasta River sub-basin for the years 2017–2022. Anomalies calculated as a field's current year ET_a minus the field's mean long-term ET_a. Data summarized from OpenET.

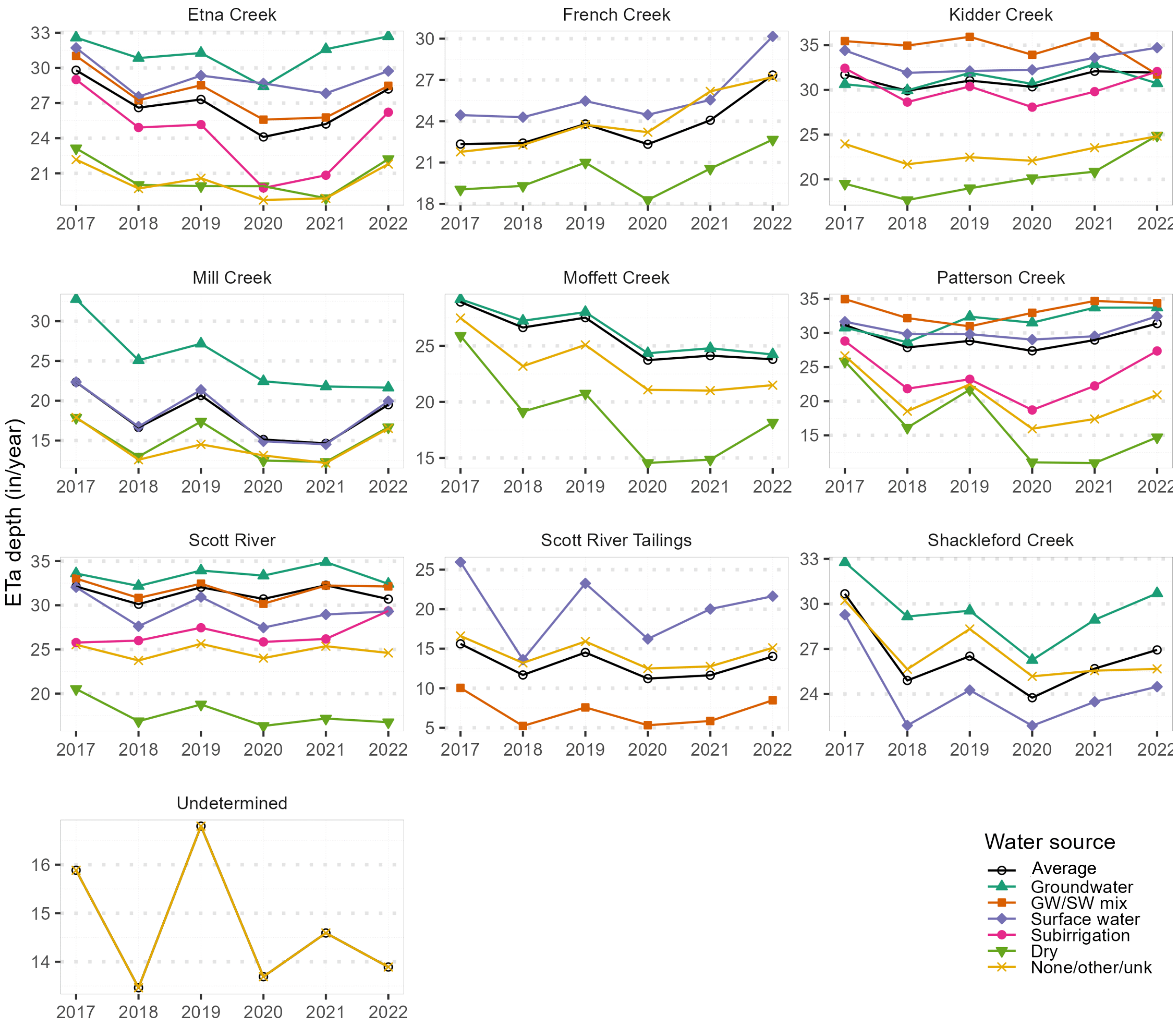


Figure A33. Annual time series of actual evapotranspiration (ET_a) depth for agricultural fields in each Scott Valley sub-watershed of Scott Valley for 2017–2022, color-coded by irrigation source. An alternative version of this figure with ET_a volume is available as Figure 20.

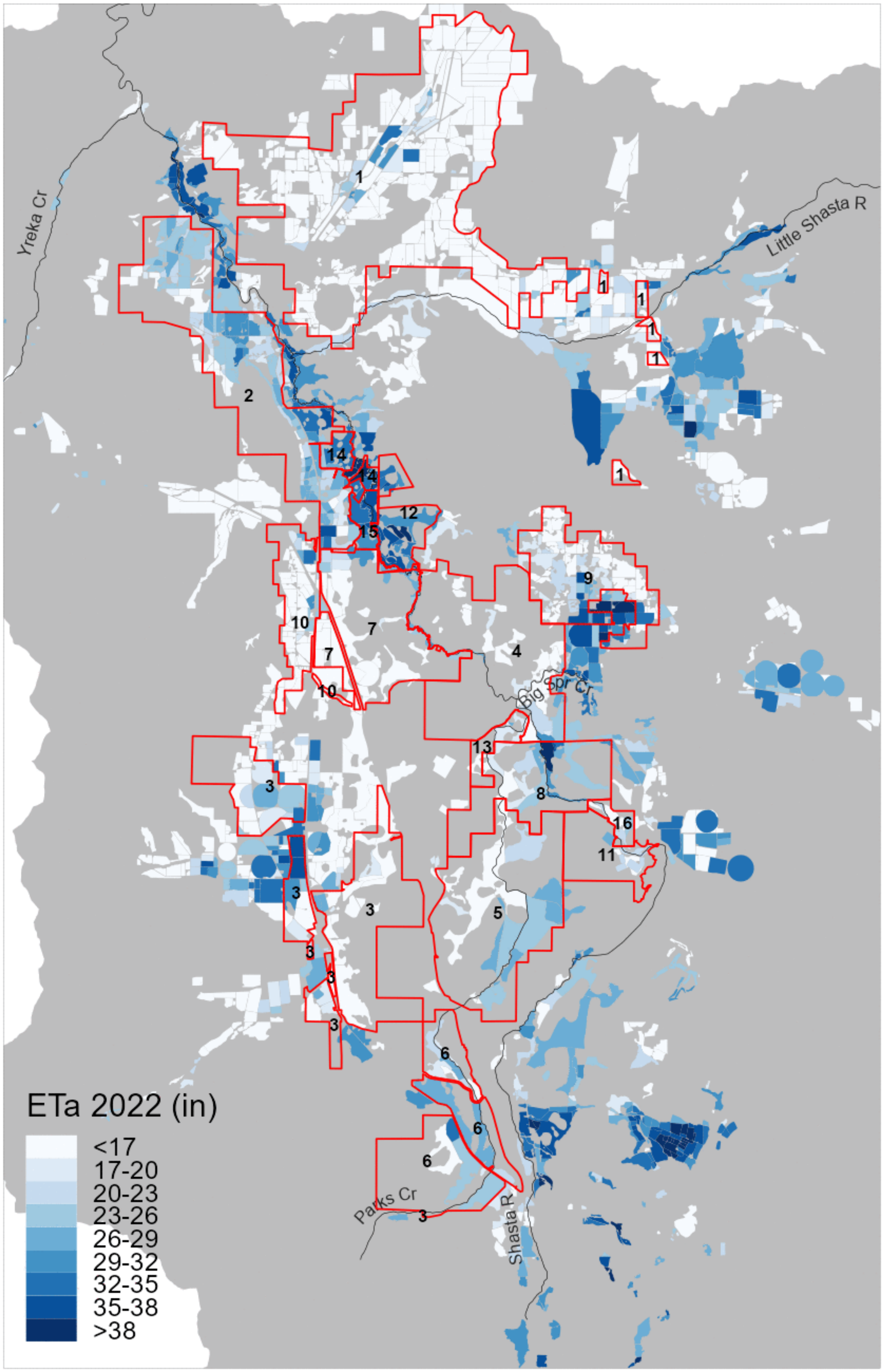


Figure A34. Actual evapotranspiration (ET_a) depth for Shasta Valley agricultural fields in 2022, with management units (irrigation districts and Safe Harbor Agreements) overlaid as labeled red polygons. See Table B4 in Appendix B for key to management unit numbers. Data summarized from OpenET.

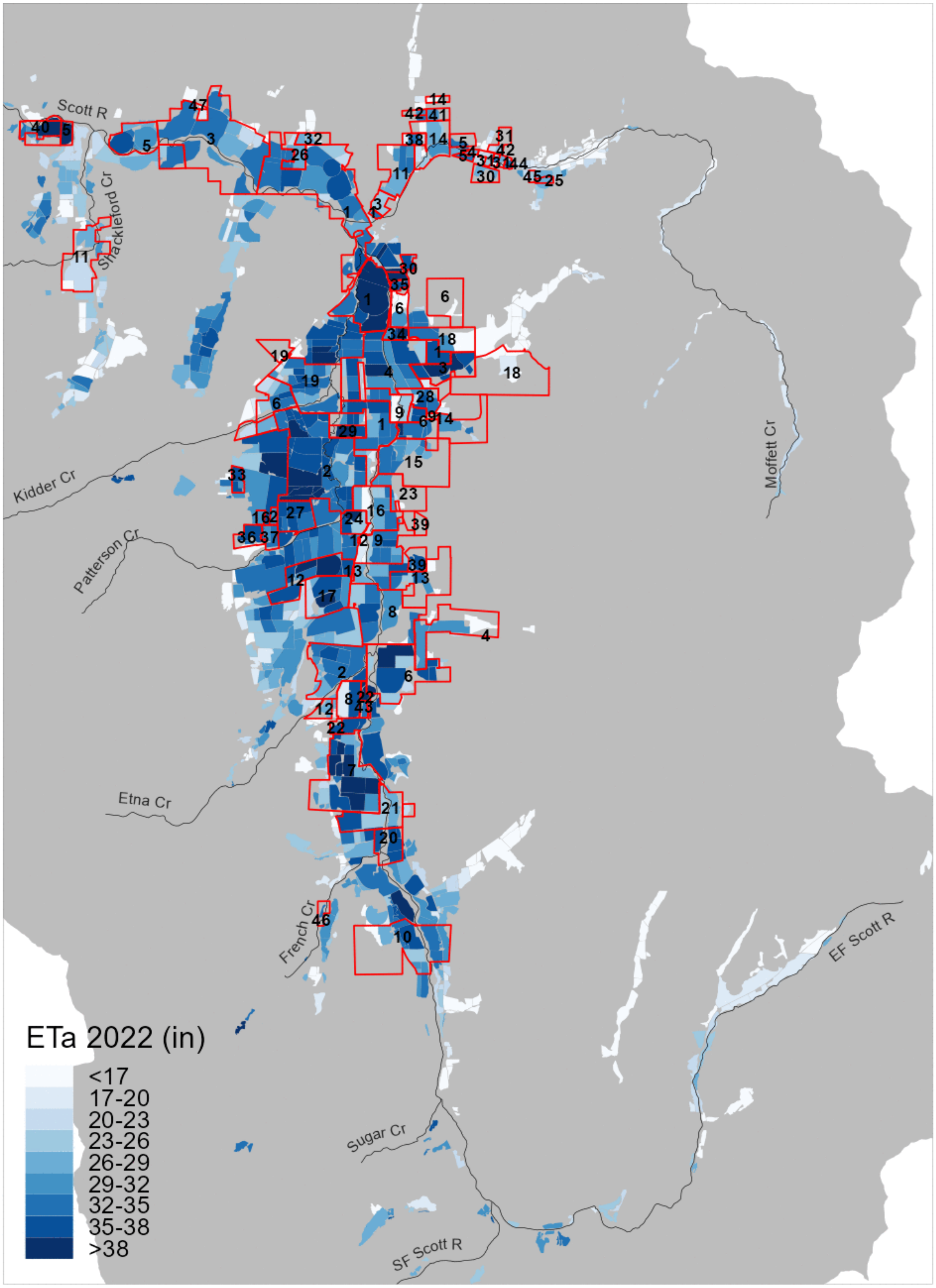


Figure A35. Actual evapotranspiration (ET_a) depth for Scott Valley agricultural fields in 2022, with Local Cooperative Solutions (LCS) overlaid as numbered gray polygons. See Table B3 in Appendix B for key to LCS numbers. Data summarized from OpenET.

APPENDIX B: KEY TO SCOTT LCS NUMBERS AND SHASTA MANAGEMENT UNIT NUMBERS

Table B3. Local Cooperative Solutions (LCS) in the Scott Valley for the 2022 irrigation season. LCS number is based on ranked reported irrigated acres (1 = largest, 47 = smallest). Pumped water amounts (converted from volume to depth by dividing reported volumes by reported baseline irrigated acres), reported acres, and sum of parcel areas are from SWRCB, collated from individual LCS reports. OpenET fields acres calculated by summing the area of OpenET field within LCS parcels. SRCD = Siskiyou Resource Conservation District. LCS #47 was for surface water and groundwater, so did not provide reported water use in the same format as groundwater-only LCS agreements and therefore reported water use is not included in this table.

			Water reported pumped in LCS (in)			Area (acres)			OpenET ET_a (in)						OpenET ET_a (%)
LCS Ranch number	LCS name		Baseline 2020	Baseline 2021	2022	LCS reported irrigated	Sum of parcels	OpenET fields	2017	2018	2019	2020	2021	2022	2022 as % of 2020
0	[No LCS]	none				17768.0		17487.6	26.7	23.6	25.5	22.7	23.6	24.8	109.1
1	Finley Farms	CDFW	36.3		25.2	2179.0	2988.5	2481.1	35.4	33.8	35.5	35.5	36.8	33.9	95.7
2	Jenner Cattle Co.	SRCD	53.2		36.4	1575.0	2509.1	2245.2	34.3	32.2	32.4	32.7	33.8	34.2	104.6
3	Menne Ranch Hay	CDFW	41.7		29.2	1541.5	2200.3	1460.2	31.7	31.7	32.9	33.4	32.7	31.6	94.7
4	Hanna Bros. Ranch	SRCD	33.4		21.2	1179.0	1655.0	1252.2	33.3	31.2	33.7	31.8	33.3	31.3	98.5
5	Fawaz Farming	CDFW	50.3		32.9	1049.6	890.8	678.5	35.1	34.4	34.9	34.3	34.4	33.9	98.8
6	California Heritage Farms	SRCD	47.5		32.0	997.0	2083.0	1292.9	32.8	30.9	32.6	30.0	32.5	30.5	101.4
7	Scott Valley Farms, LLC	SRCD	39.8		26.9	826.0	1061.4	862.6	34.2	33.5	34.6	33.4	35.9	34.6	103.7
8	Paul Sweezy Farm	SRCD		45.8	32.1	697.0	1107.8	797.3	31.6	30.4	31.7	31.5	33.6	30.8	97.7
9	Hurlimann Brothers	CDFW	40.6		28.4	597.0	663.6	543.1	31.3	27.1	30.5	26.1	28.7	28.1	107.8
10	Richard G and Nancy J Barnes 1991 Trust	SRCD		17.2	11.9	560.0	1163.3	557.0	34.4	29.6	31.4	26.7	26.5	30.1	113.0
11	Rocking M Ranch	SRCD	20.3		13.4	515.0	958.3	608.8	32.0	27.5	27.6	26.3	27.0	25.6	97.2
12	Crystal Creek Ranch/Richard Anstead	SRCD	74.5		42.7	412.0	560.8	471.1	29.0	28.0	33.5	35.0	36.8	35.2	100.6
13	Bryan/Morris Ranch	SRCD		33.9	22.9	411.0	532.7	191.1	30.6	28.2	28.7	28.8	31.1	28.9	100.4
14	Frederick & Karen Kraus Trust	CDFW	19.0		8.8	360.5	766.1	378.2	28.5	28.7	32.1	29.2	29.4	26.5	90.7
15	H & H Land and Livestock	CDFW	45.0		30.3	320.0	782.8	281.0	35.1	32.9	34.8	33.1	34.4	31.4	94.6
16	Hurlimann Ranch	SRCD	135.2		91.5	291.0	463.1	399.5	31.6	31.1	32.3	28.2	30.8	27.2	96.4
17	Hayden Ranch	CDFW	52.0		35.8	277.0	447.7	408.0	36.0	31.7	32.0	29.8	34.2	32.4	108.7
18	Piersall Ranch	CDFW	30.3		21.1	277.0	1268.4	443.7	26.3	21.9	23.4	19.9	21.7	20.9	105.0
19	Martin Dairy	SRCD	52.0		33.6	249.0	893.2	564.5	31.4	28.0	29.6	26.7	28.5	31.0	116.2
20	Thackeray Ranch	SRCD		65.4	45.9	225.0	257.8	169.7	34.8	33.8	34.6	34.5	34.5	35.8	103.8
21	KK Bar Ranch	SRCD	61.1		34.1	217.0	484.6	387.2	30.9	27.7	30.3	25.0	28.2	28.8	115.1
22	Arrow J Ranch LLC	CDFW	52.3		30.6	190.0	96.1	59.6	36.3	32.1	29.8	32.0	39.2	38.3	119.6
23	Black Ranch	SRCD	44.2		31.1	187.5	328.8	94.2	31.6	30.6	31.0	27.9	32.1	29.3	104.9
24	Kohl Creek Angus	CDFW	72.1		45.2	165.0	157.3	147.4	38.6	35.7	36.6	36.4	37.7	31.2	85.7
25	Bob Daws Ranch	CDFW	9.0		5.4	151.0	27.8	27.2	33.9	27.0	32.7	31.7	26.9	28.6	90.1

LCS Ranch number	LCS name		Water reported pumped in LCS (in)			Area (acres)			OpenET ETa (in)						OpenET ETa (%)
			Baseline 2020	Baseline 2021	2022	LCS reported irrigated	Sum of parcels	OpenET fields	2017	2018	2019	2020	2021	2022	2022 as % of 2020
26	Christine and Gary Hullquist	CDFW	36.0		25.1	125.0	159.1	126.2	32.4	30.9	34.1	34.4	34.5	27.5	79.8
27	Tom Hayden Ranch	SRCD	48.4		34.1	120.4	294.0	280.0	34.4	33.1	31.4	33.8	33.1	35.3	104.2
28	Giacomelli Ranch	SRCD	85.3		55.3	120.1	267.1	173.7	34.0	29.1	32.8	28.9	32.6	30.2	104.5
29	O'Brien Ranch	CDFW	47.6		29.9	116.0	123.9	92.1	34.2	34.6	35.2	33.3	37.3	39.0	117.0
30	Fisher Family Ranch	SRCD	47.7		32.5	115.5	211.5	132.4	32.9	29.8	32.0	35.3	35.8	34.7	98.3
31	Christopher Whitehead Ranch	CDFW	50.2		12.5	111.0	154.0	80.7	21.5	23.3	25.9	23.7	25.8	23.8	100.5
32	Isbell Ranch	CDFW	27.8		16.6	110.0	106.5	55.8	21.0	19.0	26.5	26.8	27.8	26.7	99.6
33	Mark and Shelene Johnson Ranch	SRCD	44.4		28.8	108.0	81.7	75.3	35.9	30.2	33.3	34.3	36.2	35.1	102.2
34	Newton Family Ranch	CDFW	44.4		29.4	108.0	99.4	76.2	37.3	35.6	35.1	33.5	36.7	35.4	105.6
35	Fisher Ranch	CDFW	67.2		39.9	105.0	46.6	37.3	35.6	34.1	35.1	36.7	38.8	36.6	99.8
36	Patterson Creek Ranch	SRCD	30.8		21.0	94.0	141.8	99.2	32.6	30.5	28.8	30.0	30.4	32.7	109.2
37	Don and Maxine Dedobbeleer	SRCD	11.7		6.3	84.5	99.5	86.4	32.7	30.1	30.0	25.5	27.5	32.3	127.0
38	Sousa Farm	CDFW	63.7		33.2	80.0	75.3	64.8	34.1	30.3	31.1	21.8	28.2	27.1	124.2
39	Bernard and Beverly Dowling Ranch	SRCD	46.8		32.6	77.0	188.6	64.3	24.7	21.7	31.4	35.0	36.4	35.7	101.8
40	Emory and Heidi Gray	CDFW	56.4		36.8	49.0	260.7	155.9	34.1	32.4	32.3	29.4	33.2	35.6	121.1
41	Ellis Trust	CDFW	29.8		20.5	40.0	76.7	39.6	33.6	29.6	30.9	24.2	25.1	30.0	124.1
42	Grassman Farming	CDFW	36.0		17.6	36.0	56.7	30.4	24.5	24.3	21.6	23.7	29.3	27.9	117.6
43	Matt and Brenda Johnson	CDFW	48.0		33.4	27.0	36.5	25.3	33.7	31.2	31.1	32.2	35.6	34.9	108.6
44	Reece Gomes	CDFW	79.4		37.2	22.0	22.8	18.9	33.7	33.0	33.5	30.1	30.6	31.2	103.6
45	Don Parry	CDFW	20.1		10.8	16.8	19.9	15.8	34.5	24.9	30.7	29.6	21.9	23.5	79.1
46	French Creek Ranch	CDFW				13.0	60.1	10.1	27.5	28.4	28.4	30.3	33.6	32.0	105.6
47	Renee Grove	CDFW	50.6		34.0	9.4	13.9	9.2	16.2	15.3	16.4	18.5	19.0	19.7	106.6

Table B4. Shasta Valley management units (irrigation districts and Safe Harbor Agreements). Shasta Water Users Association is legally an association, but for simplicity it is categorized here as an irrigation district. Unit numbers are based on total area calculated from GIS (1 = largest, 16 = smallest).

Management unit num	Management unit name	Entity Type	GIS area (acres)
1	Montague Water Conservation District	Irrigation District	15484.9
2	Shasta Water Users Association	Irrigation District	6943.7
3	Edson Foulke	Safe Harbor	6812.9
4	Big Springs Ranch Wildlife Area	Safe Harbor	5823.3
5	Shasta Springs Ranch	Safe Harbor	5819.5
6	Parks Creek Ranch	Safe Harbor	4497.9
7	Belcampo-North Annex Property	Safe Harbor	4033.5
8	Hole in the Ground Ranch	Safe Harbor	3098.1
9	Big Springs Irrigation District	Irrigation District	3080.6
10	Grenada Irrigation District	Irrigation District	1771.8
11	Seldom Seen Ranch	Safe Harbor	1418.3
12	Novy Ranches	Safe Harbor	1130.4
13	Cardoza Ranch	Safe Harbor	492.1
14	NB Ranches	Safe Harbor	464.3
15	Rice Livestock	Safe Harbor	431.0
16	Hidden Valley Ranch	Safe Harbor	317.3

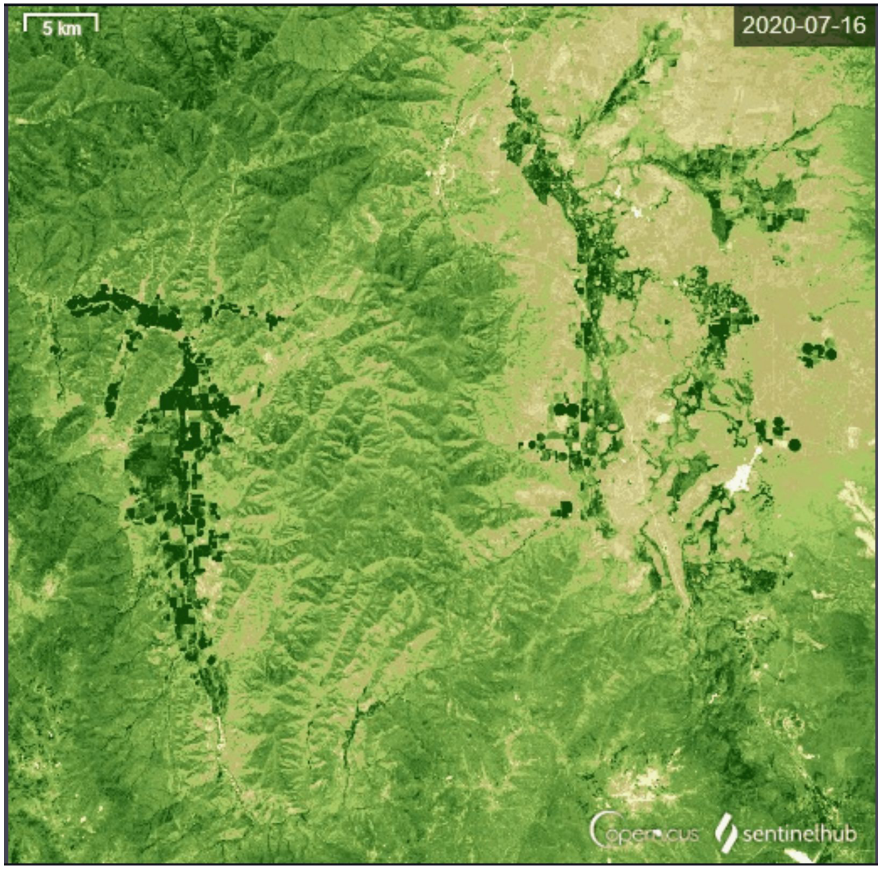
APPENDIX C: LINKS TO SENTINAL EO BROWSER ANIMATIONS OF SATELLITE IMAGERY 2017–2022

The images below are screen shots from animations of satellite imagery of the Scott and Shasta valleys, generated using the Sentinel EO Browser. Use the links to view the animations online. Animations can be viewed without logging in, but if you want to edit them you will need to sign up for a free Sentinel EO Browser account and log in.

Sentinel 2 greenness (EVI, Enhanced Vegetation Index)

Mar–Oct 2017–2022, 148 days with available imagery, using 10% cloud cover and 50% tile coverage as selection criteria.

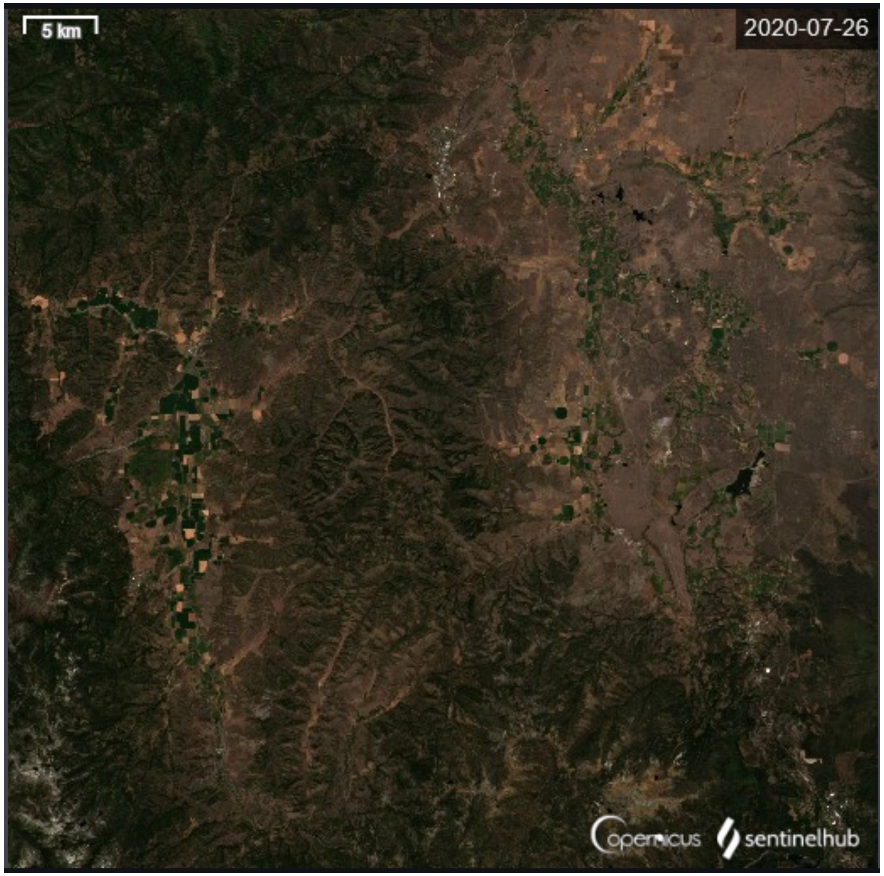
https://sentinelshare.page.link/eqeN



Sentinel 2 true color

Mar–Oct 2017–2022, 148 days with available imagery, using 10% cloud cover and 50% tile coverage as selection criteria.

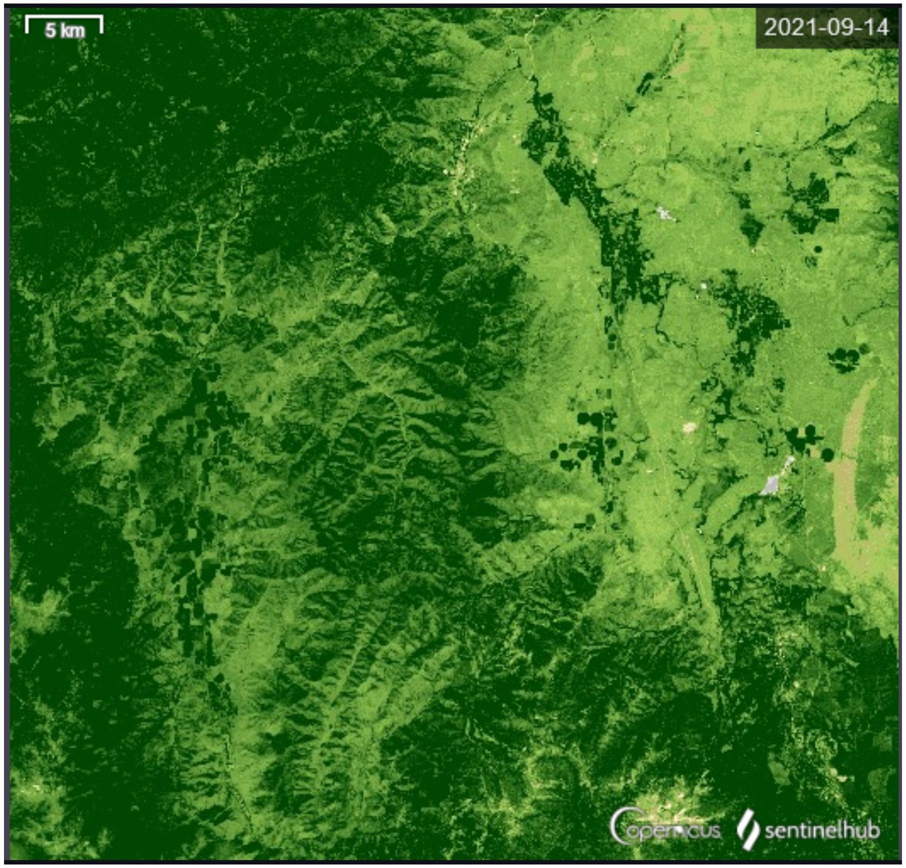
https://sentinelshare.page.link/WKFf



Harmonized Landsat Sentinel (HLS) greenness (NDVI, normalized difference vegetation index)

Mar–Oct 2017–2022, 155 days with available imagery, using 10% cloud cover and 50% tile coverage as selection criteria. HLS data are available back to 2013 but early years were not included in this animation to avoid exceeding maximum allowable animation length. HLS combines Sentinel 2 and Landsat so is available more frequently than either dataset in isolation.

https://sentinelshare.page.link/frJZ



Harmonized Landsat Sentinel (HLS) true color

Mar–Oct 2017–2022, 155 days with available imagery, using 10% cloud cover and 50% tile coverage as selection criteria HLS data are available back to 2013 but early years were not included in this animation to avoid exceeding maximum allowable animation length. HLS combines Sentinel 2 and Landsat so is available more frequently than either dataset in isolation

https://sentinelshare.page.link/dH4x

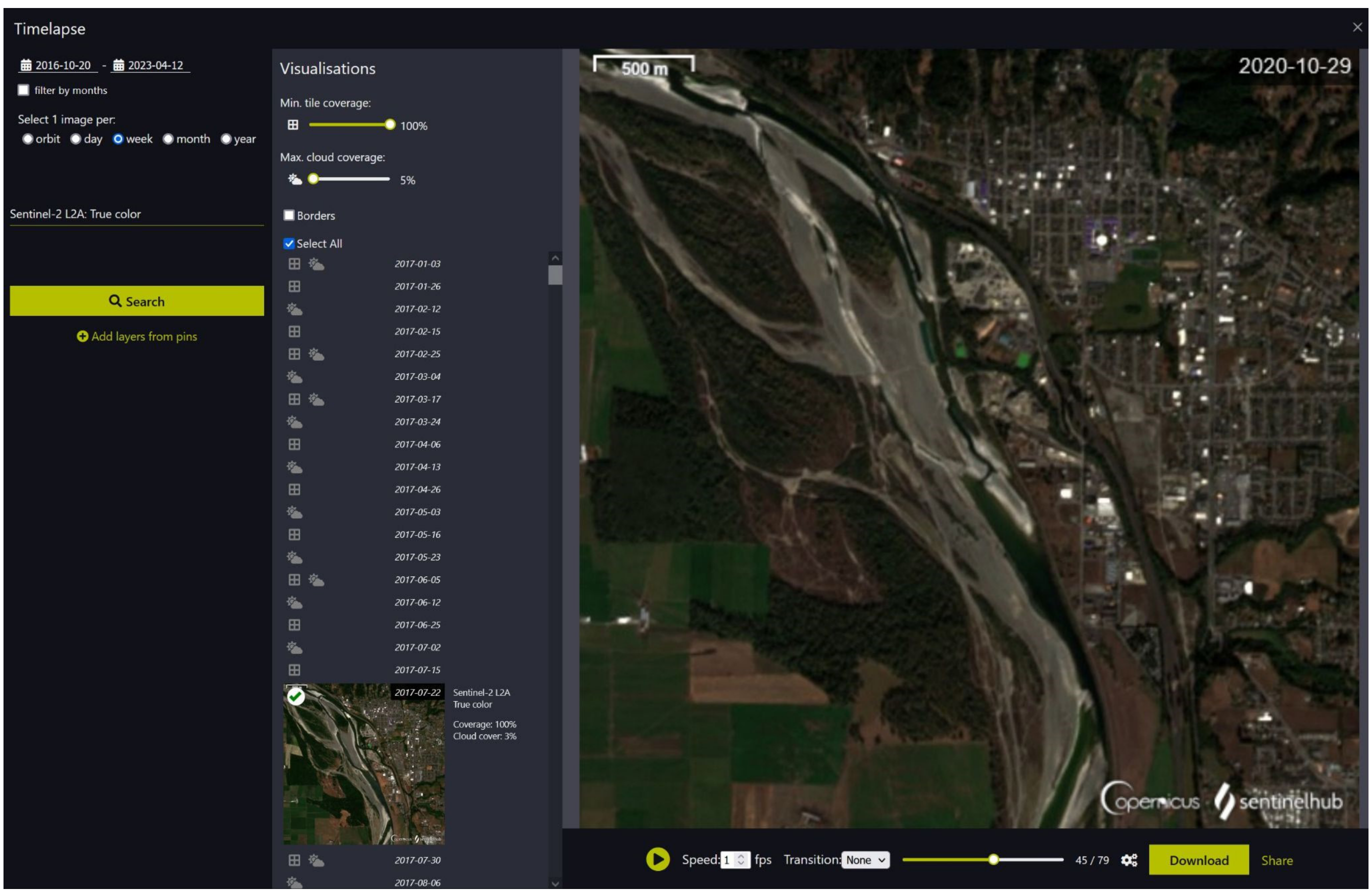
APPENDIX D: BRIEF INTRODUCTORY TUTORIALS TO OPENET, SENTINEL EO BROWSER, AND CLIMATE ENGINE

These tutorials were originally created for a workshop at the 2023 Salmonid Restoration Federation (SRF) conference in Fortuna, CA titled *The Future Is Now: How To Use Practical Remote Sensing Tools To Gain New Perspectives In River Restoration And Watershed Assessment*. Workshop materials are available online at https://www.riverbendsci.com/projects/remote-sensing and have been slightly adapted here.

Create true-color time lapse movie using Sentinel EO Browser

Time: 15–30 minutes

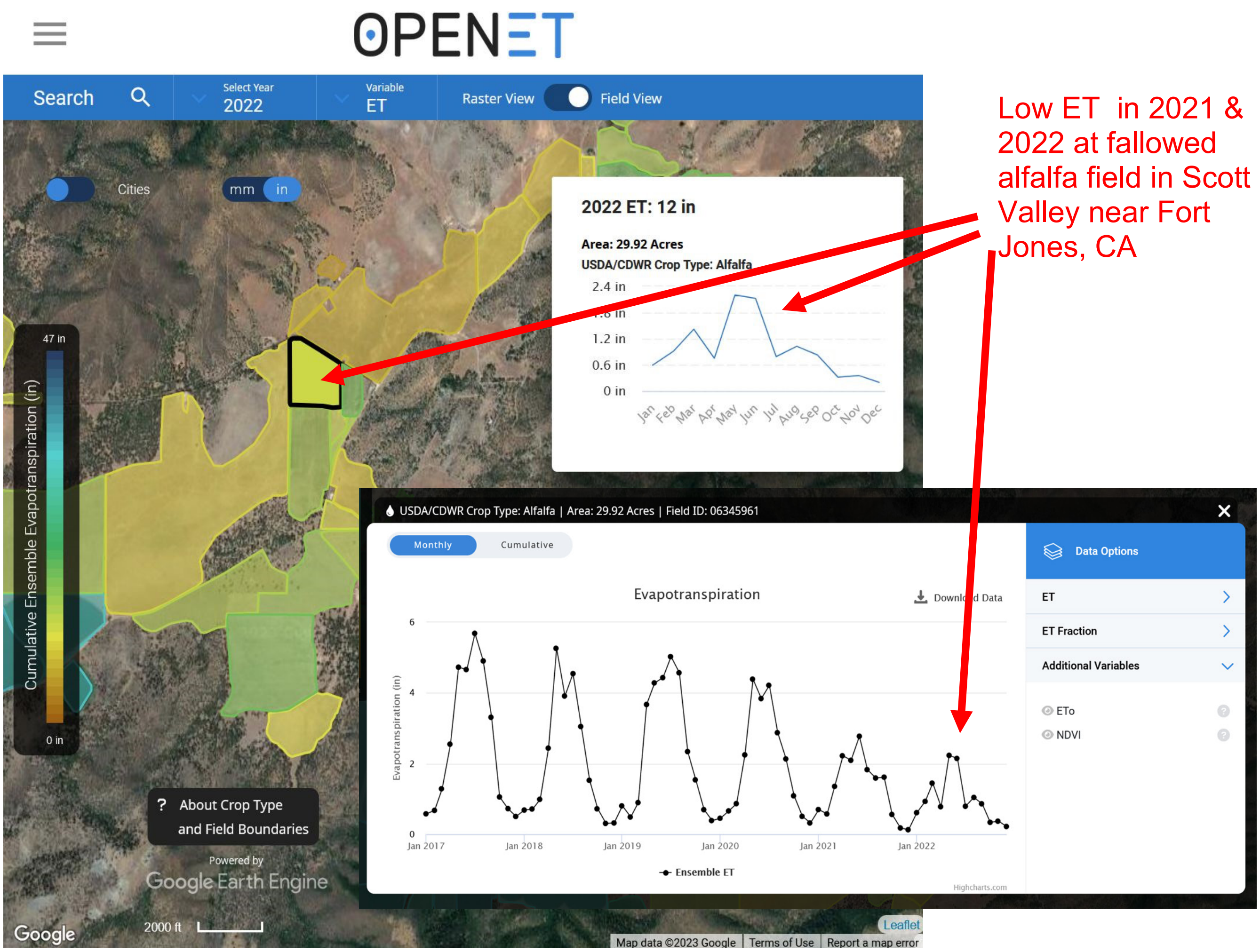
Description: Sentinel EO (https://apps.sentinel-hub.com/eo-browser/) is a web tool for browsing, downloading, and summarizing satellite data including Sentinel 2, Landsat, and MODIS. It includes a Time Lapse feature that allows creation of animated movies from the 10-meter resolution Sentinel 2. You must create a free account and login before you can create a Time Lapse. Follow instructions at: https://www.esa.int/ESA_Multimedia/Videos/2020/05/How_to_create_a_time_lapse_on_EO_Browser to login, create an area of interest, and generate a Time Lapse movie. The following example shows a screen shot from a weekly 2017–2023 animation of the lower Eel River, using a maximum cloud coverage of 5% and minimum tile coverage of 100% (watch at: https://sentinelshare.page.link/Pn3h):



Generate evapotranspiration time series for a farm field using OpenET website

Time: 10–20 minutes

Description: OpenET (https://openetdata.org/) provides consumptive water use (i.e., evapotranspiration, ET) data at different scales. You can view the data summarized for millions of individual agricultural fields or in the original raster format, or you can create a custom report to define your own boundaries, time frames, and data summaries. ET estimates are based on thermal and optical sensors aboard the 30-meter resolution Landsat satellites. The "Watch Video" link on https://openetdata.org provides an overview of the context and value of OpenET (or just browse the web pages). The map interface is available at https://explore.etdata.org, where I recommend you start clicking the "Field View" option. A guided tour to the map interface is available by clicking the "New here? Take a tour" button in the upper-right corner of the map https://explore.etdata.org. Zoom to your geographic area of interest and then click on a field polygon to see a time series of monthly ET estimates for that field.



Generate a time series of climate remote sensing data using Climate Engine website

[This example uses precipitation data but you can also choose OpenET or other remote sensing data like NDVI or EVI].

Time: 15–30 minutes

Description: The Climate Engine Research App (https://app.climateengine.org/climateEngine) generates a table with summarized time series (or maps or charts) of remote sensing datasets and climate data for an area of interest that can be drawn on map, uploaded from a shapefile, or chosen from pre-selected options like HUCs. It offers no-code access to summarize many (but not nearly all) datasets from the Google Earth Engine catalog. Climate datasets include precipitation and air temperature from several models including PRISM (daily and monthly), or remote sensing satellite data like Landsat NDVI and OpenET. *The Research App is only free for academic and non-commercial use*. You must have a Google account (i.e., gmail or other Google-run organizational account) and login to use the App. When you enter the App, the welcome pop-up has two green buttons: Video Tours has two 5-minute narrated videos (Graphs and Maps), and Guided Tours has a clickable guided tour. If needed, additional help is available at: https://support.climateengine.org/article/14-get-started. Watch the Graph video, then create an annual Summary Time Series of monthly PRISM Precipitation for your geographic area of interest. This example shows the Lower Eel HUC8 for 1895-2023: