MONITORING NEAR REAL-TIME EVAPOTRANSPIRATION USING SEBAL®: AN OPERATION TOOL FOR WATER AGENCIES/GROWERS

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ABSTRACT

The Surface Energy Balance Algorithm for Land (SEBAL®) is used worldwide to estimate actual evpotranspiration (ET) at different spatial scales (individual fields to entire basins) and temporal scales (water year, growing season, individual day, etc.). SEBAL has been successfully applied on various surface types including crops, riparian, natural vegetation, playas, and wetlands. Comparisons of SEBAL actual ET results with reliable ground based measurements (Eddy covariance, Bowen ratio, lysimeter, water balance and scintillometer) have shown close agreement with differences ranging from 1 to 5% when compared to reliable ground-based estimates over a growing season when the model is applied by experienced operators.

This paper describes near real-time application of SEBAL® (Version 2009) to produce weekly maps of actual ET, crop coefficients, and biomass production for California's Central Valley. Each week, the maps for the prior week are produced and posted to the Internet. The maps are developed using MODIS multispectral satellite imagery with an end resolution of 250 meters. This paper discusses potential application of near real time actual ET maps by water managers, water supply agencies and irrigators.

INTRODUCTION

Accurate evapotranspiration (ET) estimates are necessary to quantify irrigation demands and support better utilization and management of existing water supplies. In California and other arid areas of the West, where fresh water supplies are limited and perhaps becoming scarcer, it is becoming more difficult to satisfy urban, environmental, and agricultural demands.

The Surface Energy Balance Algorithm for Land (SEBAL) is a widely used energy balance model that uses satellite based surface radiances coupled with ground based meteorological data to estimate evapotranspiration (ET) (Bastiaanssen et al., 2005). ET is the major component of the crop water requirement for agricultural areas and of the depletion of stored precipitation in non-agricultural areas.

SEBAL ET estimates have been compared with reliable ground-based ET estimates from methods including eddy covariance, Bowen ratio, scintillometer and water balance.

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These validation studies have shown that SEBAL ET estimates agree with reliable ground-based estimates within 5% (estimated 95% confidence interval) across a series of monthly or more frequent images representing a growing season. Table 1 provides a summary of selected projects in California where SEBAL results were validated with reliable ground-based estimates.

Most of the information used by SEBAL is extracted from remotely-sensed satellite images. Additionally, local meteorological data is used when available. SEBAL is a cost effective way of monitoring ET over large areas. A study conducted in Idaho by Morse (2003) showed that the cost of monitoring water use with traditional methods in the eastern Snake River Plain was three to five times the cost of using the SEBAL energy balance model.

Table 1. Validations of SEBAL ET in California

Comparison Technique	Location	Duration	Crop	Difference	Reference
Surface Renewal	Sacramento Valley	7 months	Rice	5 %	Unpublished
Weighing Lysimeter	San Joaquin Valley	7 months	Peach	5%	Cassel (2006)
Weighing Lysimeter	San Joaquin Valley	7 months	Alfalfa	2%	Cassel (2006)
Water Balance	Imperial Irrigation District	12 months	Irrigated Agriculture	1%	Soppe et al (2006)

SEBAL is currently being applied to generate near-real time ET, crop coefficient, and biomass production estimates for California's Central Valley. The operational data products consist of spatially distributed grids of actual evapotranspiration, crop coefficients, and dry biomass production and are available on a weekly basis. A combination of satellite images from the MODIS Aqua and Terra satellites and a combination of ground-based observations and gridded weather data from the California Irrigation Management Information System (CIMIS) are used to produce these data.

This paper presents sample results and discusses the potential uses and applications of SEBAL as an operational tool to support water management.

METHODOLOGY

SEBAL Model

SEBAL (Version 2009) is culmination of more than 20 years of active research and has been applied successfully in fifteen countries over a variety of surface types. SEBAL utilizes an energy balance approach by partitioning the net solar radiation (R_n) available at the Earth's surface into its major consumers, including soil heat flux (G) and sensible heat flux (H), calculating latent heat flux (a measure of ET) as a residual term. A detailed explanation of the SEBAL model, its applications and validations can be found in Bastiaanssen et al. (2005). A brief conceptual summary is provided herein.

The net radiation flux (R_n) is estimated from the incoming solar radiation, accounting for incoming and outgoing shortwave and long wave components (both reflected and emitted). The soil heat flux is estimated as a function of R_n, surface temperature and Normalized Difference Vegetation Index (NDVI) that accounts for the effect of vegetation cover. The sensible heat flux (H) in SEBAL is estimated using a unique 'self-calibration' procedure. H is first estimated at two extremes ("hot" and "cold" pixels) and is then scaled between these two extreme temperatures for all pixels within the satellite image. The latent heat flux (LE), which is the amount of R_n consumed to vaporize available water as ET, is estimated as a residual of the energy balance based on the principle that energy can neither be created nor destroyed. The latent heat flux is converted into an equivalent depth of water consumed during the process of evapotranspiration using Equation 1:

$$ET_a = \frac{1}{\lambda \rho_w}\left[R_n - (G + H)\right], \qquad (1)$$

where ET_a is the actual evapotranspiration at the instant of satellite overpass, λ is the latent heat of vaporization of water, and ρ_w is the density of water.

The instantaneous ET_a is extrapolated to daily and longer periods by combining spatially distributed weather conditions from ground-based meteorological stations, evaporative fraction (Λ), and net available energy (R_n-G). Advection effects are estimated from average daily and periodic weather conditions and are incorporated in the ET_a estimates. The advection correction accounts for additional horizontal transfer of energy between pixels in the satellite image.

SEBAL Lumped Crop Coefficients

Crop coefficients are utilized to estimate crop ET and may be developed for other land surfaces as well. Most published crop coefficients assume stress-free conditions (optimal soil moisture levels, disease/pest free crops, etc.,) with no environmental and/or management related stresses; however, actual growing conditions often include such stresses that reduce ET from potential levels.

To a certain extent, published crop coefficients can be calibrated to represent actual growing conditions, but the process requires detailed field information. To overcome this difficulty, SEBAL utilizes actual ET to derive crop coefficients that represent actual field conditions (Equation 2).

$$K_{cs} = \frac{ET_a}{ET_o}, \qquad (2)$$

where K_{cs} is the actual crop coefficient, ET_o is the CIMIS reference ET and ET_a is the actual ET estimated by SEBAL.

SEBAL Biomass Module

Total dry biomass production is estimated as a function of photosynthetically active radiation (Monteith, 1972), light use efficiency (Field, et al., 1995) and normalized difference vegetation index (NDVI). Details of the formulation, application and validation of SEBAL biomass estimation can be found in Bastiaanssen and Ali (2003).

Photosynthetically active radiation (PAR) is the fraction of incoming solar radiation that can be potentially intercepted by a canopy and is estimated from incoming solar radiation Under actual conditions, only a fraction of PAR is absorbed by the canopy (APAR). APAR is estimated by accounting for the reflected portion of the radiation from the upper surface of the canopy and the fraction transmitted through the canopy based on total PAR and NDVI. The light use efficiency (ε) varies with c3 or c4 crops and is adjusted for environmental and/or management induced stresses based on estimated stresses from soil moisture deficit and ambient temperature. Moisture stress is estimated based on the evaporative fraction from SEBAL.

Input Data

A combination of satellite images from the Moderate Resolution Imaging Spectroradiometer (MODIS), meteorological data from CIMIS, and weather grids from the Coast-to-Mountain Environmental Transect (COMET) project are being utilized to develop the weekly SEBAL operational data products. Other data include a land use map from the National Agricultural Statistics Service (NASS) and a digital elevation model from the U.S. Geological Survey (USGS).

Satellite Images. SEBAL requires surface radiances in the visible, near-infrared and thermal bands of the electromagnetic spectrum. Surface radiances are estimated from satellite images acquired by the MODIS sensor on-board the Aqua and Terra satellites, which each have a one day return interval for a given area. A single MODIS image is selected each week to minimizing cloud cover and sensor zenith angle in order to maximize the area of coverage and the spatial precision of the results.

Weather Data. A combination of weather parameters from individual CIMIS stations and gridded weather data from COMET are utilized. A total of nine CIMIS stations (Table 2) located within the Central Valley are currently used to provide ground based weather data. These stations have been selected to achieve a reasonable representation of weather conditions for the Valley. Measurements utilized include relative humidity, wind speed, air temperature, and vapor pressure.

Gridded weather data utilized include dew point temperature, air temperature, wind speed, CIMIS reference ET, and K, a parameter describing the clearness of the sky.

Table 2. Selected CIMIS stations

ID	Station	County	Elevation (feet)	Latitude (Deg)	Longitude (Deg)
2	Five Points	Fresno	285	36.336	-120.113
6	Davis	Yolo	60	38.536	-121.775
15	Stratford	Kings	193	36.158	-119.850
30	Nicolaus	Sutter	32	38.871	-121.545
39	Parlier	Fresno	337	36.598	-119.503
56	Los Banos	Merced	95	37.009	-120.760
61	Orland	Glenn	198	39.692	-122.152
71	Modesto	Stanislaus	35	37.645	-121.188
145	Madera	Madera	230	37.018	-120.187
166	Lodi West	San Joaquin	25	38.130	-121.383
169	Porterville	Tulare	400	36.081	-119.092

Digital Elevation Model (DEM) and Land Use Map. The DEM is used to account for the effects of elevation, slope and aspect at each pixel on solar radiation and other factors and was obtained from USGS.

The land use map in SEBAL is used to estimate obstacle heights for land use classes within the study area. A land use map from developed by NASS for 2007 has been selected. The land use map has been generalized and resampled to 250 m spatial resolution to be consistent with the resolution of other input data.

RESULTS

Operational Data Products

The operational data products are available on the SNA website (www.sebal.us) in three formats: color coded maps, tables with summary statistics, and Google Earth overlays (Table 4). Raw data grids can also be made available to support hydrologic analyses. The color coded maps (.tif format) provide an overview of the spatial distribution of the data for each product. The spatial data from these individual operational products are summarized in a table format for the primary Hydrologic Regions (HRs) of the Valley: the Sacramento River HR, the San Joaquin River HR, and the Tulare Lake HR.

The Google Earth overlays provide color coded maps of the individual operational products that can be viewed in Google Earth. Google Earth overlays provide enhanced visualization of the spatial data and enable the user to view land surface of the areas of interest.

Table 4. Operational Products

No.	Product	Formats	Units
1	Actual ET	Map, Table, Google Earth Overlay	Inches/day
2	Total Dry Biomass Production	Map, Table, Google Earth Overlay	Pounds/acre/day
3	SEBAL Crop Coefficients	Map, Table, Google Earth Overlay	Unitless

Sample Results

The sample data selected for discussed herein represent two weeks in 2009: the period from 10/07 to 10/13 (Week 1) and the period from 10/14 to 10/20 (Week 2). Substantial rainfall occurred at the end of the Week 1 analysis period. Figure 1 presents the daily precipitation measurements for Weeks 1 and 2 for the selected CIMIS stations (Table 3).

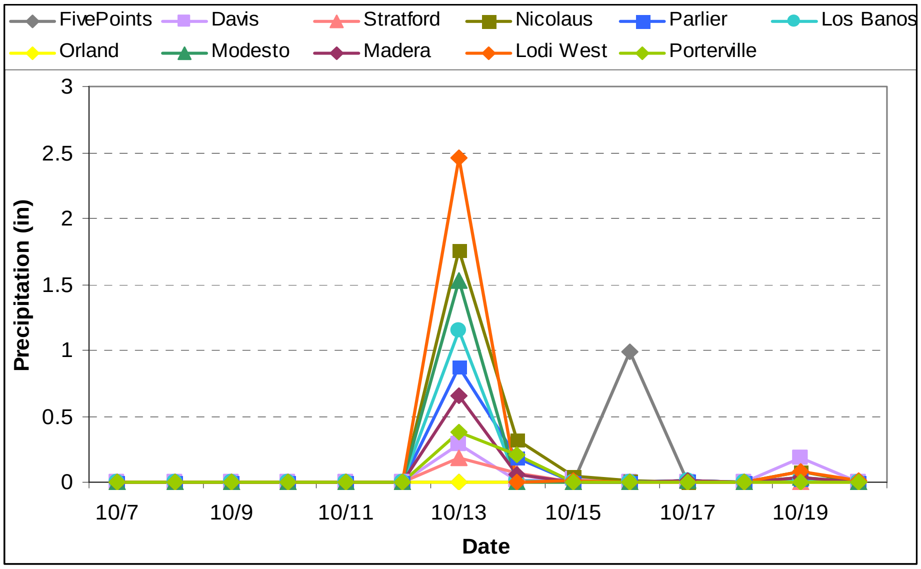

Figure 1. Precipitation Measured at the Selected CIMIS Stations

It is apparent from Figure 1 that the Valley, in general, received rainfall between 0.2 and 2.5 inched on 10/13/09, with no precipitation reported for the CIMIS stations at Five Points and Orland. In week 2 the CIMIS stations at Five Points and Davis reported precipitation of 1 and 0.25 inch, respectively.

Actual Evapotranspiration (ETa). Figure 2 provides color coded maps of spatially distributed average daily ETa (inches) for Weeks 1 and 2. Portions of the San Joaquin and Tulare Lake HRs for week 2 were obscured by the clouds; hence, ETa (including Kcs and Biomass) was not computed for those areas.

Although precipitation occurred on the last day of Week 1, its effects are not apparent in the Week 1 ETa map. ETa values estimated for Week 2 reflect the impact of precipitation on average daily ETa. The lack of an apparent rainfall effect in Week 1 is due to SEBAL ETa being estimated based on an image acquired prior to the rainfall occurring and then being extrapolated to the full week. The extrapolation is based on the assumption that the soil moisture and crop growing conditions on the day of image are representative of the entire period represented by the image.

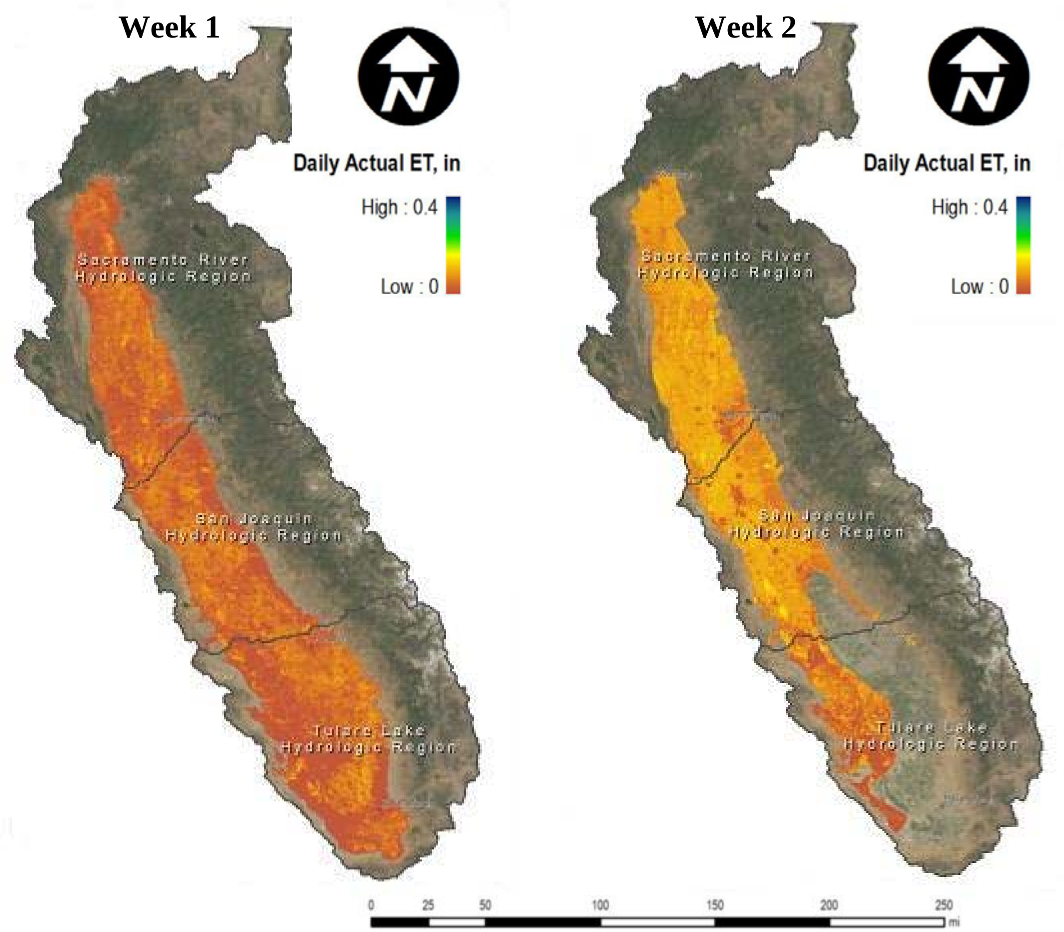

Figure 2. Spatially distributed ETa maps for the Central Valley. Week 1 is the period from 10/07 to 10/13 and week 2 is the period from 10/14 to 10/20.

Although changes in weather conditions that influence ET are taken into consideration by incorporating average weather conditions for the period represented by an image, events such as irrigation/and or precipitation on the day following the day of the image have not been explicitly accounted for. The effects of such irrigation/and or precipitation events are, however, represented in the image selected for the following period. This is apparent in the present case where a relatively greater ETa is seen in the Week 2 results, which represent the week starting on the 14th of October, a day after the rainfall occurred.

Figure 3 summarizes the spatial ETa results from Weeks 1 and 2. It is apparent from Figure 3 that the areas with non-zero ETa have increased considerably in Week 2. The mean daily ETa rate summarized individually for SR, SJ and TL hydrologic regions was also greater in Week 2 (0.075, 0.070 and 0.038 in, respectively) than in Week 1 (0.028, 0.032 and 0.026 in, respectively). The overall increase in ETa apparent in Week 2 is primarily due to an increase in soil surface evaporation in Week 2 as compared to Week 1.

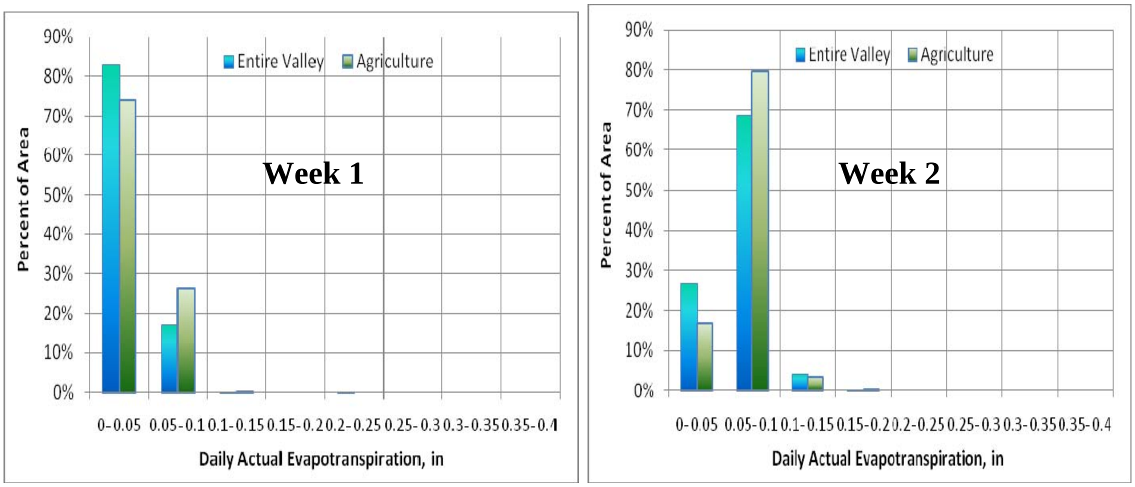

Figure 3. ETa Distribution in the Central Valley. Week 1 is the period from 10/07 to 10/13 and week 2 is the period from 10/14 to 10/20.

Lumped Crop Coefficients (Kcs). Maps of spatially distributed lumped crop coefficients and their histograms are presented in Figures 4 and 5, respectively. Week 1 results (Figure 5) show that more than 40% of the Valley as a whole has a Kcs of 0.2 or less. Crop coefficients for the agricultural area are similarly low with almost 80% of the area showing crop coefficient of 0.5 or less. The effects of bare fields and lack of soil moisture in the absence of irrigation or precipitation are apparent in the Week 1 Kcs values.

Crop coefficients in Week 2 follow a similar trend as ETa, showing an overall increase compared to Week 1 (Figures 4 and 5). Following the precipitation on the 13th of October, the increase in evaporation and evapotranspiration from Week 1 is apparent. Most of the areas in the Valley show non-zero Kcs values except for those areas that are potentially impervious surfaces e.g., rocks, foothills, or pavement, which are unable to hold moisture.

The increase in Kcs (Figure 5, Week 2) apparent in agricultural areas is due to increased soil surface evaporation or increased transpiration for existing vegetation.

The average daily Kcs values summarized individually for the SR, SJ and TL hydrologic regions for Week 1 were 0.28, 0.30 and 0.22, respectively. The average Kcs values in Week 2 for the SR, SJ and TL hydrologic regions were 0.91, 0.74 and 0.37, respectively and indicate an overall increase in Kcs in all the three hydrologic regions.

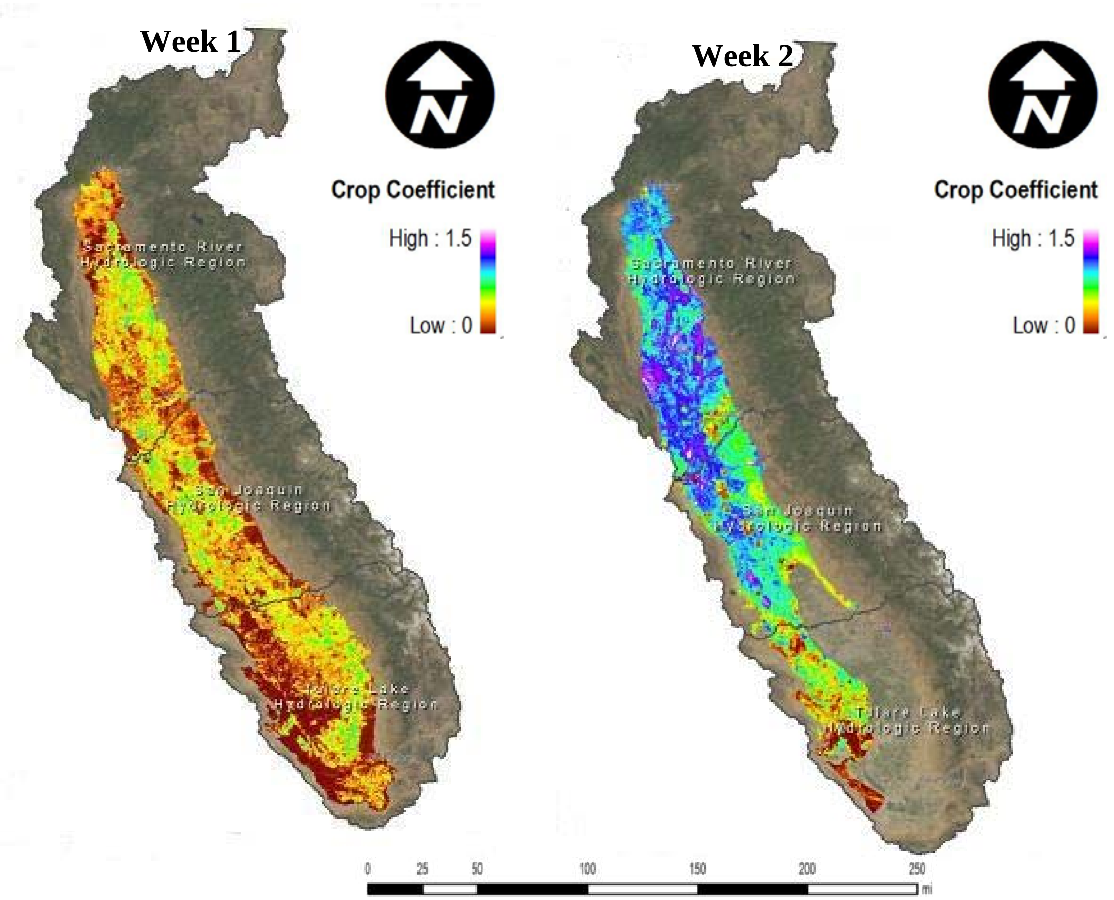

Figure 4. Spatially distributed weekly Kcs maps for the Central Valley. Week 1 is the period from 10/07 to 10/13 and week 2 is the period from 10/14 to 10/20.

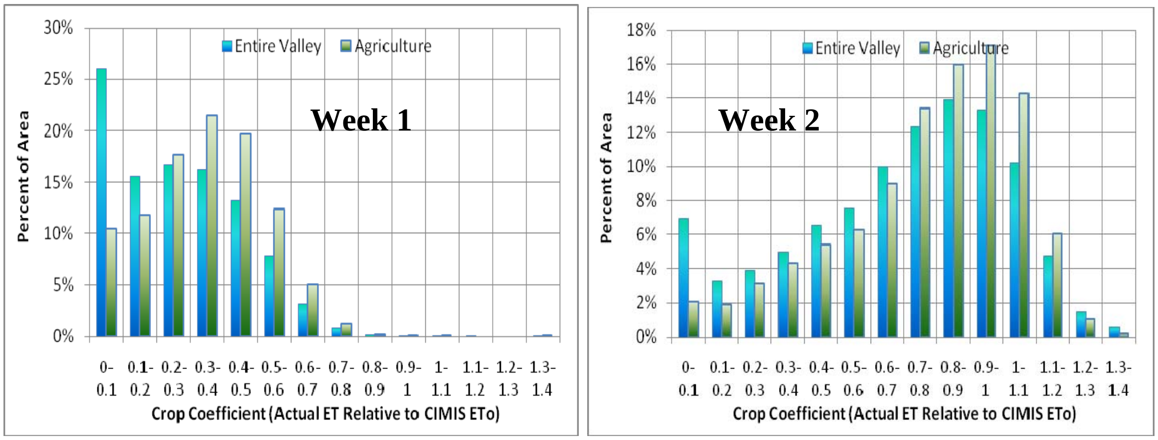

Figure 5. Kcs Distribution in the Central Valley. Week 1 is the period from 10/07 to 10/13 and week 2 is the period from 10/14 to 10/20.

<u>Biomass Production.</u> Maps of dry biomass production for the Central Valley and their frequency distributions for Weeks 1 and 2 are presented in Figures 6 and 7, respectively.

The biomass production in week 1 for SR, SJ and TL hydrologic regions was found to be 186, 211 and 168 lbs/acre respectively. An increase in Biomass was apparent in Week 2 with 199 and 239 lbs/acre of production for SR and SJ hydrologic regions respectively.

In Tulare Lake region, biomass production decreased from 168 lbs/acre in first week to 97 lbs/acre in the second week. This decrease in biomass production in TL region could be attributed to potential harvest that might have occurred before the satellite image acquisition that represents week 2 results or due to reduced PAR in Week 2.

An overall increase in biomass production for agricultural areas in the Valley is apparent in the 0 – 25 lbs/acre category for week 2 (Figure 7). This increase in biomass could be due increased transpiration rates (biomass being proportional to transpiration) of existing vegetation in the area. The precipitation event may also have initiated growth of new vegetation.

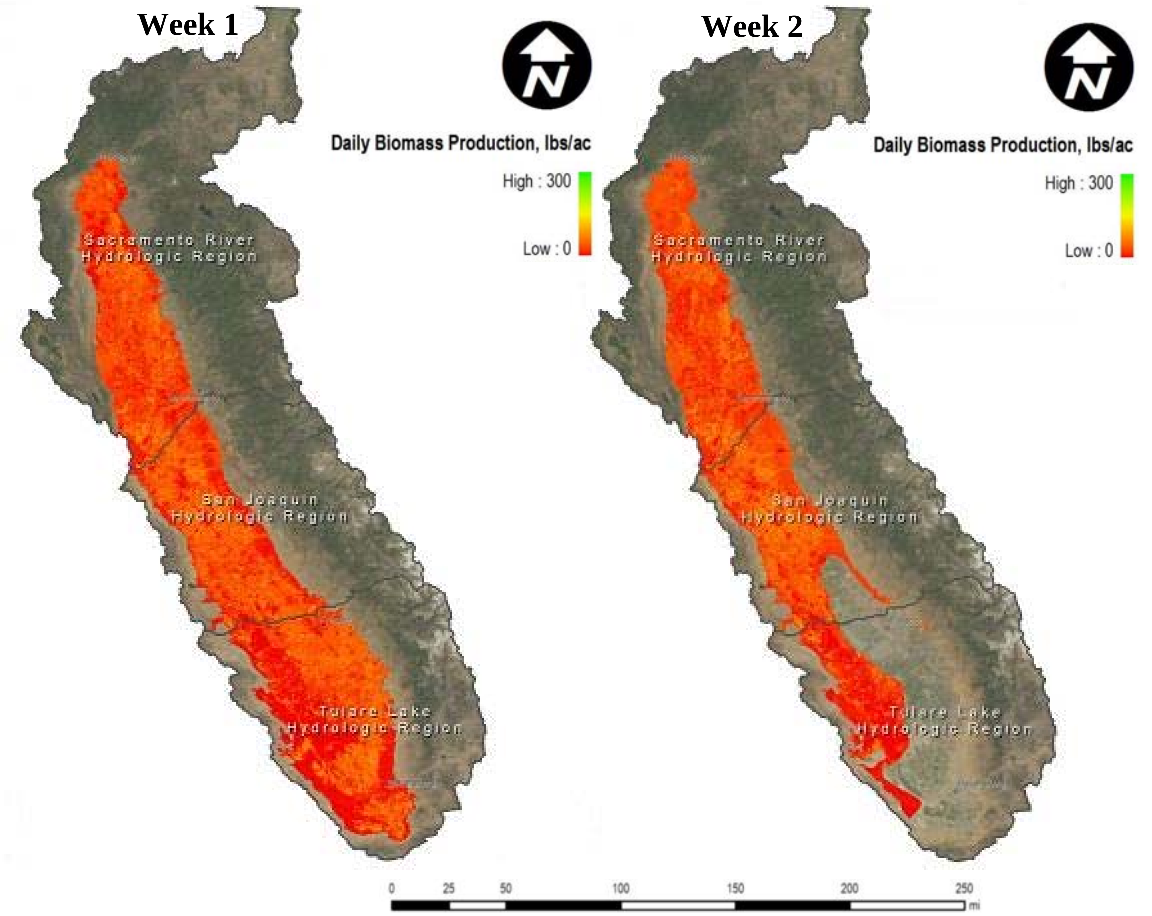

Figure 6. Spatially Distributed Weekly Biomass Production for the Central Valley. Week 1 is the period from 10/07 to 10/13 and week 2 is the period from 10/14 to 10/20.

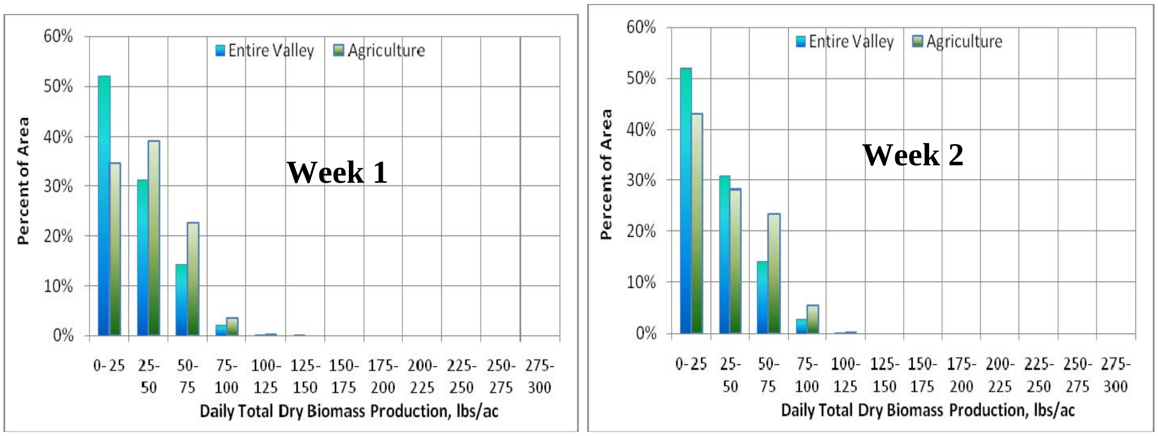

Figure 7. Biomass Distribution in the Central Valley. Week 1 is the period from 10/07 to 10/13 and week 2 is the period from 10/14 to 10/20.

DISCUSSION

The examples presented in Results section demonstrate that the SEBAL operational data products are able to capture variations in ETa, Kcs and Biomass, both spatially and temporally. These data offer efficient monitoring of crop consumptive use and production in near-real time which could assist irrigation districts, water agencies, growers, and water managers in general in decision making and natural resource management.

In addition to actual ET, the lumped crop coefficients (Kcs) developed using SEBAL are useful for irrigation management and planning. The lumped Kcs represent actual growing conditions for a given crop and can be utilized to determine accurate crop water requirements.

Weekly biomass production estimates can be used to improve crop management and to understand drought impacts. Biomass production can be utilized to monitor overall crop growth, incorporating the effects of environmental and management related stresses including disease, pests, moisture stress, fallowing, etc. Biomass production can be utilized to predict yield for a given crop by using crop specific harvest indices (Bastiaanssen and Ali, 2003). Predicting yield could help in assessing the value of a crop prior to coming into the market. Additionally, biomass production and ET can be combined to estimate water productivity of a given crop. Water productivity is defined as the crop yield per unit of water used and is a useful index to gauge water use efficiency.

CONCLUSIONS

Satellite based near-real time ET, Kcs and Biomass are being generated using SEBAL on a weekly basis. SEBAL is the most widely applied energy balance model for estimating ET, and over the years it has been validated in various parts of the world, including California.

Weekly data are available for California's Central Valley with a spatial resolution of 250 m. Satellite images from MODIS along with weather data from CIMIS have been utilized to generate these data products. Operational products for most recent weeks can be accessed on SNA's website (www.sebal.us). The SNA website is updated every week with the operational products for the prior week.

Using MODIS images, actual ET, crop coefficients, and biomass production can be estimated in a near-real time. Water supplies in the Central Valley are limited, and efficient utilization of available water is critical. Detailed water consumption patterns provided by spatially distributed weekly ET maps along with Kcs and Biomass can assist in improving understanding of water use in both agricultural and natural systems.

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