Arnold Schwarzenegger
Governor

ESTIMATING IRRIGATION WATER USE FOR CALIFORNIA AGRICULTURE: 1950s TO PRESENT

PIER PROJECT REPORT

Prepared For:
California Energy Commission
Public Interest Energy Research Program

Prepared By:
Dr. William Salas and Pamela Green, Applied Geosolutions, LLC

Dr. Steve Frolking, Dr. Changsheng Li, and Steve Boles, Consultants

APPLIED GEOSOLUTIONS, LLC

May 2006
CEC-500-2006-057

California Climate Change Center
Report Series Number 2006-006

Prepared By:
Dr. William Salas and Pamela Green
Applied Geosolutions, LLC
87 Packers Falls Road, Durham, NH 03824
wsalas@agsemail.com, pamela.green@agsemail.com
603-292-5747

Dr. Steve Frolking, Dr. Changsheng Li, and Steve Boles
Durham, NH 03824
Steve.Frolking@unh.edu, Changsheng.li@unh.edu, stephen.boles@unh.edu
603-862-0244

Contract No. 500-02-004
Work Authorization MR-025

Prepared For:
California Energy Commission
Public Interest Energy Research (PIER) Program

Guido Franco,
Contract Manager

Kelly Birkinshaw,
Program Area Manager
Energy-Related Environmental Research

Martha Krebs, Ph.D.
Deputy Director
ENERGY RESEARCH AND DEVELOPMENT DIVISION

B. B. Blevins
Executive Director

Acknowledgements

We are grateful for the funding provided by the California Energy Commission and Scripps Institution of Oceanography for this research. We would like to thank Guido Franco and Dan Cayan for their comments and assistance for this project.

Please cite this report as follows:

Salas, W., P. Green, S. Frolking, C. Li, and S. Boles. 2006. *Estimating Irrigation Water Use for California Agriculture: 1950s to Present*. California Energy Commission, PIER Energy-Related Environmental Research. CEC-500-2006-057.

Preface

The Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The PIER Program, managed by the California Energy Commission (Energy Commission), annually awards up to $62 million to conduct the most promising public interest energy research by partnering with Research, Development, and Demonstration (RD&D) organizations, including individuals, businesses, utilities, and public or private research institutions.

PIER funding efforts are focused on the following RD&D program areas:

- Buildings End-Use Energy Efficiency
- Energy-Related Environmental Research
- Energy Systems Integration
- Environmentally Preferred Advanced Generation
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy Technologies

The California Climate Change Center (CCCC) is sponsored by the PIER program and coordinated by its Energy-Related Environmental Research area. The Center is managed by the California Energy Commission, Scripps Institution of Oceanography at the University of California at San Diego, and the University of California at Berkeley. The Scripps Institution of Oceanography conducts and administers research on climate change detection, analysis, and modeling; and the University of California at Berkeley conducts and administers research on economic analyses and policy issues. The Center also supports the Global Climate Change Grant Program, which offers competitive solicitations for climate research.

The California Climate Change Center Report Series details ongoing Center-sponsored research. As interim project results, these reports receive minimal editing, and the information contained in these reports may change; authors should be contacted for the most recent project results. By providing ready access to this timely research, the Center seeks to inform the public and expand dissemination of climate change information; thereby leveraging collaborative efforts and increasing the benefits of this research to California's citizens, environment, and economy.

The work described in this report was conducted under the Continuing Climatic Data Collection, Analyses, and Modeling contract, contract number 500-02-004, Work Authorization MR-025, by Applied Geosolutions, LLC.

For more information on the PIER Program, please visit the Energy Commission's website www.energy.ca.gov/pier/ or contract the Energy Commission at (916) 654-5164.

Table of Contents

Abstract

The Denitrification-Decomposition model (DNDC) is employed to model irrigation water demand in California under historic (circa 1950) and contemporary (circa 2000) crop conditions. Model simulations are applied at a daily time step and high spatial resolution (5-kilometer grid) yielding gridded surfaces of daily water demand for agricultural areas throughout California. The model is run for contemporary and historic cropland conditions under three reference climate years representing nominal (1996), early spring/dry (1997), and late spring/wet (1983) conditions.

The study illustrates the large increases in crop irrigation and transpiration from historic to the contemporary state. Inter-annual analysis shows the early spring/dry climate year requires greater irrigation water use to meet crop needs, while the late spring/wet year shows decreased irrigation needs. County-level analysis demonstrates a strong seasonality in water use driven by climate and cropping practices, with the spring and summer months showing greatest irrigation water demand.

Model results offer a baseline for contemporary and historic water demand that are suitable for both state and finer regional-scale applications. This work demonstrates that mesoscale regional climate and water demand models can be successfully employed at finer spatial and temporal scales moving beyond current models such as CALSIM.

1.0 Background

The CALSIM model is a generalized water resources planning tool developed by California Department of Water Resources (DWR). CALSIM is not ideal for driving mesoscale regional climate models for the following reasons:

Issue 1: CALSIM does not simulate all of the agricultural regions of California.

Issue 2: CALSIM uses large geographical units called DSA (Depletion Study Areas) with 2–3 per county.

Issue 3: CALSIM operates at a monthly time-step.

The authors used the Denitrification-Decomposition model (DNDC) and its embedded crop models to model agricultural demand for irrigation water based on soil conditions, climate (e.g., daily minimum and maximum temperatures, daily precipitation, radiation), and general cropping systems. This modeling simulation was performed at higher spatial (5 x 5 km resolution) and temporal (daily) resolution than CALSIM. Three reference climate years (1983, 1996, and 1997) were used to simulate the range in climate conditions from the early 1950s though early 2000s. Model outputs include greenhouse gas (GHG) emissions and crop water demand that accounts for crop use, evapotranspiration (ET) losses, and infiltration/leaching below the rooting zone. Total irrigation use is estimated based on DNDC-modeled irrigation demand to meet agronomic demand, adjusted by an irrigation efficiency factor to account for over-irrigation and efficiency of irrigation systems in California.

2.0 Project Objectives

The overall objective of this project was to create estimates of irrigation water use for California agriculture for 1950 and contemporary conditions. To accomplish this task, this project's researchers identified the following six specific objectives:

- Review existing literature on agricultural management practices and cropping systems (e.g., use of irrigation, types of irrigation systems, planting and harvesting dates for major crops), as well as historical agricultural census to improve/constrain estimates of historical cropping areas at the sub-county level.
- Build a geographical information systems (GIS) database of soils and climate for DNDC model runs.
- Estimate historical extent of irrigated crop lands and irrigation intensity in California in the 1950s.
- Run DNDC at 5 x 5 km grid cell resolution for all irrigated areas in California using three reference climate years to represent a nominal year (1996), an early spring/dry year (1997), and a late spring/wet year (1983), to estimate a range in demand for irrigation water. Model estimates of water use will be provided as ranges, because of uncertainties in soil conditions (GIS soil survey data provide minimum and maximum values for each soil property for each GIS polygon).

- Perform a scaling analysis to look at variability of irrigation demand within the counties and CALSIM regions (provided GIS boundary files are available for CALSIM regions).
- Perform a scaling analysis, for selected regions, to look at variability of irrigation demand within the CALSIM regions at a daily versus monthly time step.

3.0 Model Development

3.1. DNDC Model

The process-oriented computer simulation model, Denitrification-Decomposition (DNDC), was developed based on the biogeochemical concepts for predicting soil biogeochemistry (Li et al. 1992, 1994, 1996; Li 2000). The first component (see Figure 1), consisting of the soil climate, crop growth and decomposition sub-models, predicts soil temperature, moisture, pH, redox potential (Eh) and substrate concentration profiles (e.g. ammonium, nitrate, dissolved organic carbon) based on ecological drivers (e.g., climate, soil, vegetation and anthropogenic activity). The second component, consisting of the nitrification, denitrification and fermentation sub-models, predicts nitric oxide (NO), nitrous oxide (N_2O), methane (CH_4), and ammonia (NH_3) fluxes based on the environmental variables in the soil. The entire model forms a bridge between basic ecological drivers including management of agro-ecological systems, and water, carbon, and nitrogen cycles. DNDC utilizes GIS databases with spatially and temporally differentiated information on climate, soil, vegetation and farming practices for local, regional and national scale analyses.

DNDC has a one-dimensional soil water flow to calculate an average hourly and daily soil moisture profile. The thickness of a modeled soil profile is usually 50 centimeters (cm) (20 inches, in) but can be extended to 100 cm (40 in) or deeper. DNDC characterizes soil physical properties by soil texture, following the work of Clapp and Hornberger (1978). The soil profile is divided into a series of horizontal layers. Typical vertical spatial resolution is 2 cm (0.8 in), and the time step is an hour. Each layer is assumed to have uniform texture and moisture. For each time step, water flow between layers is determined by the gradients of soil water potential (Ritchie et al. 1988). During a simulated rainfall event, rainwater is added on the surface of the soil then infiltrates into the soil profile layer by layer to fill the soil pore. Gravity drainage occurs when the soil moisture is higher than the field capacity (i.e., 0.033 megapascals (Mpa) for a North American system, and 0.006 Mpa for a European soil system) in a layer. Water efflux from the bottom of the modeled profile is driven by gravity drainage only (Van Bavel et al. 1978). If the rainfall intensity, which is fixed as 0.5 cm/hr (0.2 in/hr) in DNDC, is higher than the soil saturated hydraulic conductivity, ponding water will form on the soil surface and a surface runoff flow will be calculated based on the defined soil slope. Water withdrawal from the soil profile is calculated based on transpiration and evaporation. Potential ET is calculated as daily average values using the Thornthwaite formula, in which potential ET is determined by mean air temperature and then adjusted for daylight length relative to 12 hours (Dunne and Leopold 1978). Potential ET is separated into potential transpiration and evaporation. Daily potential transpiration is determined by daily water demand by plants, which is quantified based on the modeled daily increment of crop biomass. Actual plant transpiration is jointly determined by potential transpiration and soil water content. Potential evaporation is the difference of potential ET and actual transpiration. Evaporation is allowed to occur only for the top 20 cm (8 in) of soil profile. By tracking precipitation, plant interception, ponding water, surface runoff, infiltration, gravity drainage, transpiration, and evaporation, DNDC simulates water movement in the vertical dimension of soil profiles. A routine of heat transmission in soil has been built in DNDC to simulate soil freezing and thawing processes, which significantly affect water movement in the soil profile. Detailed descriptions of the hydrological equations and parameters have been reported in several former publications (e.g., Li et al. 1992; Zhang et al. 2002). DNDC was recently modified by adding a water recession curve and a virtual deep water pool to improve predictions of water leaching.

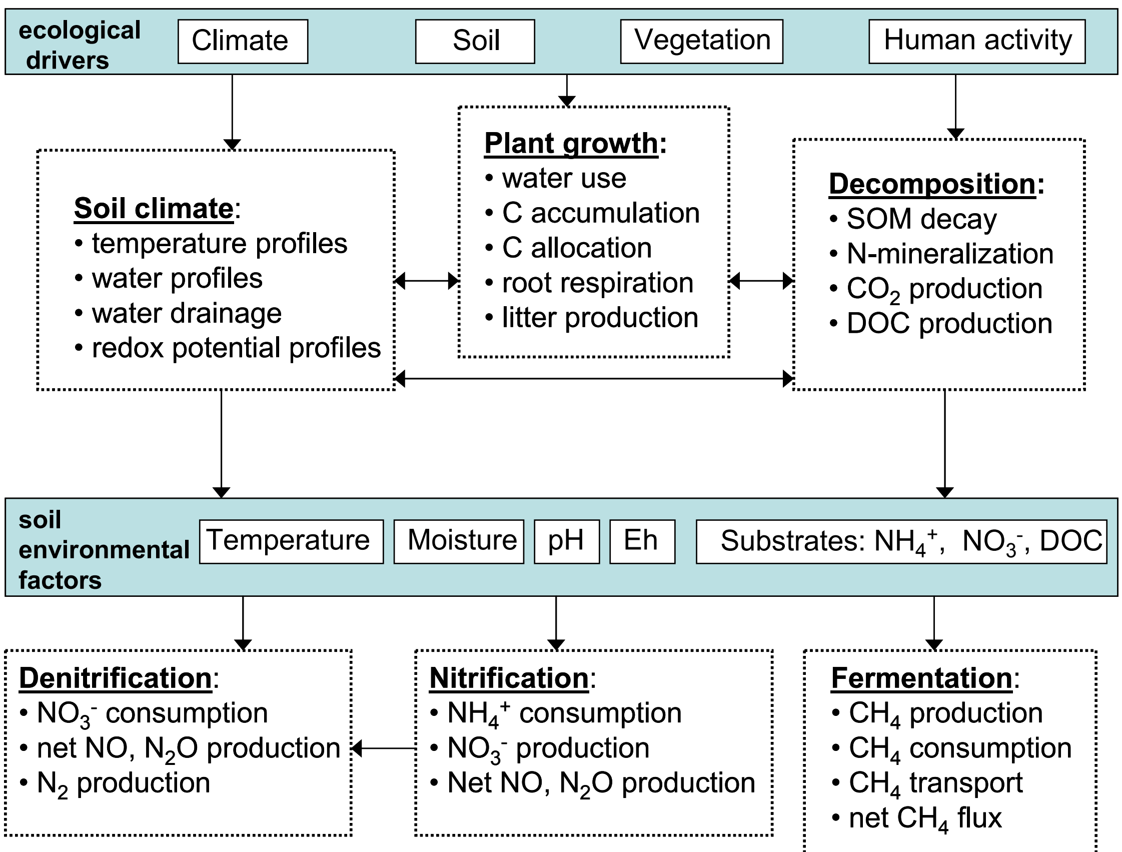


Figure 1. DNDC model structure

DNDC has been linked to a crop model (Zhang et al. 2002; Li et al. 2004) to simulate crop growth, crop water use, soil organic carbon (SOC) dynamics and emissions of dinitrogen (N_2) and several trace gases, including N_2O, NO, NH_3, and CH_4 from both upland and wetland agricultural ecosystems. DNDC is a unique process-based biogeochemical model because it (1) simulates both aerobic and anaerobic conditions, (2) tracks redox potential (Eh), (3) can provide a relatively complete suite of nutrient releases to air and water, including emissions of ammonia, greenhouse gases, and nitrate leaching, and (4) contains tools for examining sensitivity and uncertainties in emission estimates. This model has been independently tested and validated by many researchers and under a wide range of conditions worldwide and now is utilized for national trace gas inventory studies in the United States, Canada, the United Kingdom, Germany, Italy, New Zealand, China, India, Japan, Thailand, and the Philippines. The extensive validation and applications indicate that the fundamental processes embedded in DNDC provides a sound basis for modeling C and N dynamics across a broad range of climatic zones, soil types, and management regimes.

3.2. Development of GIS Databases

3.2.1. 5 x 5 Kilometer Basemap

All data for this California agricultural water use study are compiled at 5 x 5 km spatial resolution to serve mesoscale climate modeling and regional air quality studies for regions with irrigated agriculture. A 5 x 5 km gridded basemap was created for the entire state of California to aggregate cropland, soils, and climate data to the project spatial resolution. Statistics and input files were created for each of the DNDC input layers based on this basemap grid.

3.2.2. Climate Database

Three reference climate years were chosen for the analysis to simulate an "average/nominal" year (1996) and two extremes years (wet/late spring (1983) and dry/early spring (1997)). The University of Nevada's Daymet database was used to provide a surface of precipitation, temperature, and radiation for each of the reference years for input into the DNDC model.

The Daymet database includes daily surfaces of temperature, precipitation, humidity, and radiation over large regions of complex terrain. Daymet was developed by the University of Montana's Numerical Terradynamic Simulation Group (NTSG), to model the fine resolution, daily meteorological and climatological data needed to model plant growth dynamics. Daymet provides an 18-year daily dataset (1980–1997) of temperature, precipitation, humidity, and radiation as a continuous surface at a 1 km resolution. A wide range of summary and point daily data over the conterminous United States is also available from the Daymet website (www.daymet.org).

Climate data was downloaded from the Daymet website using an automated mining routine for each of the 5 x 5 km basemap grid cell centroids. Where no data were available at the centroid location, a 0.1 degree spiral search was initiated to find available data closest to the grid cell center. Daily data from 1983, 1996, and 1997 for minimum and maximum temperature, average precipitation and solar radiation were downloaded for each 5 x 5 km grid cell for input into the DNDC model.

3.2.3. Soils Database

Soil data on organic carbon content, pH, bulk density and soil texture required for input to the DNDC model were complied using the United States Department of Agriculture's (USDA's) Natural Resources Conservation Service (NRCS) State Soil Geographic

(STATSGO) database. The 1:250,000 STATSGO dataset is generated from Landsat satellite image interpretation and generalization of the more-detailed Soil Survey Geographic (SSURGO) database utilizing field surveys and aerial photograph interpretation. The database is designed to be used for broad planning and management uses covering state, regional, and multi-state areas. The STATSGO attribute database gives the proportionate extent of the component soils and their properties for each map unit and includes over 25 physical and chemical soil properties, interpretations, and productivity. The STATSGO dataset was used to obtain the minimum and maximum ranges for the soil attributes required by DNDC (pH, clay content, bulk density, soil organic matter) aggregated to the 5 x 5 km basemap grid.

The STATSGO database is arranged in a multi-layer format, whereas each polygon (referred to as ″map unit″ by STATSGO) can have multiple components, and each component can have multiple layers. A soil component is a set of properties that are used to describe a certain soil type that exists. The percent areas that each soil component occupies within the STATSGO polygons are provided (″*comparea*″ variable), however there is no information provided as to the actual spatial distribution of each component within the polygons.

It is evident that each STATSGO polygon has the potential for dozens of scenarios based on multiple soil components and layers; however the DNDC model requires a single set of input ranges for the soil input variables. In order to take advantage of the detail that is available in the STATSGO database, an area-weighted approach was used. First, all soil layers except the top layer were eliminated, because this layer is typically deeper than the rooting depth for most crops, which is the depth used for DNDC simulations. Second, based on the *comparea* variable, soil components greater than 10% of the surface layer were area-weighted to be used as DNDC soil inputs.

Three of the STATSGO soil variables (pH, clay content, bulk density) were in the format required by DNDC. However, STATSGO provides organic matter content as a percent by weight, whereas DNDC requires the fraction of soil organic carbon by weight. This study assumed that organic matter is 58% carbon.

Several soil texture categories in the STATSGO dataset were identified that have ″no data″ for the DNDC variables. These soil texture categories include: cemented, fragmented, ice, indurated, mucky-peat, muck, peat, unweathered bedrock, weathered bedrock, and variable. It was assumed that cropland would not occur on any of these soil texture types; thus data from these soil texture categories were excluded.

To generate a database of soil input variables at the 5 x 5 km modeling scale, the STATSGO polygon map was merged with the 5 x 5 km basemap grid. Area-weighted DNDC soil variables were then calculated for each 5 x 5 km grid in California. A map of minimum and maximum soil texture represented at the area weighted 5 x 5 km grid scale is shown in Figure 2 below.

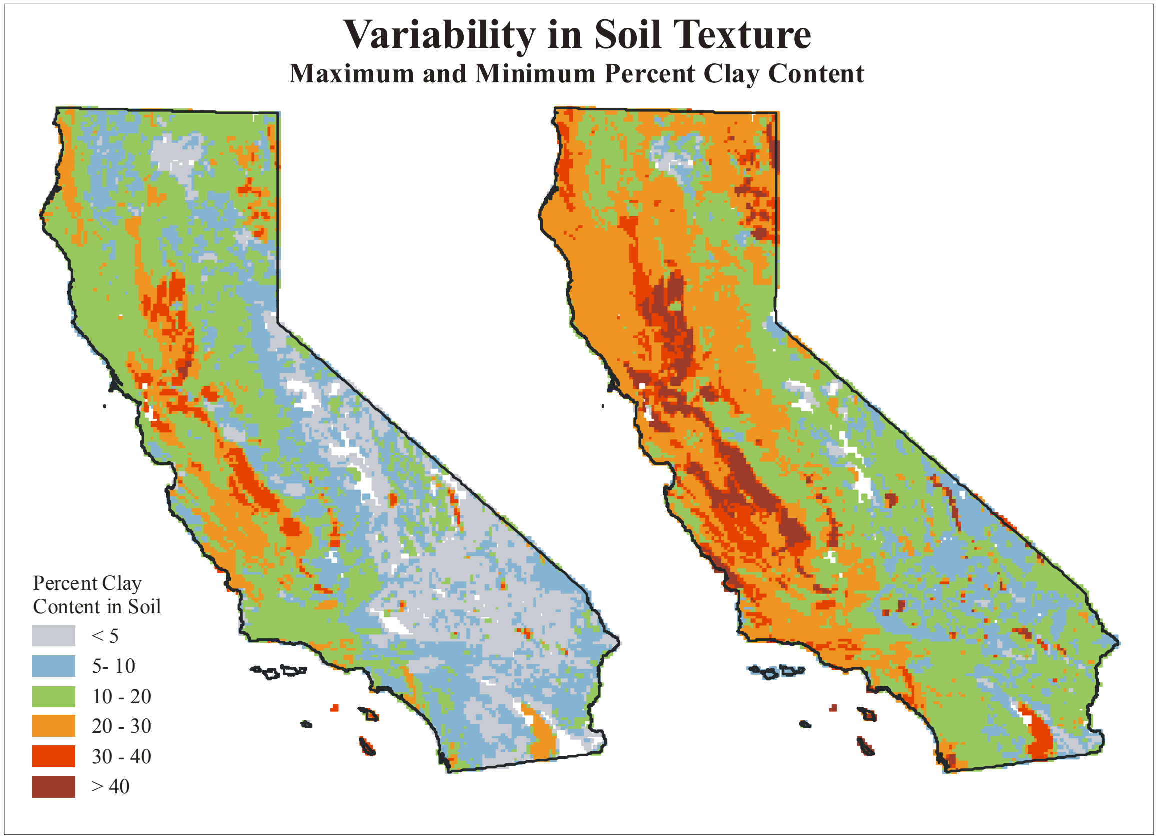


Figure 2. Maximum and minimum soil texture for each 5 km grid cell

3.2.4. Crop Management Practices Database

Crop Planting, Harvesting and Tillage Practices: For each crop, this study's researchers collected data from California Air Resources Board (CARB) on planting, cultivation, and harvesting periods, as well as on land preparation (e.g., tillage type, tillage dates, and tillage frequency). The California Air Resources Board collected the data through numerous consultations with University of California (UC) extension, UC agronomists, crop consultants, and farmers as part of their fugitive dust study. Data were obtained directly from Patrick Gaffney and Hong Yu at CARB.

Fertilizer Use: Summary data on fertilizer application rates by DWR crop class were obtained from Potter et al. (2001). They derived the fertilizer rates based on numerous discussions with faculty at California State University Fresno Plant Science Department, UC Extension, various growers associations, and Dow Agrosciences. Potter et al. (2001) have a table with rates for eight general DWR classes and four major growing regions. This study did not vary fertilizer application rates by region.

3.2.5. Cropland Database

3.2.5.1. Contemporary Irrigated Croplands

Contemporary cropland and irrigated areas in California are defined principally using the DWR land use survey database. The DWR supports ongoing efforts to conduct county land use surveys on an annual basis. Since 1950, the DWR has conducted over 250 land use surveys for all or part of California's counties. The main emphasis and detail of the surveys is agricultural land, with the results of the surveys used to determine agricultural area and water use for the survey year. Potentially, over 70 different crop types can be mapped in the survey and both irrigation type and irrigation water source can also be identified.

The DWR land use database contains a spatial distribution of land use and cropland polygons for 42 of the 53 counties with irrigated cropland in California, plus partial coverage for San Bernardino, Riverside, and Los Angeles counties. The database includes descriptions of crop type, multi-cropping (including double and triple crop rotations), and irrigation practices. The statewide distribution of irrigated cropland was derived by appending the individual county land use survey GIS coverages available through the DWR website (www.landwateruse.water.ca.gov/) into a single statewide coverage.

The DWR crop types and rotations were grouped into one of the 42 DNDC crop classes for input into in the model. Where multiple crop rotations were present, a combination DNDC class was assigned (i.e., a vegetable crop rotated with a hay crop was assigned a "double-vegetable-grass" class). Ten multi-cropping DNDC classes were identified including double and triple crop rotations with vegetable, grain, and grass crop combinations. DNDC crop assignments were then aggregated to the 5 x 5 km basemap grid defining the type and acreage of crops in each 5 km grid cell.

3.2.5.2. Missing Contemporary Counties

Fourteen counties identified as having irrigated cropland in the 2002 U.S. agricultural census (USDA-NASS 2005) were not available, or only partially available, in the DWR land use survey database: Alameda, Calaveras, El Dorado, Inyo, Los Angeles, Mendocino, Nevada, Orange, Riverside, San Bernardino, San Mateo, Santa Clara, Sierra, and Sonoma. For missing counties a methodology was designed to estimate the spatial distribution and quantity of irrigated cropland across these regions. County-level irrigated crop statistics from the USDA National Agricultural Statistical Service (NASS) online database (www.usda.gov/nass/) for year 2002 were used in conjunction with the U.S. National Land Cover Data set (NLCD) (Vogelmann et al. 1998a,b) to distribute irrigated cropland for the 14 missing counties.

The NLCD is a 21-class land cover classification scheme derived from early to mid-1990s Landsat Thematic Mapper (TM) satellite data at 30 meter (98 foot) resolution. The NLCD classification was created using an unsupervised clustering algorithm to process TM multi-band mosaics classifying the clusters with aerial photography and ground observations. A hierarchical land cover classification scheme of 21 classes (a modified Anderson Land Cover Classification)[1] was developed and applied in a consistent manner across the entire United States. Of the 21 NLCD classes four cultivated classes were identified as representing crop and pasture lands for this study. These classes include Orchards/Vineyards/Other (61), Pasture/Hay (81), Row Crops (82), and Small Grains (83).

[1] See http://landcover.usgs.gov/pdf/anderson.pdf.

The 2002 Census of Agriculture contains agricultural statistics for each county in California, including data on irrigated crop area for 15 crop types as well as area in irrigated pasture. The 2002 census crops and pasture were grouped into one of the four NLCD cultivated groups (Orchards/Vineyards/Other, Pasture/Hay, Row Crops, and Small Grains) and their irrigated areas summed. The amount of total irrigated area in each NLCD cultivated group from the 2002 census was then evenly distributed across the NLCD grid cells for each county. Where the amount of cropland in the 2002 agricultural census database exceeded the spatial area from the NLCD data the total irrigated area was set equal to the NLCD area extent for that cultivated class.

For counties with partial DWR coverage (San Bernardino, Riverside, and Los Angeles), the total amount of 2002 county census irrigated land by NLCD crop group was decreased by the amount of irrigated area overlapping the county in the existing DWR database. The remaining irrigated area by NLCD cultivated group was then distributed across the crop/pasture area in the county not covered by the DWR database.

A preliminary comparison of cultivated area from overlapping areas of the DWR and NLCD databases was carried out to assess the efficacy of this study's methodology. The two datasets were compared for total cultivated area as well as the four NLCD cultivated classes. Table 1 below shows the results of the comparison of DWR and NLCD crop/pasture classes for the state of California. The "Correct %" field represents the percent of total acres where NLCD correctly classified areas of crop/pasture in DWR as being crop/pasture. The "Omission %" represents the percent of total acres where NLCD classified areas of cultivation in DWR as being non-cultivated. And the "Commission %" represents the percent of total acres where NLCD classified non-cultivated areas in DWR as being crop/pasture. The map accuracy was calculated as the sum of area in the "Correct %" divided by the sum of "Correct %", "Omission %" and "Commission %" areas.

Table 1. Comparing NLCD and DWR cultivated lands

Crop	Total Area (acres)	Correct %	Omission %	Commission %	Map Accuracy %
All Cultivated	10,972,781	85	15	12	76
Orchard/Vineyard	2,492,958	75	25	39	54
Pasture/Hay	3,436,782	32	68	40	23
Row Crop	3,112,495	47	53	43	33
Small Grain	1,930,546	50	50	80	28

When comparing the NLCD and DWR datasets for all cultivated areas, the NLCD does a good job of capturing the extent of cultivated land relative to the higher-quality DWR database, with 85% of the area correctly classified at cultivated land and an overall map accuracy of 75%. Comparing NLCD and DWR for the four NLCD cultivated classes shows less agreement between the datasets for the individual crop/pasture classes. Although there is good agreement with the Orchard/Vineyard class (75% correct and 54% map accuracy) the Small Grain, Row Crop, and Pasture/Hay classes are only correctly classifying 50%, 47%, and 32% of these crops in NLCD, respectively. However, further analysis of the data reveals that the majority of the omissions and commissions for the Small Grain, Row Crop and Pasture/Hay are within the four NLCD cultivated classes (i.e., Small Grain being classified as Row Crop). Therefore the authors conclude that overall there is a good match between the crop/pasture classes in the NLCD dataset and cropland definitions in the existing DWR counties. In addition, a visual comparison of the DWR cropland distribution and overlapping NLCD data also showed a good agreement between the two datasets. Appendix A provides a similar analysis for DWR and NLCD cultivated areas by county.

Following distribution of the irrigated cropland for the missing counties, the NLCD crop/pasture types were grouped into one of the 42 DNDC crop classes for input into in the model. No information on multiple cropping systems was provided in the 2002 agricultural census, and therefore all NLCD crop/pasture assignments were treated as single planting crops. The DNDC crop assignments were then aggregated to the 5 x 5 km basemap grid defining the type and acreage of crops in each 5 km grid cell for the missing county areas.

Figure 3 shows the distribution of irrigated cropland from the combined DWR and NLCD datasets, organized by DNDC crop class. There are 4282 5-km grid cells with irrigated crop lands in this database.

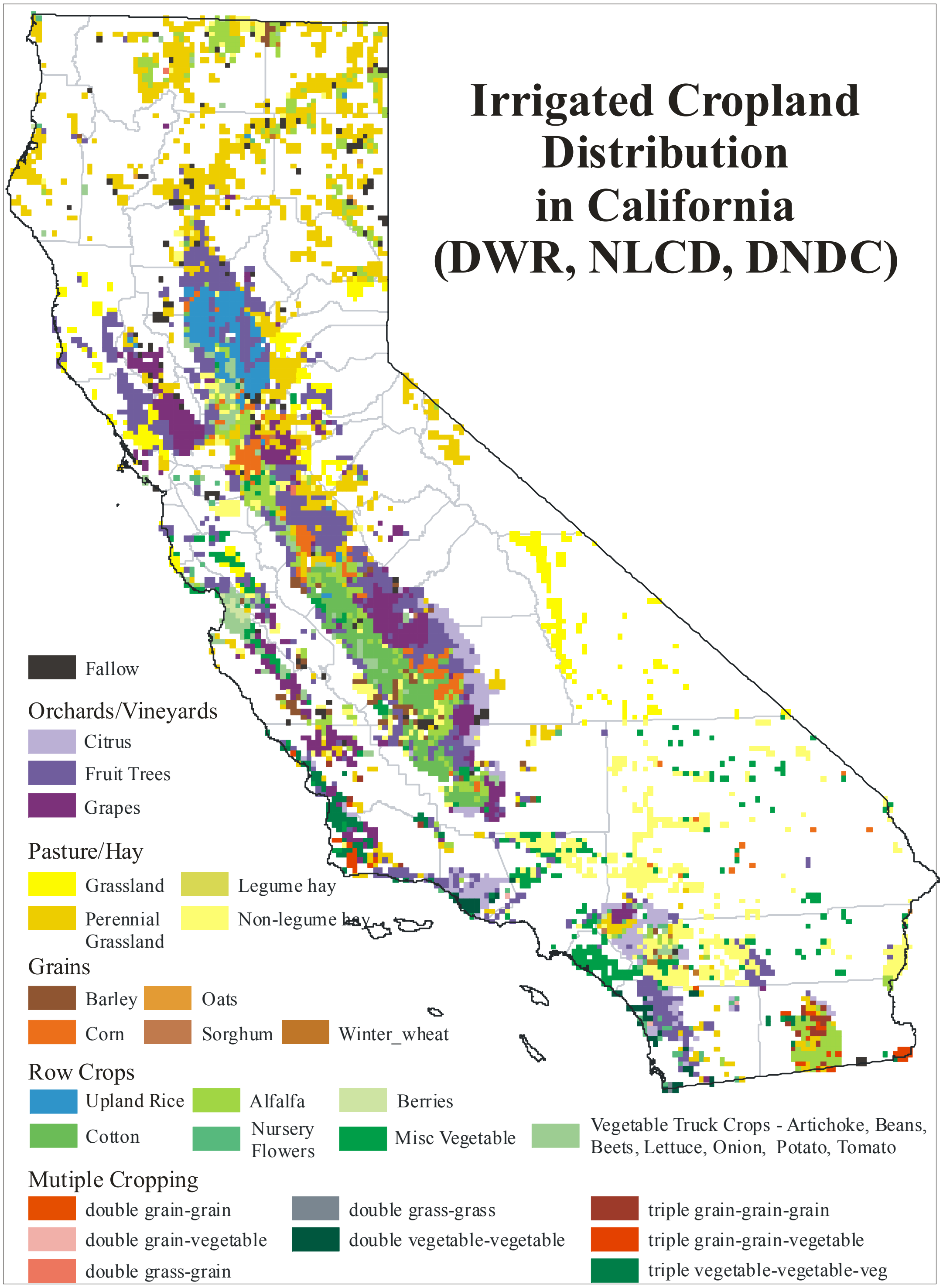


Figure 3. Contemporary distribution of irrigated cropland for California. Note that while the legend indicates dominant crop type within each 5 km grid cell, each cell contains information on extent of up to 39 crop classes.

3.2.5.3. Historic Distribution of Cropland for 1950

During this phase of the project, this project's researchers assembled and compiled datasets from several sources to support development of the 1950s cropland distribution dataset. These data include:

- **DWR+**: The contemporary map of irrigation (Figure 3) based on the DWR database and supplemented for missing counties and regions with data from the NLCD high-resolution national landcover product and 2002 county-scale data from the 2002 Agricultural Census (USDA-NASS 2005). Hereafter, this will be dated as 2000 (though it represents several different years from the late 1990s to the early 2000s) to differentiate it from 1950 and 1930 data.
- **1930 irrigation map**. Paper map of "Approximate Location and Extent of Irrigated Land: California" from the 1930 Census (U.S. Bureau of the Census 1932, p. 85).
- **1950 county-scale census data on irrigated area** (U.S. Bureau of the Census 1932, 1952; USDA-NASS 2005). These data gives total irrigated area by county in 1950 as well as irrigated area broken down by crop type including pasture.

The 1930s map has been scanned, digitized, and rubber-sheeted to overlay the DWR+ map. This identifies regions irrigated in both 1930 and 2000; regions irrigated in 1930 that are no longer irrigated in 2000 (e.g., Los Angeles and Orange Counties); and regions irrigated in 2000 that were not irrigated in 1930 (e.g., Sonoma County and western Sacramento County), and therefore were probably less extensively irrigated in 1950 than they are now. Since the 1930s map appears to be a "sketch" map, and very generalized when compared with the spatial detail of the DWR database, four main strategies were used to create a refined map of the extent of irrigated croplands in 1930, based on the DWR contemporary map:

1. Areas in 1930s that were clearly offset from DWR+ due to poor registration (rubber sheeting) were aligned with the DWR+ dataset.
2. Areas identified as irrigated croplands in 1930 and as urban areas in DWR+ were assumed to be areas of croplands that were lost to urbanization.
3. Areas identified as 1930s irrigated croplands, not urban areas, in DWR+ and appeared to be a generalization of DWR+ irrigated croplands were adjusted to match the DWR+ extent.
4. Area identified as irrigated croplands in both 1930s and DWR+ databases were not altered.

Figure 4 shows the comparison of the DWR+ spatial dataset and the modified 1930 irrigation map. Areas in pink represent irrigated land existing in both 1930 and the present day. The areas in blue represent expansions in irrigated land developed after 1930. The areas in green represent irrigated land lost from 1930 to the present day, typically due to urban expansion. The areas surrounding Los Angeles are an excellent example of agricultural lands lost to urban development. This map, used in conjunction with the county census data, serves as the foundation for distribution of irrigated cropland area and intensity in 1950.

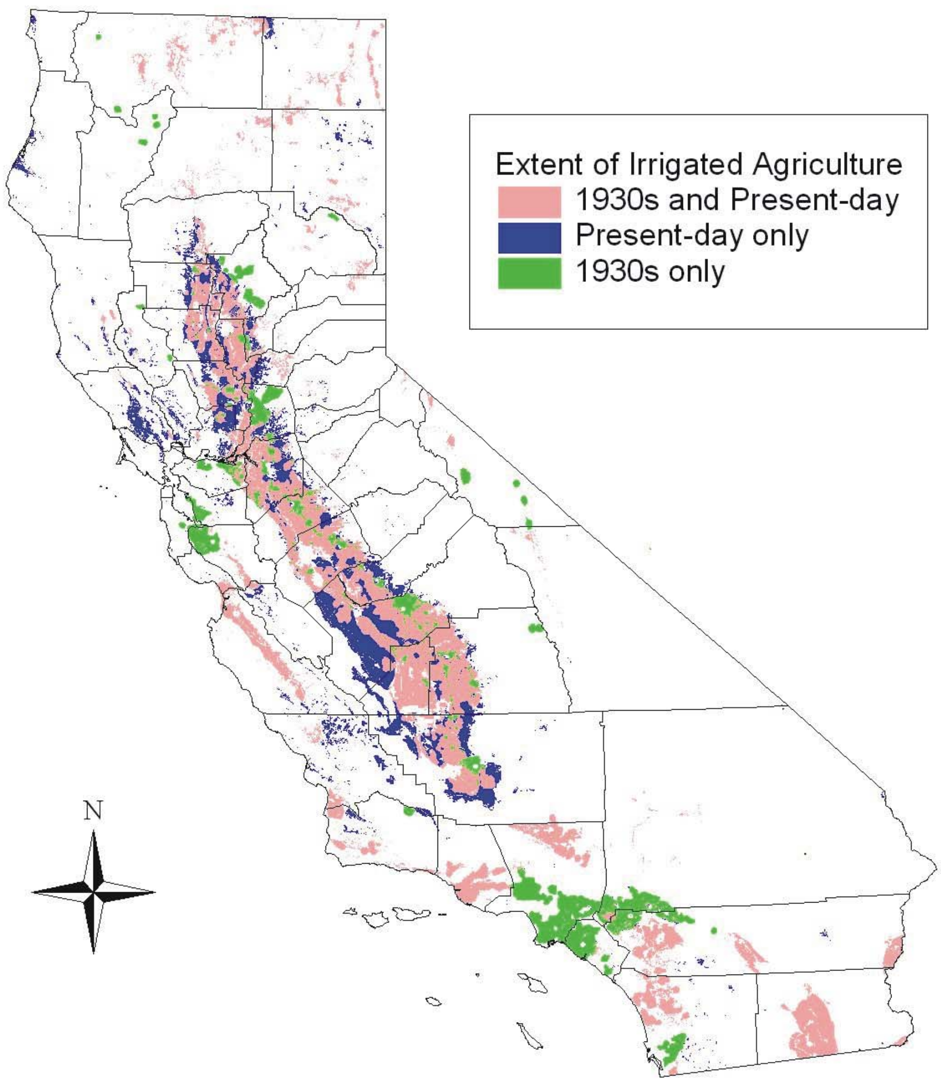


Figure 4. Extent of irrigated agriculture in 1930 and in the present day

To build a map of the distribution of irrigation in 1950 it was determined to primarily focus on changes in irrigation intensity as denoted by the historic water use statistics. Changes in the location and/or extent between 1930 and 1950 were deemed less important given the intended comparison to mesoscale modeling applications. Therefore, the 1930 mapped extent of irrigated area was accepted as an adequate approximation of irrigated area extent in 1950.

In developing the 1950 irrigated area map, researchers assumed that irrigation intensity in 1950 was relatively uniform across each county. First determined was the amount of irrigated area by crop type in each county from the 1950 county level statistics. This irrigated cropland and pasture area was then allocated across the 1930 spatial domain of irrigated cropland extents with uniform irrigation intensity (i.e., uniform ratio of 1950 irrigated area to 1930 irrigated cropland area extent).

All counties showed a good agreement between 1930s spatial extent of cropland and 1950 county totals for irrigated areas (with most county crop spatial extent exceeding county irrigation area totals). The one exception was San Benito County, which showed less spatial cropland area than listed in the county irrigated area totals. In this case, this study's researchers chose to use the spatial extent of cropland from the contemporary DWR irrigated cropland database for San Benito County, because county statistics showed little change in area from 1950 to contemporary conditions.

There were no data available on the irrigated crop type spatial distribution within each county for 1950, and consequently, spatial disaggregation of crop type within counties was not modeled. No information on multiple cropping systems was provided in the 1950 agricultural census thus all historic crop/pasture assignments were treated as single planting crops.

In 1950 the majority of the irrigated crop areas received irrigation via surface irrigation practices (e.g., furrow, gravity, wild flooring) with only 2.9% of irrigation distributed by sprinkler systems. Therefore, this study considered 1950 irrigation type to be 100% surface irrigation for this analysis.

3.3. Processing to Estimate Irrigation Efficiency

The DNDC model provides estimates of water use to meet crop physiological demand (i.e., transpiration) and cropland ecosystem demand, including evaporation and leaching based on crops, soils, and local climate conditions. Based on the agronomic demand, it is possible to estimate irrigation water use by determining crop water demand not met by precipitation and stored root-zone soil moisture. However, irrigation systems are not completely efficient in delivering water for crop use. The water application efficiencies vary considerably based on the type of irrigation system, technology used and how that system is managed. To estimate total irrigation water use, this study's researchers adjusted the DNDC model estimate of total crop demand for irrigation water based on irrigation water application efficiency. General water application efficiencies were obtained from CIT 1988; the Bureau of Reclamation (no date); Kruse et al. 1990; Keller et al. 1981; and Roe 1950. In nearly all cases, a range of efficiencies was given for each irrigation system. Table 2 presents the mean irrigation efficiency value used in this analysis from the given range of water application efficiencies by type of irrigation system. From Table 2 it is clear that there is a wide range in water use efficiencies both across major types of irrigation systems (Sprinkler versus Surface) and various subtypes of systems.

Table 2. Irrigation Efficiency

Type of Irrigation System	Efficiency (%)
Surface Irrigation	
Basin	85
Border	77.5
Furrow	67.5
Wild Flooding	60
Gravity	75
Sprinkler	
Hand Move or Portable	70
Center Pivot and Linear Move	82.5
Solid Set or Permanent	75
Side Roll Sprinkler	70
Micro Sprinkler	87.5
Trickle Irrigation	
Surface Drip	87.5
Buried Drip	90
Subirrigation	90
LEPA (Low Energy Precision Application)	90
Unknown	75.5

Sources: CIT 1988; Bureau of Reclamation (no date); Kruse et al. 1990; Keller et al. 1981; Roe 1950

Irrigation efficiency for the "Unknown" irrigation system class listed in the DWR database was estimated as an area-weighted average percent of the known irrigation system types in the DWR database. As mentioned in the previous section, irrigation for 1950 was assumed to be predominantly surface irrigation, with an average efficiency of 72.5% assigned.

The DNDC model uses an irrigation index to set irrigation practices. An irrigation index of 1 simulates a level of irrigation that is used to meet the agronomic demand (100% efficient). To examine the impact of over irrigation, a simulation was run with the irrigation index set to simulate over-irrigation due to irrigation inefficiency. For example, for systems with average efficiency of 80%, this study assumed over-irrigation of 25% and set the irrigation index at 1.25. This irrigation index was set for each crop using an area-weighted average percent based on irrigation system type. This approach enables us to partition the fate of the excess irrigation water into either leaching or crop/soil evapotranspiration. The *disadvantage* of this approach is that it implies a broad generalization of irrigation efficiency by crop type only and loses the DWR polygon-specific irrigation type information.

4.0 Modeling Results

For this project, the DNDC model was modified to create daily records of water use for California cropland. The DNDC model was run for each of the 5290 (contemporary) and 4124 (historic) 5 km grid cells using two sets of soil conditions (because the soil survey data provide a range in soil texture, carbon content, bulk density, and pH for each polygon). The model was run for contemporary and historic cropland conditions under the three reference climate years of nominal (1996), early spring/dry (1997), and late spring/wet (1983) years to create the following outputs:

- Daily crop biomass
- Daily soil/water surface evaporation, crop transpiration, water leaching, and irrigation use
- Daily NO, NH_3, N_2O, CO_2, and CH_4 fluxes
- Daily changes in soil carbon
- Annual leached C and N
- Annual yields, crop biomass, and crop residues
- Annual N deposition
- Annual N uptake

Figure 5 shows water use for the State of California. The bars in the chart represent water use values for irrigation, transpiration, evaporation, and leaching over the entire state for historic and contemporary cropland under different climate conditions. Historic (blue) and contemporary (red) cropland water demands for the nominal climate year (1996) are shown with a clear increase in all four water use parameters realized from the historic to the contemporary state. The largest increases in water-use for the contemporary cropland state are in crop irrigation and transpiration. This study's estimates of total water use for California agriculture (irrigation plus rainfall) ranges from 28 to 36 10^9 cubic meters (m^3) per year (using 1997 and 1983 as the extremes). The estimate is a little lower than the California DWR broad estimate of 30 million acre-feet (which is approximately 37 10^9m^3). It is unclear if the California DWR estimate is based on total field use or includes transmission losses and water use (rainfall) for non-irrigated crops.

Early spring/dry (yellow) and late spring/wet (green) climate years are presented for the contemporary cropland state. In comparison to the contemporary nominal year, the early spring/dry climate year requires greater irrigation water use to meet crop needs. Crop transpiration shows a slight increase, and both evaporation and leaching are reduced due to lower available water for these drier climate conditions. In contrast, the late spring/wet year shows a decrease in irrigation needs relative to the nominal year, with higher precipitation levels meeting crop water needs during this time period. The wetter climate conditions yield lower crop transpiration and elevated evaporation and leaching, due to excess available water.

Because DNDC does not model water flow below the rooting zone, the leaching estimates provided represent mass balance general trends; whereas, DNDC fully models the water use estimates for irrigation, transpiration, and evaporation.

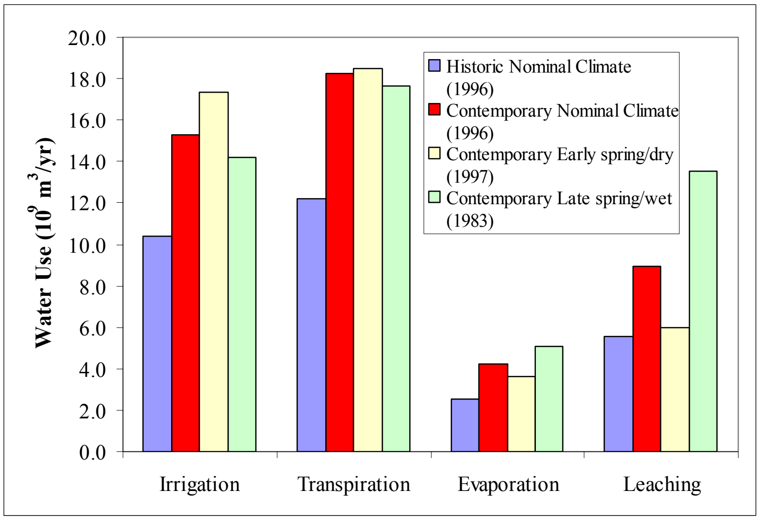
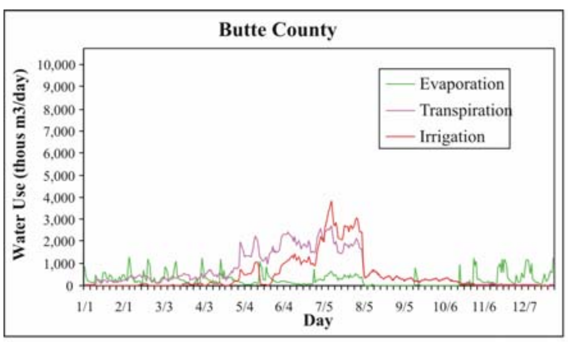
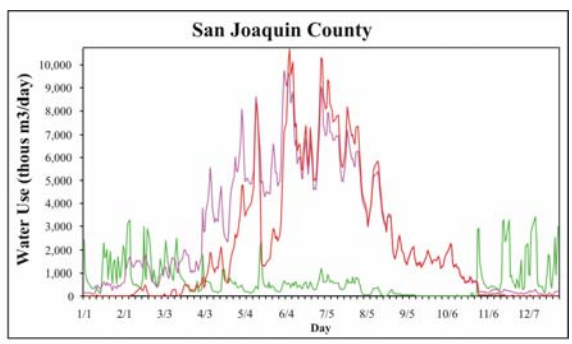


Figure 5. DNDC modeled water use for the State of California

The figures below illustrate the temporal and spatial range of results. Figure 6 presents daily soil/surface water evaporation, crop transpiration, and irrigation for three counties in the northern (Butte), central (San Joaquin), and southern (Kings) Central Valley in California. Values in the graphs represent thousands of cubic meters of water used per day over the entire county for nominal climate year 1996. From this figure it is clear there is a strong seasonality in water use and that seasonality is driven by climate and cropping practices (planting and harvesting dates). In addition, there appears to be a significant variation in water use at sub-weekly scale.





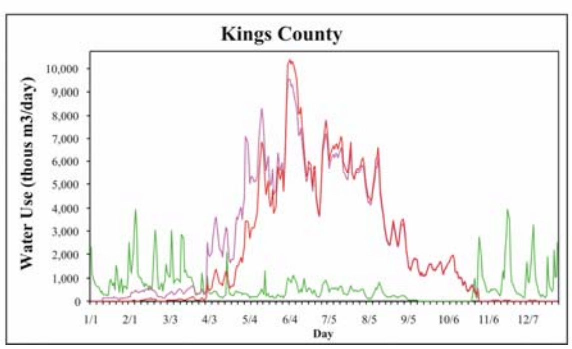


Figure 6. DNDC-modeled daily water use for three California counties

Figure 7 presents the intra-annual variability in irrigation water demand. Seasonal totals of DNDC-modeled irrigation water demand (crop demand not met by precipitation and soil water storage) by 5 km grid cell are shown for nominal climate year 1996. This figure coveys a strong seasonality in water use driven by climate and cropping practices, with the spring and summer months showing the greatest irrigation water demand.

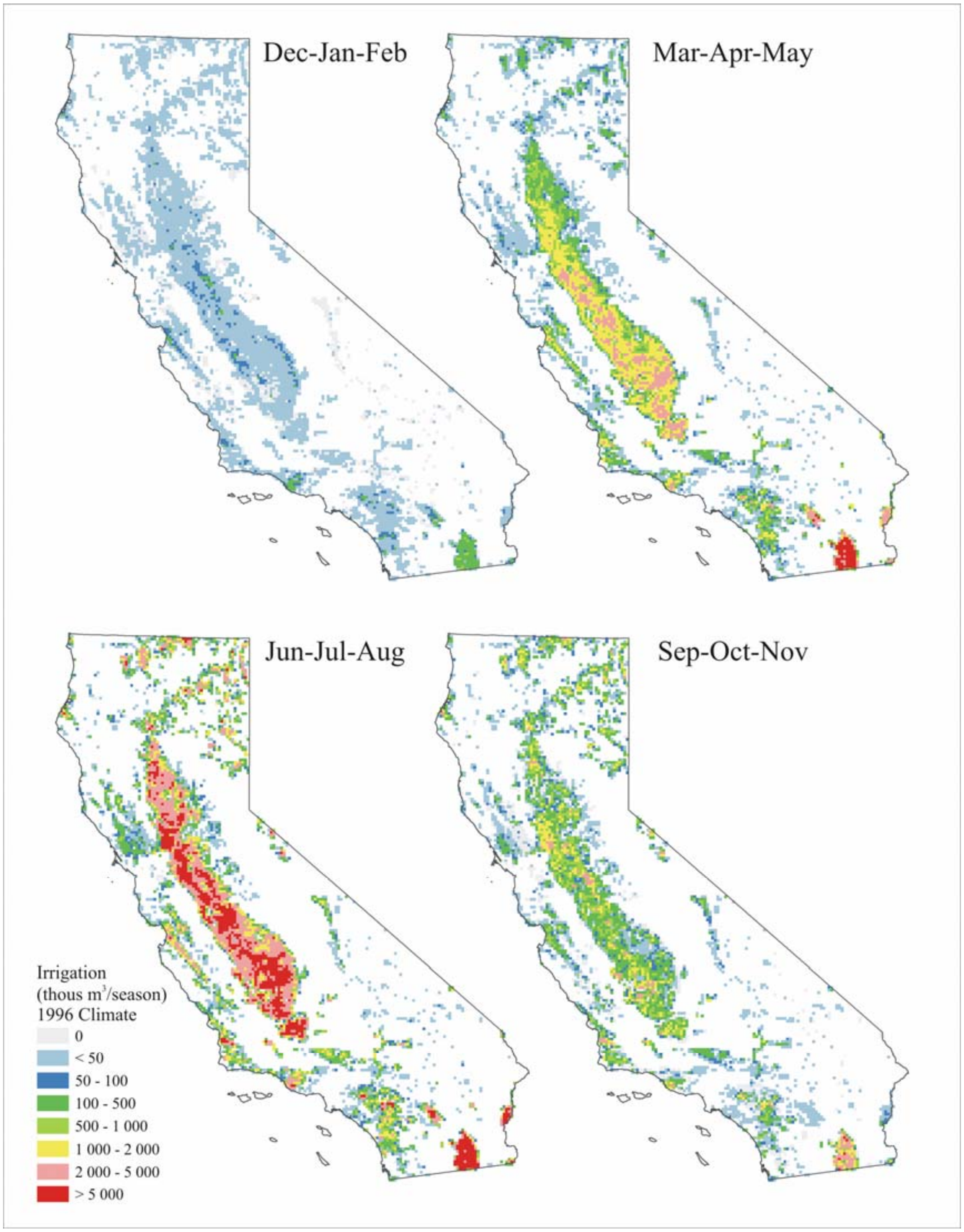


Figure 7. Seasonal irrigation demand for nominal climate year 1996

Figure 8 illustrates the inter-annual variability in irrigation water demand comparing reference climate years for late spring/wet (1983) and early spring/dry (1997) to the nominal climate year (1996). The figure shows the ratio of irrigation water demand in the late spring/wet and early spring/dry climate reference years to irrigation demand in the nominal year for the contemporary cropland extents. Increases or decreases in the +/-10% range (i.e., 0.9–1.1 class) were considered as little to no change and were colored a neutral grey. The late spring/wet year ratio shows decreases in irrigation demand, relative to the nominal year for the majority of the state. Some areas in the northern part of the state do show increases in irrigation demand relative to the nominal which may be attributable to drier regional weather patterns. The early spring/dry year ratio predominantly shows increases in irrigation demand relative to the nominal year throughout the state.

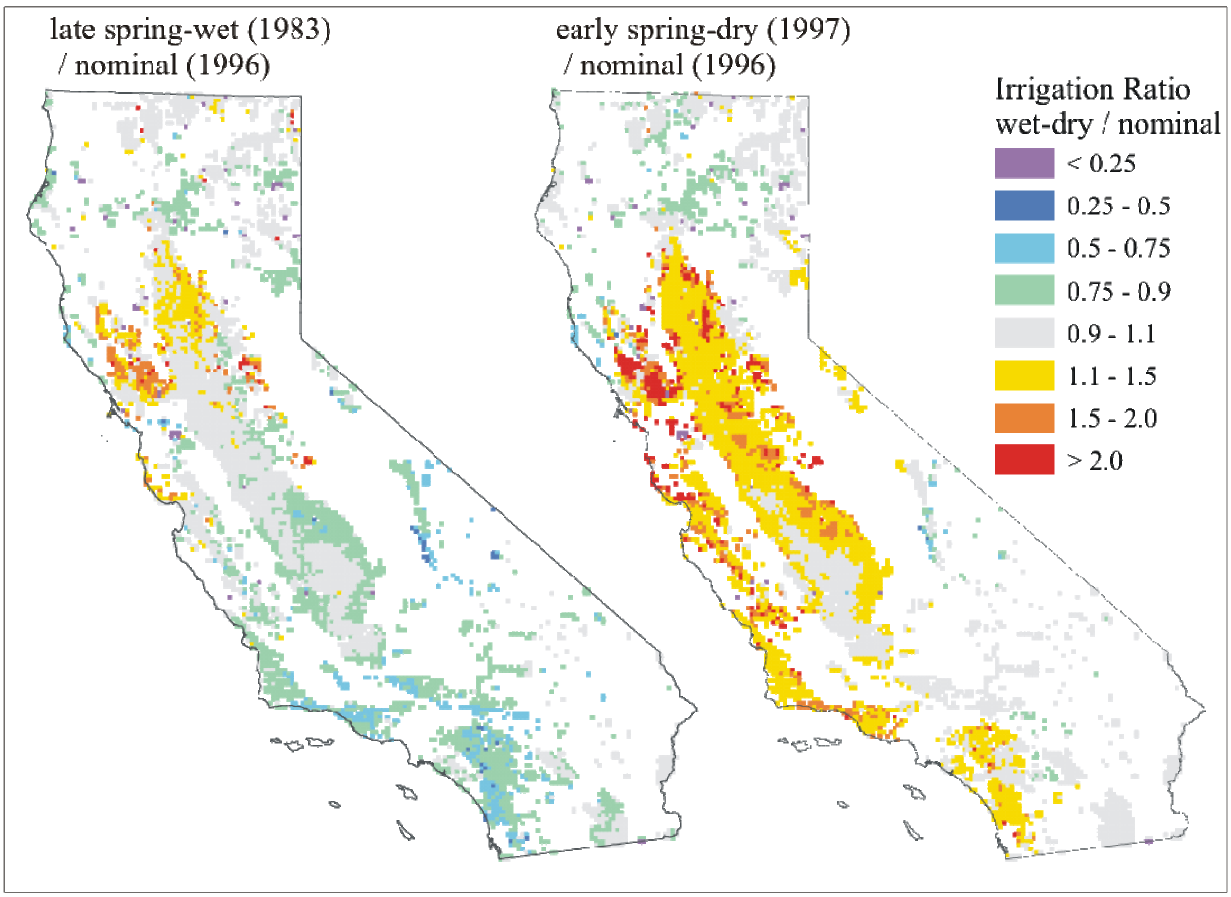


Figure 8. Irrigation water demand comparing reference climate years for late spring/wet (1983) and early spring/dry (1997) to the nominal climate year (1996)

Figure 9 presents a comparison of the historic and contemporary estimates for irrigation water demand. This figure clearly illustrates the expansion of irrigated agriculture in California from 1950 to circa 2000. The Central Valley stands out as the major area where expansion of irrigated agriculture has occurred. Areas of urban expansion where historic agriculture has been lost can be identified in and surrounding the Los Angeles area, as well as in small urban pockets within the Central Valley.

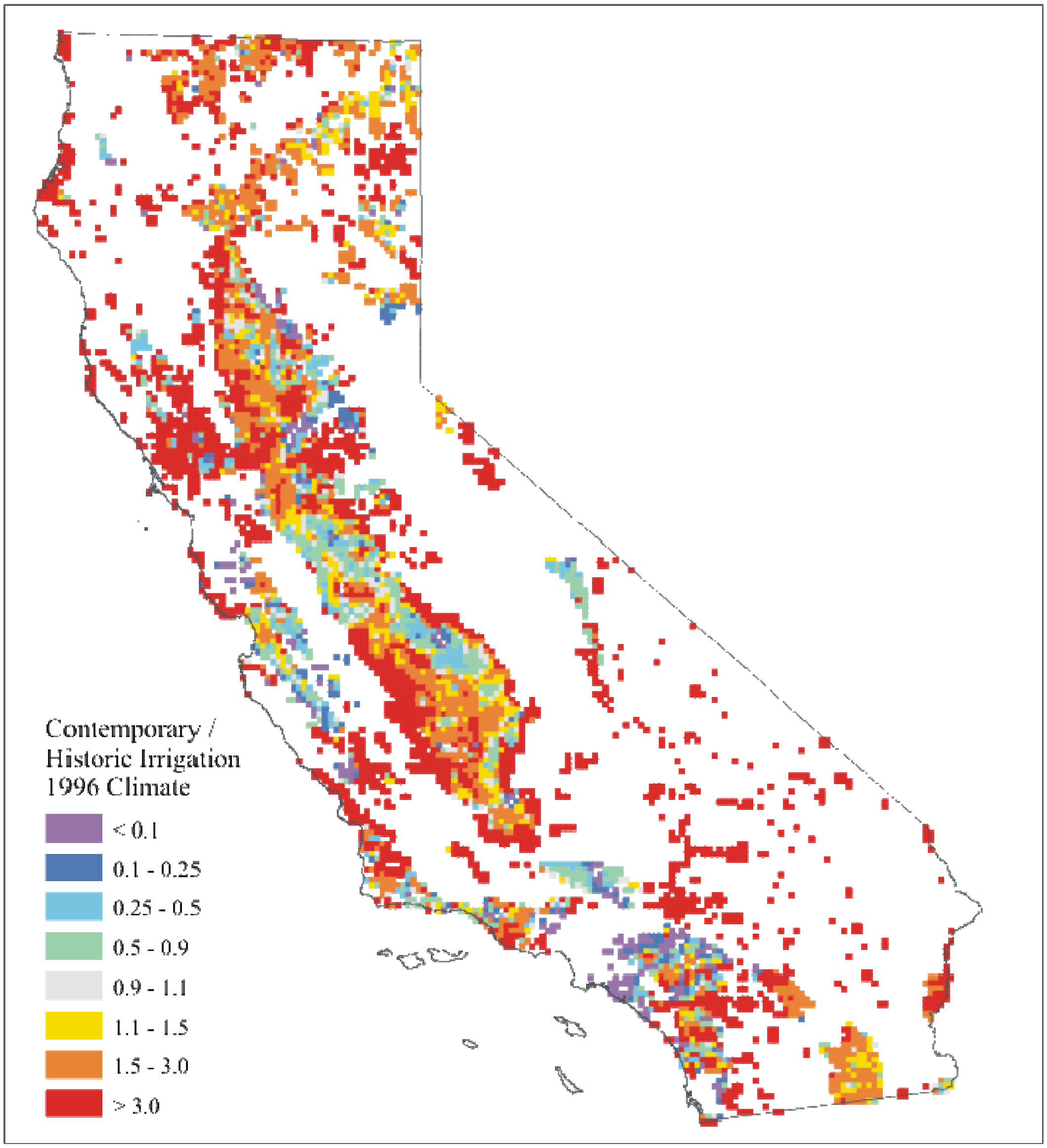


Figure 9. Change in irrigation water demand from 1950 to circa 2000. The figure shows the ratio of circa 2000 irrigation demand to 1950 irrigation demand.

5.0 Conclusions and Recommendations

This study used DNDC and its embedded crop algorithms to model agricultural demand for irrigation water based on soil conditions, climate (daily min and max temp, daily precipitation, radiation), and general cropping systems. This modeling simulation has been implemented with the most recent and best available spatial datasets for cropland distribution, soils and climate across the State of California at a spatial resolution of 5 x 5 km and a daily time step. The spatial and temporal resolution used in this analysis is a great improvement over the currently used CALSIM generalized water resources planning tool developed by DWR, which is based on the coarser scale DSA spatial units and operates at a monthly time step. This work demonstrates that mesoscale regional climate and water demand models can be successfully and easily employed at a spatially and temporally disaggregated level that moves beyond the current available models.

The DNDC model was run for contemporary and historic cropland conditions under the three reference climate years of nominal (1996), early spring/dry (1997), and late spring/wet (1983) years to simulate the range in climate conditions from the early 1950s though early 2000s. The analysis provides a comprehensive picture of irrigation activities and crop water requirements in the State of California under varying climatic conditions. Model outputs include GHG emissions and crop water demand that accounts for crop use, ET losses, and infiltration/leaching below the rooting zone. Total irrigation use was estimated based on DNDC modeled irrigation demand to meet agronomic demand adjusted by an irrigation efficiency factor to account for over irrigation and efficiency of irrigation systems in California.

5.1. Benefits to California

Model results offer a baseline for contemporary and historic water demand (both spatially and temporally disaggregated) that are suitable for both state and finer regional scale applications. Datasets and results developed during this project can be utilized in present crop management and water use planning, as well as in future modeling activities. All output data including model results and animations for the contemporary and historic cropland state from the Scripps Irrigation Water Use project are available on a two CD-ROM set (please contact William Salas [wsalas@agsemail.com] for copy of the CD-ROM set).

6.0 Data Products

All output data from the Scripps Irrigation Water Use project have been provided on a two CD-ROM set. The first CD contains model results and animations for the contemporary cropland state; the second CD contains model results and animations for the historic cropland state.

Products include:

- Tabular daily and monthly model results by 5 x 5 km grid cell in California for:
  - Biomass
  - CH_4
  - CO_2
  - dSOC (change in soil carbon content)
  - N_2O
  - NH_3
  - NO
  - Evaporation
  - Irrigation
  - Leach
  - Transpiration
- Animation maps by 5 x 5 km grid cell in California for:
  - Daily irrigation and transpiration
  - Monthly mean irrigation and transpiration
  - Monthly standard deviation of irrigation and transpiration

A detailed list of the data output is given in Appendix B.

7.0 References

Bureau of Reclamation Pacific Northwest Region, The Pacific Northwest Cooperative Agricultural Weather Network. No date. AgriMet Irrigation Guide. (www.usbr.gov/pn/agrimet/irrigation.html).

CIT. 1988. Irrigation systems and water application efficiencies. *Irrigation Notes*. Center for Irrigation Technology, CSU Fresno.

Clapp, R. B., and G. M. Hornberger. 1978. "Empirical equations for some soil hydraulic properties." *Water Resour. Res.* 14:601–604.

Dunne, T., and Leopold, L. B. 1978. *Water in Environmental Planning*. New York: W. H. Freeman. 818 p.

Li, C. 2000. "Modeling trace gas emissions from agricultural ecosystems." *Nutr. Cycl. in Agroecosys*. 58:259–276.

Li C., Frolking, S., and T. A. Frolking. 1992. "A model of nitrous oxide evolution from soil driven by rainfall events: 1. Model structure and sensitivity." *J. Geophys. Res,* 97:9759–9776.

Li, C., S. Frolking, and R. C. Harriss. 1994. "Modeling carbon biogeochemistry in agricultural soils." *Global Biogeochemical Cycles* 8:237–254.

Li, C., V. Narayanan, and R. Harriss. 1996. "Model estimates of nitrous oxide emissions from agricultural lands in the United States." *Global Biogeochemical Cycles* 10:297–306.

Li, C., A. Mosier, R. Wassmann, Z. Cai, X. Zheng, Y. Huang, H. Tsuruta, J. Boonjawat, and R. Lantin. 2004. "Modeling Greenhouse Gas Emissions from Rice-Based Production Systems: Sensitivity and Upscaling." *Global Biogeochemical Cycles* 18: GB1043, doi:10.1019/2003GB002045.

Keller, J., F. Corey, W. R. Walker, and M. E. Varva. 1981. Evaluation of irrigation systems. In *Irrigation: Challenges of the 1980s.* pp. 95–105. Am. Soc. Agric. Engineers, St. Joseph, Mich.

Kruse, E. G., D. A. Bucks, and R. D. von Bernuth. 1990. Comparison of irrigation systems. In *Irrigation of Agricultural Crops–Agronomy Monograph #30,* Stewart, B. A. and D. R. Nielsen (eds.), pp. 475–508. Am. Soc. Agron. Madison, Wisconsin.

Potter, C., C. Krauter, and S. Klooster. 2001. *Statewide Inventory Estimates of Ammonia Emissions From Fertilizer Applications in California.* Project report to California Air Resources Board, Sacramento, CA. Contract# ID98-76. June.

Ritchie, J. T., D. C. Godwin, and S. Otter-Nache. 1988. *CERES-Wheat. A simulation model of wheat growth and development.* College Station, TX: Texas A&M Univ. Press.

Roe, H. B. 1950. *Moisture Requirements in Agriculture: Farm Irrigation.* New York: McGraw Hill. 413 pp.

U.S. Bureau of the Census. 1932. *Fifteenth Census of the US: 1930; Irrigation of Agricultural Lands*. Washington D.C.: U.S. Govt. Printing Office.

U.S. Bureau of the Census. 1952. *Census of Agriculture 1950, Vol. 1 Counties and State Economic Areas, Part 33*. Washington D.C.: U.S. Govt. Printing Office.

USDA NASS (National Agricultural Statistical Service) online data: www.usda.gov/nass/. Visited spring 2005.

Van Bavel, C. H. M., R. J. Lascano, and D. R. Wilson. 1978. "Water relations of fritted clay." *Soil Sci. Soc. Am. Proc.* 32:317–321.

Vogelmann, J. E., T. Sohl, P. V. Campbell, and D. M. Shaw. 1998a. "Regional land cover characterization using Landsat Thematic Mapper data and ancillary data sources." *Environmental Monitoring and Assessment* 51: 415–428.

Vogelmann, J. E., T. Sohl, and S. M. Howard. 1998b. "Regional characterization of land cover using multiple sources of data." *Photogrammetric Engineering and Remote Sensing* 64(1): 45–57.

Zhang, Y., C. Li, X. Zhou, and B. Moore III. 2002. "A simulation model linking crop growth and soil biogeochemistry for sustainable agriculture." *Ecological Modeling* 151:75–108.

8.0 Glossary

CARB	California Air Resources Board
CH_4	methane
DNDC	Denitrification-Decomposition
DSA	depletion study areas
DWR	California Department of Water Resources
Eh	redox potential
ET	evapotranspiration
GHG	greenhouse gas
GIS	geographical information systems
Mpa	megapascal
NASS	National Agricultural Statistical Service
NH_3	ammonia
NLCD	U.S. National Land Cover Data set
NO	nitric oxide
N_2O	nitrous oxide
NRCS	USDA's Natural Resources Conservation Service
NTSG	Numerical Terradynamic Simulation Group, University of Montana
SOC	soil organic carbon
SSURGO	Soil Survey Geographic database
STATSGO	State Soil Geographic database
UC	University of California
TM	Thematic Mapper

Appendix A: NLCD/DWR Cropland Comparison by County

FIPS	COUNTY	Total Acres	% Correct	% Omission	% Commission	Map Accuracy (%)
3	Alpine	3,507	82	18	56	53
5	Amador	11,139	62	38	38	45
7	Butte	278,384	88	12	6	83
11	Colusa	346,105	92	8	5	87
13	Contra Costa	64,814	76	24	14	67
15	Del Norte	9,660	85	15	38	62
19	Fresno	1,382,542	94	6	5	89
21	Glenn	299,673	87	13	6	82
23	Humboldt	59,460	65	35	25	52
25	Imperial	543,358	93	7	6	88
29	Kern	1,098,281	85	15	7	79
31	Kings	663,207	86	14	3	83
33	Lakes	33,791	62	38	56	40
35	Lassen	104,140	68	32	72	39
37	Los Angeles	107	1	99	89	1
39	Madera	366,444	93	7	9	85
41	Marin	8,999	40	60	66	24
43	Mariposa	51	0	100	9989	0
47	Merced	601,647	90	10	7	84
49	Modoc	205,365	71	29	29	55
51	Mono	22,940	88	12	51	58
53	Monterey	291,739	78	22	20	65
55	Napa	56,948	66	34	42	47
61	Placer	95,646	55	45	12	49
63	Plumas	39,057	65	35	55	42
65	Riverside	123,019	60	40	39	43
67	Sacramento	200,931	84	16	15	73
69	San Benito	88,806	54	46	10	49
71	San Bernardino	42,658	55	45	43	38
73	San Diego	120,292	42	58	48	28
77	San Joaquin	618,811	93	7	4	89
79	San Luis Obispo	217,462	53	47	48	36
83	Santa Barbara	129,384	67	33	26	54
87	Santa Cruz	15,430	83	17	88	44
89	Shasta	77,506	62	38	41	44
93	Siskiyou	197,033	73	27	33	55
95	Solano	225,413	83	17	11	74
99	Stanislaus	420,404	94	6	6	89
101	Sutter	309,254	94	6	4	91
103	Tehama	136,708	68	32	31	52
105	Trinity	579	28	72	739	3
107	Tulare	840,990	89	11	7	83
109	Tuolumne	2,005	17	83	103	9
111	Ventura	128,603	68	32	24	55
113	Yolo	373,376	93	7	7	87
115	Yuba	108,731	86	14	8	79

Appendix B: DNDC Output Data Format

Data format for contemporary and historic DNDC runs for $YEAR = climate years 1983, 1996, and 1997. Data files describe herein are contained on two CD-ROMs for contemporary cropland model results and historic cropland model results. Contemporary cropland model results include **(a)** tabular data for daily and monthly model results by 5 x 5 km grid cell (Contemporary_Tables.zip), and **(b)** animation maps for daily, monthly mean, and monthly standard deviation of irrigation and transpiration by 5 x 5 km grid cell in California (Contemporary_Animations.zip). Historic model results include (**a)** tabular data for daily and monthly model results by 5 x 5 km grid cell (Historic_Tables.zip) and (**b**) animation maps for daily, monthly mean, and monthly standard deviation of irrigation and transpiration by 5 x 5 km grid cell in California (Historic_Animations.zip).

1. Daily Output data from DNDC

Folders:

/daily_mean/$YEAR – mean values for all variables

/daily_maxmin/$YEAR – maximum and minimum values for all variables

Daily output data for mean, min, and max DNDC modeled variables are contained in text files by variable name (i.e., DailyIrrigation_Yr1_mean.txt):

- Biomass (1000 kgC/day)
- CH_4 (1000 kgC/day)
- CO_2 (1000 kgC/day)
- dSOC (change in soil carbon content) (1000 kgC/day)
- N_2O (1000 kgN/day)
- NH_3 (1000 kgN/day)
- NO (1000 kgN/day)
- Evaporation (m^3/day)
- Irrigation (m^3/day)
- Leach (m^3/day)
- Transpiration (m^3/day)

Tabular information on minimum and maximum rates and sums by crop type are also provided in the daily_maxmin directory (i.e., "rate_min_WaterIrri_yr1983").

2. Monthly Aggregate Data

Folders:

/monthly_aggr/$YEAR

Daily output data for DNDC modeled variables is aggregated to the monthly time step and contained in text files by variable name (i.e., DailyIrrigation_Yr1_mean.txt, DailyIrrigation_Shangrila_Yr1_max.txt). Statistics for mean, min, max, standard deviation and coefficient of variation are provided for each month as well as an annual estimate.

3. County and DSA Aggregate Data

Folders:

/county_aggr/$YEAR

/dsa_aggr/$YEAR

Daily output data for DNDC modeled variables are aggregated to California county and Depletion Study Area (DSA) mapping units and contained in text files by variable name (i.e., DailyIrrigation_County_Yr1_max.txt). Daily county and DSA data are aggregated to the monthly time step and contained in the "monthly" directory by variable name. Statistics for mean, min, max, standard deviation and coefficient of variation are provided for each month as well as an annual estimate. Counties are designated by FIPS code (reference list given in "/county_aggr/Counties.txt" file); DSA units are designated by DSA identification number provided by CALSIM (ARC/INFO shape files are provided in "/dsa_aggr/shapefile" directory).