VIC-CropSyst: A regional-scale modeling platform to simulate the nexus of climate, hydrology, cropping systems, and human decisions

Keyvan Malek [1], Claudio Stockle [1], Kiran Chinnayakanahalli [3], Roger Nelson [1], Mingliang Liu [2], Kirti Rajagopalan [2], Muhammad Barik [2], Jennifer Adam [2]

[1]Department of Biological Systems Engineering at Washington State University
[2]Department of Civil and Environmental Engineering at Washington State University
[3]Air Worldwide Corp.

Correspondence to: Jennifer Adam (jcadam@wsu.edu) and Keyvan Malek (keyvanmalek@gmail.com)

Abstract

Food supply is affected by a complex nexus of land, atmosphere, and human processes, including short- and long-term stressors (e.g., drought and climate change, respectively). A simulation platform that captures these complex elements can be used to inform policy and best management practices to promote sustainable agriculture. We have developed a tightly-coupled framework using the macroscale Variable Infiltration Capacity (VIC) hydrologic model and the CropSyst agricultural model. A mechanistic irrigation module has been developed for inclusion in this framework. The performance of VIC-CropSyst was evaluated using two flux tower sites located in agricultural fields in the U.S. (Nebraska and Illinois). The agreement between recorded and simulated evapotranspiration (ET), applied irrigation water, soil moisture, leaf area index (LAI), and yield indicated that, although the model is intended to work at regional scales, it also captures field scale processes in agricultural areas. We also evaluated the regional simulations of VIC-CropSyst's ET over the Washington, Idaho and Oregon in the U.S. VIC-CropSyst is being used in conjunction with socio-economic models, river system models and atmospheric models to simulate the feedback processes between regional water availability, agricultural water management decisions and land-atmospheric interactions.

Keywords: integrated platform, hydrologic model, agricultural model, adaptation strategies, irrigation management, regional scale, climate change

Nomenclature			
E_{si}	Evaporation from soil during irrigation	A_p	Irrigated covered area
E_c	Evaporation from intercepted water	D	Droplet size
E_d	Evaporation from irrigation droplets	V_0	Initial velocity of droplets
T	Transpiration	MAD	Maximum allowable depletion
ET_p	Potential evapotranspiration	g	Acceleration of gravity
A_w	Soil wetted area	Y_0	Height of nozzle
T_i	Time of irrigation	Y	Canopy height
D_p	Deep percolation	S	Sorptivity coefficient
K_s	Saturated hydraulic conductivity	B_i	Runoff calibration parameter
R_o	Runoff loss	D_s	VIC base flow calibration parameter
q	Emitter discharge	Ds_{max}	VIC base flow calibration parameter
ρ_b	Soil bulk density	W_s	VIC base flow calibration parameter
$\Delta\theta$	Change in the water content	GDD	Growing degree days
LAI	Leaf area index	E_s	Evaporation from soil
K_c	Crop coefficient	ET_a	Actual evapotranspiration

1. Introduction

Projected increases in food demand (Godfray et al., 2010) along with other stressors such as droughts and extreme heat
5   events contribute to threats on global food supply (Wheeler and Braun, 2013). Despite existing research on food scarcity,
there are still unanswered questions about the relationship between food supply and the nexus of water resources, agriculture
and human decisions. Regional consequences of decisions intended to mitigate the damages of future stressors are not well
understood (Robertson and Swinton, 2005). These knowledge gaps limit our ability to explore viable adaptation strategies,
particularly in understanding unintended consequences. Integrated modeling platforms can contribute to the systems-level
10 understanding of dynamics between agricultural processes, large-scale water resources management decisions, and land-
atmospheric interactions.

The overall goal of this study is to develop a computational modeling platform that mechanistically captures the interactions
between hydrology, crop growth and phenology, and crop and water resource management decisions in the context of global
change. Such a platform allows for investigation around multiple objectives: 1) understanding how climate dynamics and
15 land-atmosphere interactions affect water and agricultural sustainability; and (conversely) 2) exploring the role of

agricultural (biophysical and socioeconomic) processes in driving land-atmosphere interactions, including climate feedback mechanisms at larger scales.

1.1. Future Food Demand and Supply

While over 800 million people throughout the world suffer from undernourishment (FAO, 2013), global change is expected
5   to exacerbate food security problems. The demand for food is increasing due to population growth and changes in food dietary tendency towards higher consumption of meat products (Long et al., 2015). Food supply, on the other hand, is unlikely to increase as fast as demand (Wheeler and Braun, 2013), as it is affected by complicated interactions between climate, the hydrologic cycle, cropping systems, and human decisions. Table 1 shows the variety of ways that climate change can impact crop yield, with some impacts being positive and others negative; the net result is dependent on region, crop, and
10   future time period. Mechanistic integrated modeling platforms are necessary to assess the net impact of global change on crop production.

[TABLE 1]

1.2. Interactions between Cropping Systems, the Hydrologic Cycle, Climate, and Human Decisions

15   Although agricultural productivity is affected by disturbances in the regional cycles of water and energy (Pielke Sr. et al., 2007), agriculture itself feeds back to alter the hydrological cycle by changing evapotranspiration (ET), and the magnitude and temporal regime of soil moisture, infiltration and runoff generation (Haddeland et al., 2006). The impact of irrigated agriculture on energy and water cycles is particularly important (Ferguson and Maxwell, 2011; Lobell et al., 2009; Puma and Cook, 2010; Scanlon et al., 2007; Sridhar, 2013). Irrigation uses 70% of total global water withdrawals (Rost et al., 2008)
20   and boosts soil moisture storage available for crop uptake, and ultimately increases ET. Irrigation losses also increase the amount of deep percolation and runoff.

While farmers can adjust their management decisions to reduce the negative impacts of climate change, these human decisions can result in unintended impacts on regional water and energy cycles. The consequences of anthropogenic disturbances (e.g. irrigation withdrawal and dam constructions) on the regional water cycle can be even greater than the
25   impacts of climate change (Haddeland et al., 2014). Irrigation management and changes in cropping patterns are two examples of management decisions influencing the amount of evapotranspiration, runoff, deep percolation, and soil moisture which alter timing and magnitude of return flow. In many agricultural basins, the availability of water for downstream users depends greatly on the return flow from upstream lands. For example, in the Yakima River basin of the northwestern U.S., 40% of mid-summer available water is provided through return flow (USBR, 2002). Therefore, regional-scale simulation of
30   the hydrologic cycle is crucial to the analysis of the impacts of water management in large river basins with significant agricultural activities.

Large-scale results may be more informative for decision makers and other stakeholders (Zhao et al., 2013) who's mission is to sustain agriculture productivity while preserving the environment specific to a region. Allen et al., (2015) interviewed about twenty stakeholders including governmental and non-governmental agencies to understand their priorities, concerns and decision-making processes. They found that many of these stakeholders are interested in local and basin-scale

5 information about impacts of climate change, infrastructural developments, and land management practices on quantity, quality and temporal regimes of available water. Therefore, large-scale integrated modeling platforms are also needed to inform regional natural and agricultural resource management policies and management actions.

1.3. Agricultural Processes within Macroscale Hydrologic Models

1.3.1. Capturing Cropping Systems within Land Surface Models

10 Land Surface Models (LSMs) are used for regional to global-scale simulations of water and energy cycles. LSMs usually provide terrestrial processes to the general circulation models (GCMs). Results of modeling studies have indicated that, despite the tremendous advances in earth system modeling, the current state of LSMs is not capable of capturing agricultural processes in a detailed manner (e.g. Chang et al., 2014; Haddeland et al., 2006; Hansen et al., 2006; Lobell et al., 2009, 2008; Ozdogan et al., 2010a). In many of them, agricultural processes are similar to natural vegetation (Chang et al., 2014);

15 due to phenological similarities, agricultural lands are often represented by grass vegetation. Also, management or harvesting activities as well as CO_2 fertilization effects may be ignored (Drewniak et al., 2013). Mitchell et al. (2004) compared the results of four different models and reported poor overall performance among LSMs in capturing warm season ET. In most cases, this inconsistency can be explained by weak representation of agricultural processes. For example, Schwalm et al. (2010) compared 22 terrestrial biosphere models with North American flux tower sites and found the performance of models

20 in natural vegetation areas to be better than in cropland areas.

Using prescribed seasonally and spatially variable leaf area index (LAI) and root density, Wei et al. (2013) modified aerodynamic and soil deficit thresholds in the NOAH land surface model and the simulation on warm season processes was significantly improved. In their model, however, crop growth and development does not mechanistically respond to climate, CO_2 concentrations, and soil moisture; this limits the accuracy of model simulation over agricultural areas where the

25 feedback of agricultural management on hydrologic and climate conditions is significant. Drewniak et al. (2013) enhanced the Community Land Model (CLM) performance in agricultural areas by using an improved representation of crop processes. The simulated yield was in agreement with other models; however, model performance in simulating yield was generally poor and CO_2 fertilization effects and irrigation management activities were neglected. In their simulations, they considered only three crop species (winter wheat, corn and soybean) and used a fixed planting date, which can lead to a

30 discrepancy with observations in that actual planting dates vary in time as a function of weather (Zeng et al., 2013), and can result in an over-estimation of the negative impacts of warming on crop yield, as an earlier planting date is a viable adaptation strategy in many regions of the world (Waha et al., 2013).

1.3.2. Capturing Irrigation Systems within Land Surface Models

Irrigation is one of the important but under-appreciated processes in LSMs (Gordon et al., 2008; Ozdogan et al., 2010). Normally, irrigation processes are treated in LSMs with one of the followings approaches. ***1- Irrigation time and amount is***
5 ***not mechanistically simulated:*** In most modeling studies, irrigation requirements are calculated using published irrigation guidelines or a time series of satellite observations (Pokhrel et al., 2011). In other models, irrigation water scarcity is not captured (e.g. Ozdogan et al., 2010), which can result in less realistic irrigation management during droughts. ***2- Irrigation is included but with unrealistic assumptions of irrigation efficiency:*** For example, CLM v4 simulates the time of irrigation based on soil deficit but does not consider irrigation losses (Leng et al.,2013). This can cause poor representation of
10 hydrologic processes in agricultural areas and underestimation of irrigation demand. ***3- Partitioning of the overall efficiency into different losses through prescribed ratios:*** Pokhrel et al. (2011) developed an irrigation module and coupled it to the Minimal Advanced Treatments of Surface Interaction and RunOff (MATSIRO) model. The irrigation module considers soil moisture deficit to calculate the time of irrigation, but their irrigation module did not consider the partitioning of the overall efficiency into different losses and did not simulate the dynamics between irrigation losses and the hydrologic cycle.
15 Haddeland et al. (2006) implemented a simple irrigation module into the Variable Infiltration Capacity (VIC) model. This irrigation module, however, was limited to prescribed losses of sprinkler systems. Also, because the VIC model does not mechanistically simulate crop processes, the timing and amount of the irrigation water is not responsive to crop growth, management, and phenology.

These shortcomings, simplifying assumptions, and lack of a mechanistic way to simulate irrigation processes in LSMs lead
20 to inaccurate ET and water demand simulations (Pokhrel et al., 2011; Sridhar, 2013). Also, because LSMs are often coupled to atmospheric models, this lack of capturing mechanistic irrigation processes will cause biases in turbulent heat flux simulations, leading to GCM errors.

2. Approach

Here, we introduce the newly integrated model VIC-CropSyst, which is a coupling between the VIC hydrologic model and
25 the CropSyst crop growth, phenology, and management model. VIC-CropSyst can be used for regional to global-scale simulations of water and energy cycles over natural and managed terrestrial ecosystems. A process-based irrigation module was also developed to simulate the interactions between irrigation management decisions and the hydrologic cycle in this integrated model.

2.1. Descriptions of Stand Alone Models

2.1.1. VIC

The VIC model is a processed-based large-scale hydrologic model developed initially by Liang et al. (1994). VIC uses the variable infiltration capacity curve introduced by Zhao et al. (1980) to simulate infiltration and surface runoff, and Franchini
5   and Pacciani's (1991) formula to calculate base flow. Liang et al. (1996) further developed the model to represent multiple soil moisture layers (the original version only had two). Cherkauer et al. (2003) added processes for more accurate simulation of soil freeze and thaw as well as the canopy energy balance in freezing conditions. VIC has been applied and evaluated by several researchers over a variety of areas (e.g., Elsner et al., 2010 and Hamlet and Lettenmaier 1999 over the Columbia River basin; Adam et al. 2007 in the Eurasian arctic; Maurer et al. 2002 over the contiguous U.S.; and Yuan et al.
10   2004 in China). In this study we coupled VIC version 4.1.2-e with CropSyst-v4, and the VIC-CropSyst will be updated simultaneously with VIC and CropSyst new developments.

2.1.2. CropSyst

CropSyst (Stockle et al., 1994, Stockle et al., 2003) is a process-based cropping system model, capturing water, nitrogen and
15   carbon cycles as well as the key processes related to crop phenology, root and shoot growth, and biomass production and yield. CropSyst simulates field operations including irrigation, fertilization, tillage, residue management and crop rotation. It also captures the effects of CO_2 concentration and stressors such as water limitation, temperature extremes and soil salinity on crop development. CropSyst has been applied to climatic conditions worldwide, as well as in climate change studies (e.g. Confalonieri and Bocchi (2005) for rice in Italy; Ferrer et al. (2000) for corn in Spain; Pala et al. (1996) for wheat in Syria;
20   Pannkuk et al. (1998) for wheat in the U.S. Pacific Northwest; and Alva et al. (2010) for potatoes in the U.S. Pacific Northwest). We used CropSyst_4.15 version in our VIC-CropSyst integrated model.

2.2. Model Integration Strategy

In the tightly coupled VIC-CropSyst model (Figure 1), hydrology, except the plant transpiration, is handled by VIC, while
25   crop growth, plant transpiration, phenology, and management are handled by CropSyst. Weather information, cropping patterns, and soil textural information are provided through the VIC side of the coupled model, while inputs on crop characteristics and management are handled by CropSyst. In the following section we briefly explain the structure of the VIC-CropSyst coupling (Figure 1). Then we discuss some of the changes we have made to each model to support this integration. Finally, we discuss the irrigation module that we have developed and implemented in VIC-CropSyst.

[FIGURE 1]

2.2.1. Water and Energy Balances in VIC-CropSyst

Figure 2 shows how VIC-CropSyst handles the water and energy budgets. VIC first simulates the energy balance (explained by Cherkauer et al., (2003) and Liang et al., (1994)). It estimates available energy per time step and uses an iterative approach to partition the available energy into each of the energy components (e.g., snowmelt and sublimation heat fluxes,

5   ground heat flux, and sensible heat flux). After these terms are calculated, the remaining energy will be available to potential evapotranspiration (ETp). Evaporation can happen from at least one of the five following processes (Thompson et al., 1993): 1- directly from irrigation water (E_d), 2- from intercepted water by the canopy (E_c), 3- from the wetted soil surface during irrigation (E_{si}), 4- from the soil surface when irrigation is not occurring (E_s), and 5- transpiration (T).

10   CropSyst is called while VIC is simulating the energy balance, but after ETp is portioned into each of its terms. Following this, potential transpiration and availability of soil moisture are passed to CropSyst (Figure 2). Actual transpiration depends on the availability of soil water. When the soil does not have enough water to meet crop demand, actual crop transpiration is less than potential. In the coupled model, CropSyst simulates actual transpiration, soil water extraction from each layer, water stress, and crop growth; it then passes the extracted soil water amount to VIC to calculate the water balance. VIC

15   updates soil moisture and simulates the rest of the hydrologic components such as runoff and baseflow.

[FIGURE 2]

2.2.2. Significant Changes to Each Model

20   ***Soil Hydrology:*** In VIC-CropSyst, CropSyst's soil hydrology is turned off and VIC simulates soil hydrologic processes including the movement of water in the soil, bare soil evaporation, and the generation of runoff and baseflow. Because crop processes are sensitive to soil moisture availability, we have modified the VIC soil structure. While VIC previously had the capacity to handle an indefinite number of soil moisture layers, the majority of VIC applications utilize three layers, where runoff and baseflow are generated from the top and bottom layers, respectively, while the middle layer is the root zone where

25   plant uptake occurs. Because the availability of water where roots are concentrated is central to unstressed crop growth, and because the dynamic simulation of root growth is sensitive to the vertical distribution of soil moisture, VIC's conventional three layering system is too coarse to accurately represent this condition, particularly during droughts and over rain-fed cropland. Therefore, we expanded the middle layer of VIC to 15 layers. Finally, the minimum soil moisture in the VIC-CropSyst is set to the wilting point (except in the top evaporative layer).

Soil File: The conventional versions of VIC directly read soil properties (e.g. soil hydraulic conductivity, field capacity, wilting point, bulk density) from input files. For a more consistent way (between VIC and CropSyst) of inputting soil input

information, empirical functions developed by Saxton et al. (1986) were implemented in the model and VIC-CropSyst internally estimates the necessary soil parameters using soil textural characteristics (i.e., sand and clay percentages).

5   ## 2.3. Irrigation Module

The irrigation module (Figure 3) is briefly explained below, while a more detailed description can be found in Malek et al (2016, in prep). The irrigation module calculates irrigation frequency, amount, and losses.

[FIGURE 3]

Currently, VIC-CropSyst simulates 40 different types of irrigation systems. These systems fall into four major categories including surface, center pivot, sprinkler, and drip irrigation systems. Characteristics of the systems have been collected from different scientific papers, reports, and commercial catalogs (e.g. Nelson Co., 2014; RainBird, 2014). This level of detail offers a more accurate representation of irrigation practices and will help users to simulate adaptation of irrigation and

15   management scenarios.

2.3.1. Irrigation Frequency

Evaporation, transpiration, and deep percolation cause reductions in root-zone soil water content. When soil moisture deficit

20   reaches one of the following two thresholds, VIC-CropSyst triggers an irrigation event: 1- capacity of the irrigation system, which sets the maximum amount of water that can be applied in an irrigation event, and 2- the Maximum Allowable Depletion (MAD), which determines what degree of soil dryness causes water stress in each crop. To define crop-specific MADs, we created a table of parameters using FAO-56 (Allen, 1998).

25   ### 2.3.2. Evaporative Losses

In the drip and surface categories, evaporative losses happen only from the soil surface because irrigation happens below the canopy level. Irrigation takes place above the canopy in sprinkler and center pivot systems; therefore, evaporation from canopy-intercepted water (E_c) and the direct loss from droplets (E_d) are considered as major irrigation losses. VIC-CropSyst neglects E_{si} for sprinkler and center pivot systems because energy is more readily available for water above the canopy and

it suppresses the below-canopy evaporation (Uddin et al., 2013; Yonts et al., 2000). Evaporative losses from drip and surface irrigation systems are based on the following formula,

$$E_{si} = ET_p \, A_w \, T_i / 24 \tag{1}$$

where ET_p is potential ET [mm/Δt; A_w is the wetted surface fraction during irrigation; and T_i is the time of irrigation [hr]. While A_w is assumed to be 1.0, 1.0 and 0.5 for border, basin and farrow irrigation, respectively, we used Malek and Peters (2011)'s equation to estimate the wetted radius of drip irrigation and calculate the wetted percentage.

10   The following formulas are used to calculate E_c and E_d from sprinkler and center pivot irrigation systems. ***Evaporation from Irrigation Intercepted Water (E_c)***: to calculate Ec, VIC-CropSyst uses the original VIC method (Liang et al., 1994). To avoid overestimation of Ec in agricultural areas, we used the equation developed by Kang et al. (2005) to set maximum Ec. ***Evaporation from Irrigation Droplets (E_d):*** Users have the option to calculate Ed using one of two methods of Malek, et al. (2016, in prep) or Playán et al. (2005).

2.3.3. Deep Percolation Loss (D$_p$)

Dp is defined as irrigated water which penetrates below the root zone. Therefore, after an irrigation event the amount of water that enters the base flow layer and becomes inaccessible for crop roots is considered a deep percolation loss.

20   ### 2.3.4. Runoff Losses (R_o)

Ro depends on soil infiltration rate and irrigation intensity. Whenever irrigation intensity is higher than soil infiltration capacity, runoff is generated as follows,

$$R_o = \frac{Ir}{t_{irr}} - f \tag{2}$$

where f is the infiltration rate $\left(\frac{mm}{hr}\right)$, I_r is the amount of irrigation water applied in each event (mm) and t_{irr} is the duration of irrigation (hr). Although irrigation intensity is usually a management decision, soil texture and hydraulic conductivity are assumed to be the key considerations in a well-managed irrigation system; therefore in the beginning of simulation, VIC-CropSyst estimates the irrigation duration (I_{du}) using the soil characteristics of each gridcell. The calculated I_{du} is used to

30 estimate the infiltration opportunity time of surface irrigation, rotation time in center pivot, and overlap and layout of sprinklers in solid-set, wheel move and big-gun irrigation systems. If approximated irrigation intensity exceeds the irrigation

infiltration rate (f), the extra water generates runoff. VIC-CropSyst uses the equation developed by Philip, (1957) to estimate the infiltration rate. Details of the runoff calculations are presented by Malek, et al. (2016, in prep).

2.4. Data and Study Sites/Areas

5 VIC-CropSyst's simulated soil moisture, ET, yield and irrigation water demand were compared to observed data obtained from FLUXNET network (Baldocchi et al., 2001). Simulated LAI was evaluated against Moderate Resolution Imaging Spectroradiometer (MODIS) remote sensing observations (Cohen et al., 2006). We also evaluated regional performance of VIC-CropSyst in simulation of ET over the U.S. Pacific Northwest, including the states of Washington, Idaho and Oregon.

10 ### 2.4.1. Site Description

The flux tower stations considered in this study are located in two U.S. states of Nebraska (NE) and Illinois (IL) (Figure 4). Available environmental and agricultural information include latent heat, soil moisture and meteorological data, crop type, LAI, and biomass production. The towers are all in agricultural fields and have relatively long periods of available data. The station in the IL is not irrigated and the site in NE is irrigated with recorded irrigation frequency and amount.

2.4.2. Meteorological, Soil, Land Cover, and Topographic Data

Daily meteorological data were acquired from the DAYMET (Thornton et al., 2012) gridded data source. Soil files were taken from Maurer et al. (2002) for associated grid cells. The soil files were modified using available information at the observation sites. Table 2 shows soil texture calculated using the United States Department of Agriculture's soil triangle
20 (Garcia-Gaines and Frankenstein, 2015).

[TABLE 2]

[FIGURE 4]

2.4.3. Calibration Parameters for Point Scale Evaluation

As with other hydrological models, the VIC model needs to be calibrated for optimized performance over a specific region. Table 3 shows VIC's key calibration parameters; more information on calibration parameters and methods can be found in past VIC studies (e.g. Elsner et al., 2010; Liang et al., 1994; Maurer et al., 2002). We used calibrated parameters determined
30 by Maurer et al. (2002) for each flux tower station (the last two columns of Table 3). We also tested the sensitivity of soil

moisture content, crop growth, and irrigation demand and losses to different calibration parameters using the ranges available in the Column 3 of Table 3 and found no significant variations.

[TABLE 3]

2.4.4. Parametrization of Growth Stages in CropSyst

Thermal accumulation time in CropSyst is used to represent crop phenological development and the rate of biological activity (McMaster and Wilhelm, 1997). Specifically, the sum of growing degree days (GDD) is used to specify the time

10 needed to reach specific phenological periods. We parameterized VIC-CropSyst for each site using published dates of crop growth stages (Table 4); meteorological information was used to convert calendar days to GDDs. Peak LAI was acquired from the MODIS LAI product (Cohen et al., 2006). Missing phenological information was estimated from the MODIS-derived peak LAIs as follows: i) flowering is 2-7 days after peak LAI, ii) filling starts 7-14 days after flowering, and iii) maturity happen 30-45 days into the filling period. Table 4 shows estimated/observed dates of the growing stages.

[TABLE 4]

2.4.5. Pacific Northwest Climate, Soil and Crop Information

We used the gridded historical climate data developed by Abatzoglou and Brown (2012), including precipitation, minimum

20 and maximum temperature and wind speed. Soil input file was developed using the STATSGO dataset (Schwarz and Alexander, 1995); to develop the soil file we used the same parameters as Elsner et al (2010) except we added the clay percentage because, as mentioned earlier, VIC-CropSyst uses Saxton et al (1986)'s Pedotransfer functions and can internally calculate the soil parameters (e.g. hydraulic conductivity, field capacity, bulk density). The calibration parameters (Table 3) used for simulation of ET over the Pacific Northwest was taken from Yorgey et al. (2011). Crop distribution information

25 over the region was developed using the Washington State's Department of Agriculture for Washington State and the United State Department of Agriculture (USDA)'s cropping information for outside of the Washington State (Boryan et al., 2011).

3.   Evaluation and Application

3.1. Point Scale Evaluation

3.1.1. Applied Irrigation Water

Figure 5 compares recorded and simulated irrigation water (mean error=13%). Discrepancies may be due to reduction of

5   crop yield in the field due to stresses that are not captured in the model such as impacts of weed or pests. Also, yields measured in small plots are subject to sampling uncertainty; In addition, simulated irrigation events are likely to include an extra event at the end of the season when irrigation managers stop irrigating earlier due to crop senescence.

[FIGURE 5]

3.1.2. Evapotranspiration (ET)

Figure 6 depicts the comparisons between monthly simulated and observed ET over irrigated and non-irrigated sites. While the model tends to overestimate ET, particularly during the month with larger ET, simulations are more accurate at the NE irrigated site. Root mean squares errors (RMSEs) for the NE and IL stations were 8.0 and 1.0 (mm/day), respectively. In

15   general, the deviation between observed and simulated ET is higher in the summer months. One explanation for this bias is that we do not consider the feedback of evaporative losses from irrigation droplets (E_d) and canopy-intercepted water (E_c) to the local microclimate system, while in reality these evaporative losses will lower ambient temperature and decrease vapor pressure deficit (Kohl and Wright, 1974; Liu and Kang, 2006), thereby reducing irrigation demand. In the Biosphere-relevant Earth system model (BioEarth) project (Adam et al., 2014) this shortcoming is being addressed through coupling of VIC-

20   CropSyst to atmospheric models. Inaccuracy of the meteorological data can be another source of error. This deviation can also be explained by a typical 20% systematic error in flux tower ET observations, which tend to underestimate the latent heat fluxes. This energy imbalance issue has been discussed in many studies by the microclimatological community (Frank et al., 2013; Leuning et al., 2012; Mahrt, 1998; Wilson et al., 2002).

25   [FIGURE 6]

3.1.3. Corn Yield

Figure 7 compares simulated and observed corn yield over the two sites. The mean error of simulated yield for NE (irrigated) and IL (non-irrigated) were 9% and 3%, respectively. The fact that the error is smaller over the non-irrigated site can be

explained by the fact that irrigation management did not have to be simulated, thereby reducing the opportunity for introducing model error.

[FIGURE 7]

3.1.4. Soil Moisture

Figure 8 compares simulated and observed soil moisture over the two sites. Because the soil moisture sensors were placed at 10 and 25 cm depths a the NE site and at 2.5 and 10 cm depths at the IL site, we aggregated the first three VIC soil moisture layers (for a total thickness of 30 cm) for comparison against observed at the NE site. We compared just the first VIC soil

10   moisture layer (10 cm depth) against observed at the IL site. The mean errors were 18% and 16% for the NE and IL sites, respectively. As with crop yield, soil moisture simulations are better for the non-irrigated site, particularly in terms of variability. The discrepancies may relate to use of Pedotransfer functions that convert soil textural characteristics to soil hydraulic properties (e.g. field capacity, permanent wilting point and hydraulic conductivity) for use in VIC-CropSyst (Pachepsky and Rawls, 1999; Tietje and Hennings, 1996). Also, scale discrepancies between the point-scale observation and

15   the grid-scale simulation is another source of error (Crow et al., 2012; Robinson et al., 2008).

[FIGURE 8]

3.1.5. Leaf Area Index (LAI)

20   Figure 9 shows that VIC-CropSyst is able to capture the magnitude and seasonality of observed LAI, with a slight underestimation of peak LAI. The information we used for calibration of phenological periods (Figure 9) are not specifically collected for the two study sites, but instead were based on state-scale studies and reports; this is a potential source of error in simulation of LAI. Because of limited information at flux tower sites, we did not consider all of the crop-related parameters (e.g. radiation use efficiency, maximum crop coefficient and maximum crop coverage) during calibration, which

25   can also lead to some discrepancies (e.g. Jalota et al., 2010; Klein et al., 2012).

[FIGURE 9]

3.2. Regional Evaluation of Evapotranspiration (ET)

30   We used VIC-CropSyst to simulate ET over the three states of Washington, Idaho and Oregon (Figure 10). Simulated ET was aggregated from the original model resolution of 1/16th to 0.5 degree for comparison against the upscaled ET product

derived from the FLUXNET eddy tower network (Baldocchi et al., 2001). Liu et al (2013) described the details of the creation of the empirically-derived or "observed" ET map. They also compared the observed ET with an offline (from CropSyst) version of VIC-simulated ET and reported a systematic underestimation of simulated ET over warm irrigated areas. Our ET results show that VIC-CropSyst's simulated ET in general produces a lower error as compared to VIC-offline, especially over irrigated areas; error over irrigated landscapes was reduced from about 28% to 17%, a 40% reduction. However, it is important to note that another source of the discrepancy is due to inaccuracy of the observed ET product because it was developed using a limited number of flux tower stations as well as empirical formulas that also have inherent errors (see Liu et al. 2013 for details).

[FIGURE 10]

4.   Examples of VIC-CropSyst Application

4.1.   Simulation of Agricultural Adaptation in Response to Climate Change

Farmers adapt their agricultural management to minimize unfavourable impacts of stressors such as climate change (Kurukulasuriya and Rosenthal., 2003). Possible agricultural adaptation strategies have been discussed (e.g. Anwar et al., 2013; Howden et al., 2007; Kurukulasuriya and Rosenthal., 2003; Smit and Skinner., 2002; Smith et al., 2000). However, lack of appropriate simulation tools to assess the effectiveness of an adaptation decision while capturing complex regional impacts is a significant shortcoming. VIC-CropSyst simulates common adaptation strategies used by farmers, and captures the consequences of these adaptation strategies on local and regional hydrology and land-atmosphere interactions. Table 5 shows a list of adaptation decisions that can be handled by VIC-CropSyst. These decisions range from short-term tactical (T) to long-term strategic (L) decisions.

[TABLE 5]

4.2.   Foundation for Integration within Other Modeling Platforms

VIC-CropSyst can be used with other modeling frameworks such as atmospheric, socio-economics, and water storage and routing models. These integrations may simulate the human-land-climate nexus and provide scientists, stakeholders and policy makers with a broader understanding of the interactions and feedbacks in this nexus. VIC-CropSyst has been already used and implemented in various projects. Examples of these implementations are as follows.

4.2.1. Water Resources Management and Socio-Economic Studies

An earlier version of VIC-CropSyst (v1 of the integrated model, which utilizes VIC v4.0.7 and CropSyst v4.15) was used in conjunction with the Columbia Simulation reservoir model (ColSim; Hamlet and Lettenmaier, 1999; Wittwer et al 2001) and economic models to forecast the impact of climate change on Columbia River basin (CRB) water supply and irrigation water demand (e.g., Rajagopalan et al., 2016; Yorgey et al., 2011). The current version of VIC-CropSyst is also being used over the Yakima River basin (YRB) to evaluate the impact of climate change on irrigation management (Malek et al., 2016; in prep.). Economic damages of future more frequent droughts (Vano et al., 2010) is considered the main incentive to invest in more efficient irrigation technology (Berger and Troost, 2014). To analyze future changes in regional irrigation patterns, VIC-CropSyst has been used in conjunction with an economic model and a River System model (Malek et al., 2016; in prep.). Figure 11 shows a result of this integration to simulate the historical (1981-2006) drought frequency and severity, and the percentage of the YRB's perennial crop growers who are simulated to switch to more efficient irrigation systems to minimize the negative consequences of droughts during the two decades of 1990-2000 and 2050-2060. Also, any changes in agricultural activities (e.g., switching to a new irrigation system) directly impacts the hydrology of agricultural fields, thus changing return flow timing and magnitude and the availability of water for downstream users; these downstream consequences can also be simulated by this modeling platform. This is an example of how the human-land-climate nexus can be captured through a modeling framework that simulates large-scale hydrologic processes and regional water availability in a highly cultivated basin, while capturing the dynamics of farm-level irrigation decisions.

[FIGURE 11]

4.2.2. Land-Atmosphere Interactions

Irrigation and other agricultural decisions modify local to regional climate through changes in land surface conditions such as temperature, water vapor content and albedo (Fernández et al., 2001; Liu and Kang, 2006). This phenomena can be used to compensate the negative impacts of heat stress (Lobell et al., 2008), which will be especially important in the future if there are more severe and frequent extreme events related to climate change (Long and Ort, 2010). These management decisions will also impact the regional water cycle, potentially leading to disruption in water availability (Adamson and Loch, 2014) and modifying fluxes of water to the atmosphere (Pielke Sr. et al., 2007). As a part of the BioEarth platform (Adam et al., 2014), VIC-CropSyst is being coupled to an atmospheric model, the Weather Research and Forecast model (WRF; (Michalakes et al., 2005; Skamarock et al., 2008) Skamarock et al. 2008) that can be used to quantify the impacts of irrigation and other agricultural management on atmospheric processes, as well as to assess how irrigation management can be used to mitigate heat stress.

5. Conclusions

Meeting future food demand will require an extensive understanding of the interactions between agricultural and other systems, such as water resources planning and management, socioeconomic, and atmospheric processes. The main purpose of this study was to develop the VIC-CropSyst platform that provides tightly-integrated and mechanistic representation of both cropping systems and water/energy cycles at regional to global scales. Tight integration between VIC and CropSyst necessitated modification of both models, including how the models handle soil movement and vertical distribution, transpiration, LAI, and irrigation. Evaluation of VIC-CropSyst over two flux tower sites shows that the coupled model captures key agronomic and hydrologic states and fluxes at the field scale. Furthermore, implementation of VIC-CropSyst over the U.S. Pacific Northwest region reduced ET simulation error by 40% over irrigated landscapes.

The VIC-CropSyst platform enables the land surface modeling community to investigate a variety of agricultural management decisions, including crop choice, planted acreage, planting and harvesting date, and multiple irrigation management options. In particular, the new mechanistic irrigation model, which is tightly coupled with both the energy and water cycles, can be used to address questions related to the interaction of climate, hydrology, river basin water management, and irrigation management strategies.

VIC-CropSyst can be integrated with different modeling platforms to capture the dynamics of the human-land-climate nexus. This can potentially improve the understanding of environmental processes in highly-cultivated basins and can be used to investigate best management practices to promote future sustainability of agricultural production while preserving water resources and minimizing the negative intended and unintended consequences of human actions. Some examples of these implementations are as follows:

Coupling with water resource management and socioeconomic models: This involves simulating regional water availability and agricultural productivity, adaptive responses of farmers to climate change, and unintended consequences of these adaptation decisions.

*Coupling with w*eather *and climate models:* VIC-CropSyst will also provide capabilities to investigate the dynamics of agricultural management decisions on local to regional weather and climate patterns through modifications of energy and water fluxes (Barnston and Schickedanz, 1984; Douglas et al., 2009; Kohl and Wright, 1974). This promotes the understanding of, for example, how irrigation management and technology can control negative impacts of heat and water stresses on crop yield.

VIC-CropSyst is being used in earth system models (EaSMs) such as BioEarth (Adam et al., 2014) and can be implemented in other EaSMs such as the Platform for Regional Integrated Modeling and Analysis (PRIMA; Kraucunas et al., 2014). Implementation of VIC-CropSyst in EaSMs facilitates a powerful representation of large-scale interactions between different biophysical and socioeconomic components over areas with significant agricultural activities. This is a transformational step

5   in the understanding of the food-energy-water nexus which can lead to efficient and more sustainable management decisions that co-balance and benefit all three sectors.

Code and/or data availability

The VIC-CropSyst is a freeware open source community model; source codes, user manual and test cases will be distributed

10   through contact to Keyvan Malek (keyvan.malek@wsu.edu), Jennifer Adam (jcadam@wsu.edu) and Mingliang Liu (mingliang.liu@wsu.edu).

Acknowledgments

This research was funded by Washington State Department of Ecology's Office of Columbia River Basin and the Department of Agriculture, National Institute of Food and Agriculture Grant Number 2011-67003-30346 (Biosphere

15   Relevant Earth System Model; BioEarth). This research is also financially supported by Washington State University's Graduate School.

References

Abatzoglou, J.T., Brown, T.J., 2012. A comparison of statistical downscaling methods suited for wildfire
20   applications. Int. J. Climatol. 32, 772–780. doi:10.1002/joc.2312
Adam, J.C., Haddeland, I., Su, F., Lettenmaier, D.P., 2007. Simulation of reservoir influences on annual and
          seasonal streamflow changes for the Lena, Yenisei, and Ob' rivers. J. Geophys. Res. Atmospheres 112,
          n/a–n/a. doi:10.1029/2007JD008525
Adam, J.C., Hamlet, A.F., Lettenmaier, D.P., 2009. Implications of global climate change for snowmelt
25   hydrology in the twenty-first century. Hydrol. Process. 23, 962–972. doi:10.1002/hyp.7201
Adam, J.C., J.C. Stephens, M.P. Brady, S.H. Chung, R.D. Evans, C.E. Krugere, B.K. Lamb, M.L. Liu, C.O.
          Stöckle, J.K. Vaughan, K. Rajagopalan, J.A. Harrison, C.L. Tague, A. Kalyanaramani, Y. Chenj, A.
          Guentherk, F.Y. Leung, L.R. Leung, A.B. Perleberg, J. Yoder, E. Allen, S. Anderson, B.
          Chandrasekharan, K. Malek, T. Mullis, C. Miller, T. Nergui, J. Poinsatte, J. Reyes, K.J.
30   Chinnayakanahalli, M. J. Choate, X. Jiang, R. Nelson, J.H. Yoon, G.G. Yorgey, J. Zhu, A.F. Hamlet, B.
          Nijssen, 2013. BioEarth: A Regional Biosphere-Relevant Earth System Model for Understanding the
          Consequences of Agricultural and Natural Resource Management Decisions. Clim. Change.
Adamson, D., Loch, A., 2014. Possible negative feedbacks from "gold-plating" irrigation infrastructure. Agric.
          Water Manag., Exploring some of the socio-economic realities of sustainable water management in
35   irrigation 145, 134–144. doi:10.1016/j.agwat.2013.09.022

Ainsworth, E.A., Rogers, A., 2007. The response of photosynthesis and stomatal conductance to rising [CO2]: mechanisms and environmental interactions. Plant Cell Environ. 30, 258–270. doi:10.1111/j.1365-3040.2007.01641.x

Allen, E., Forney, W., Harrison, J., Kruger, C., Saari, B., Stephens, J., Yorgey, G., 2015. BioEarth Water Quality
5   Stakeholder Advisory Workshop Synthesis Report. Washington State University. Groups not represented at the stakeholder workshop, but recommended for future inclusion by attending stakeholders: USDA Natural Resources Conservation Service and Agricultural Research Service, tribal governments.

Allen, R.G., 1998. Crop evapotranspiration—Guidelines for computing crop water requirements FAO Irrigation and drainage paper 56.

10 Alva, A.K., Marcos, J., Stockle, C., Reddy, V.R., Timlin, D., 2010. A Crop Simulation Model for Predicting Yield and Fate of Nitrogen in Irrigated Potato Rotation Cropping System. J. Crop Improv. 24, 142–152. doi:10.1080/15427520903581239

Anwar, M.R., Liu, D.L., Macadam, I., Kelly, G., 2013. Adapting agriculture to climate change: a review. Theor. Appl. Climatol. 113, 225–245. doi:10.1007/s00704-012-0780-1

15 Baldocchi, D., Falge, E., Gu, L., Olson, R., others, 2001. FLUXNET: A new tool to study the temporal and spatial variability of ecosystem-scale carbon dioxide, water vapor, and energy flux densities. Bull. Am. Meteorol. Soc. 82, 2415.

Barnett, T.P., Adam, J.C., Lettenmaier, D.P., 2005. Potential impacts of a warming climate on water availability in snow-dominated regions. Nature 438, 303–309. doi:10.1038/nature04141

20 Barnston, A.G., Schickedanz, P.T., 1984. The Effect of Irrigation on Warm Season Precipitation in the Southern Great Plains. J. Clim. Appl. Meteorol. 23, 865–888. doi:10.1175/1520-0450(1984)023<0865:TEOIOW>2.0.CO;2

Berger, T., Troost, C., 2014. Agent-based Modelling of Climate Adaptation and Mitigation Options in Agriculture. J. Agric. Econ. 65, 323–348. doi:10.1111/1477-9552.12045

25 Boryan, C., Yang, Z., Mueller, R., Craig, M., 2011. Monitoring US agriculture: the US Department of Agriculture, National Agricultural Statistics Service, Cropland Data Layer Program. Geocarto Int. 26, 341–358. doi:10.1080/10106049.2011.562309

Chang, K.-H., Warland, J.S., Bartlett, P.A., Arain, A.M., Yuan, F., 2014. A Simple Crop Phenology Algorithm in the Land Surface Model CN-CLASS. Agron. J. 106, 297. doi:10.2134/agronj2013.0164

30 Cherkauer, K.A., Bowling, L.C., Lettenmaier, D.P., 2003. Variable infiltration capacity cold land process model updates. Glob. Planet. Change 38, 151–159. doi:10.1016/S0921-8181(03)00025-0

Cohen, W.B., Maiersperger, T.K., Turner, D.P., Ritts, W.D., Pflugmacher, D., Kennedy, R.E., Kirschbaum, A., Running, S.W., Costa, M., Gower, S.T., 2006. MODIS land cover and LAI collection 4 product quality across nine sites in the western hemisphere. IEEE Trans. Geosci. Remote Sens. 44, 1843–1857.
35 doi:10.1109/TGRS.2006.876026

Confalonieri, R., Bocchi, S., 2005. Evaluation of CropSyst for simulating the yield of flooded rice in northern Italy. Eur. J. Agron. 23, 315–326. doi:10.1016/j.eja.2004.12.002

Crow, W.T., Berg, A.A., Cosh, M.H., Loew, A., Mohanty, B.P., Panciera, R., de Rosnay, P., Ryu, D., Walker, J.P., 2012. Upscaling sparse ground-based soil moisture observations for the validation of coarse-
40 resolution satellite soil moisture products. Rev. Geophys. 50, RG2002. doi:10.1029/2011RG000372

Douglas, E.M., Beltrán-Przekurat, A., Niyogi, D., Pielke Sr., R.A., Vörösmarty, C.J., 2009. The impact of agricultural intensification and irrigation on land–atmosphere interactions and Indian monsoon precipitation — A mesoscale modeling perspective. Glob. Planet. Change, Changes in land use and water use and their consequences on climate, including biogeochemical cycles 67, 117–128.
45 doi:10.1016/j.gloplacha.2008.12.007

Drewniak, B., Song, J., Prell, J., Kotamarthi, V.R., Jacob, R., 2013. Modeling agriculture in the Community Land Model. Geosci. Model Dev. 6, 495–515. doi:10.5194/gmd-6-495-2013

Dukes, J.S., Mooney, H.A., 1999. Does global change increase the success of biological invaders? Trends Ecol. Evol. 14, 135–139. doi:10.1016/S0169-5347(98)01554-7

5   Elsner, M.M., Cuo, L., Voisin, N., Deems, J.S., Hamlet, A.F., Vano, J.A., Mickelson, K.E.B., Lee, S.-Y., Lettenmaier, D.P., 2010. Implications of 21st century climate change for the hydrology of Washington State. Clim. Change 102, 225–260. doi:10.1007/s10584-010-9855-0

Ferguson, I.M., Maxwell, R.M., 2011. Hydrologic and land–energy feedbacks of agricultural water management practices. Environ. Res. Lett. 6, 14006. doi:10.1088/1748-9326/6/1/014006

10 Fernández, J.E., Palomo, M.J., Díaz-Espejo, A., Clothier, B.E., Green, S.R., Girón, I.F., Moreno, F., 2001. Heat-pulse measurements of sap flow in olives for automating irrigation: tests, root flow and diagnostics of water stress. Agric. Water Manag. 51, 99–123. doi:10.1016/S0378-3774(01)00119-6

Ferrer, F., Villar, J.M., Stockle, C.O., 2000. Evaluation of CropSyst, a cropping systems simulation model, for irrigated corn in the Ebro Valley. Investig. Agrar. Prod. Protección Veg. 15, 237–251.

15 Franchini, M., Pacciani, M., 1991. Comparative analysis of several conceptual rainfall-runoff models. J. Hydrol. 122, 161–219. doi:10.1016/0022-1694(91)90178-K

Frank, J.M., Massman, W.J., Ewers, B.E., 2013. Underestimates of sensible heat flux due to vertical velocity measurement errors in non-orthogonal sonic anemometers. Agric. For. Meteorol. 171–172, 72–81. doi:10.1016/j.agrformet.2012.11.005

20 Garc a-Gaines, R.A., Frankenstein, S., 2015. USCS and the USDA Soil Classification System: Development of a Mapping Scheme. DTIC Document.

Godfray, H.C.J., Beddington, J.R., Crute, I.R., Haddad, L., Lawrence, D., Muir, J.F., Pretty, J., Robinson, S., Thomas, S.M., Toulmin, C., 2010. Food Security: The Challenge of Feeding 9 Billion People. Science 327, 812–818. doi:10.1126/science.1185383

25 Gordon, L.J., Peterson, G.D., Bennett, E.M., 2008. Agricultural modifications of hydrological flows create ecological surprises. Trends Ecol. Evol. 23, 211–219. doi:10.1016/j.tree.2007.11.011

Haddeland, I., Heinke, J., Biemans, H., Eisner, S., Flörke, M., Hanasaki, N., Konzmann, M., Ludwig, F., Masaki, Y., Schewe, J., Stacke, T., Tessler, Z.D., Wada, Y., Wisser, D., 2014. Global water resources affected by human interventions and climate change. Proc. Natl. Acad. Sci. 111, 3251–3256.

30 doi:10.1073/pnas.1222475110

Haddeland, I., Lettenmaier, D.P., Skaugen, T., 2006. Effects of irrigation on the water and energy balances of the Colorado and Mekong river basins. J. Hydrol. 324, 210–223. doi:10.1016/j.jhydrol.2005.09.028

Hamlet, A., Lettenmaier, D., 1999. Columbia River Streamflow Forecasting Based on ENSO and PDO Climate Signals. J. Water Resour. Plan. Manag. 125, 333–341. doi:10.1061/(ASCE)0733-9496(1999)125:6(333)

35 Hansen, J., Challinor, A., Ines, A., Wheeler, T., Moron, V., 2006. Translating climate forecasts into agricultural terms: advances and challenges. Clim. Res. 33, 27–41. doi:10.3354/cr033027

Howden, S.M., Soussana, J.-F., Tubiello, F.N., Chhetri, N., Dunlop, M., Meinke, H., 2007. Adapting agriculture to climate change. Proc. Natl. Acad. Sci. 104, 19691–19696. doi:10.1073/pnas.0701890104

Hubble, J.D., 2012. Yakima River Basin Integrated Water Resource Management Plan: Final Programmatic
40   Environmental Impact Statement. Fish Benefits Anal. Tech. Memo. US Bur. Reclam.

Jalota, S.K., Singh, S., Chahal, G.B.S., Ray, S.S., Panigraghy, S., Bhupinder-Singh, Singh, K.B., 2010. Soil texture, climate and management effects on plant growth, grain yield and water use by rainfed maize–wheat cropping system: Field and simulation study. Agric. Water Manag. 97, 83–90. doi:10.1016/j.agwat.2009.08.012

45 Kang, Y., Wang, Q.-G., Liu, H.-J., 2005. Winter wheat canopy interception and its influence factors under sprinkler irrigation. Agric. Water Manag. 74, 189–199. doi:10.1016/j.agwat.2004.11.004

Klein, T., Calanca, P., Holzkämper, A., Lehmann, N., Roesch, A., Fuhrer, J., 2012. Using farm accountancy data to calibrate a crop model for climate impact studies. Agric. Syst. 111, 23–33. doi:10.1016/j.agsy.2012.05.001

Kohl, R.A., Wright, J.L., 1974. Air Temperature and Vapor Pressure Changes Caused by Sprinkler Irrigation1. Agron. J. 66, 85. doi:10.2134/agronj1974.00021962006600010024x

Kraucunas, I., Clarke, L., Dirks, J., Hathaway, J., Hejazi, M., Hibbard, K., Huang, M., Jin, C., Kintner-Meyer, M., Dam, K.K. van, Leung, R., Li, H.-Y., Moss, R., Peterson, M., Rice, J., Scott, M., Thomson, A., Voisin, N., West, T., 2014. Investigating the nexus of climate, energy, water, and land at decision-relevant scales: the Platform for Regional Integrated Modeling and Analysis (PRIMA). Clim. Change 129, 573–588. doi:10.1007/s10584-014-1064-9

Kurukulasuriya, P., Rosenthal, S., 2003. Climate change and agriculture: a review of impacts and adaptations.

Leakey, A.D.B., Ainsworth, E.A., Bernacchi, C.J., Rogers, A., Long, S.P., Ort, D.R., 2009. Elevated CO2 effects on plant carbon, nitrogen, and water relations: six important lessons from FACE. J. Exp. Bot. 60, 2859–2876. doi:10.1093/jxb/erp096

Leng, G., Huang, M., Tang, Q., Sacks, W.J., Lei, H., Leung, L.R., 2013. Modeling the effects of irrigation on land surface fluxes and states over the conterminous United States: Sensitivity to input data and model parameters. J. Geophys. Res. Atmospheres 118, 9789–9803. doi:10.1002/jgrd.50792

Leuning, R., van Gorsel, E., Massman, W.J., Isaac, P.R., 2012. Reflections on the surface energy imbalance problem. Agric. For. Meteorol. 156, 65–74. doi:10.1016/j.agrformet.2011.12.002

Liang, X., Lettenmaier, D.P., Wood, E.F., 1996. One-dimensional statistical dynamic representation of subgrid spatial variability of precipitation in the two-layer variable infiltration capacity model. J. Geophys. Res. Atmospheres 101, 21403–21422. doi:10.1029/96JD01448

Liang, X., Lettenmaier, D.P., Wood, E.F., Burges, S.J., 1994. A simple hydrologically based model of land surface water and energy fluxes for general circulation models. J. Geophys. Res. Atmospheres 99, 14415–14428. doi:10.1029/94JD00483

Liu, H.-J., Kang, Y., 2006. Effect of sprinkler irrigation on microclimate in the winter wheat field in the North China Plain. Agric. Water Manag. 84, 3–19. doi:10.1016/j.agwat.2006.01.015

Liu, M., Adam, J.C., Hamlet, A.F., 2013. Spatial-temporal variations of evapotranspiration and runoff/precipitation ratios responding to the changing climate in the Pacific Northwest during 1921-2006: TRENDS IN ET AND R/P ACROSS THE PNW. J. Geophys. Res. Atmospheres 118, 380–394. doi:10.1029/2012JD018400

Lobell, D., Bala, G., Mirin, A., Phillips, T., Maxwell, R., Rotman, D., 2009. Regional Differences in the Influence of Irrigation on Climate. J. Clim. 22, 2248–2255. doi:10.1175/2008JCLI2703.1

Lobell, D.B., Bonfils, C.J., Kueppers, L.M., Snyder, M.A., 2008. Irrigation cooling effect on temperature and heat index extremes. Geophys. Res. Lett. 35, n/a–n/a. doi:10.1029/2008GL034145

Long, S.P., Marshall-Colon, A., Zhu, X.-G., 2015. Meeting the Global Food Demand of the Future by Engineering Crop Photosynthesis and Yield Potential. Cell 161, 56–66. doi:10.1016/j.cell.2015.03.019

Long, S.P., Ort, D.R., 2010. More than taking the heat: crops and global change. Curr. Opin. Plant Biol. 13, 240–247. doi:10.1016/j.pbi.2010.04.008

Mahrt, L., 1998. Flux Sampling Errors for Aircraft and Towers. J. Atmospheric Ocean. Technol. 15, 416–429. doi:10.1175/1520-0426(1998)015<0416:FSEFAA>2.0.CO;2

Malek, K, Adam, J. C, Stockle, C. O, Brady, M, Rajagopalan, K, 2016. When should irrigators invest in more water-efficient technologies as an adaptation to climate change?

Malek, K., Peters, R., 2011. Wetting Pattern Models for Drip Irrigation: New Empirical Model. J. Irrig. Drain. Eng. 137, 530–536. doi:10.1061/(ASCE)IR.1943-4774.0000320

Malek, K., Stockle, C., Adam, J., Peters, T., 2016. Climate change reduces water availability for agriculture by decreasing non-evaporative irrigation losses.

Maurer, E.P., O'Donnell, G.M., Lettenmaier, D.P., Roads, J.O., 2001. Evaluation of the land surface water budget in NCEP/NCAR and NCEP/DOE reanalyses using an off-line hydrologic model. J. Geophys. Res. Atmospheres 106, 17841–17862. doi:10.1029/2000JD900828

Maurer, E.P., Wood, A.W., Adam, J.C., Lettenmaier, D.P., Nijssen, B., 2002. A Long-Term Hydrologically Based Dataset of Land Surface Fluxes and States for the Conterminous United States*. J. Clim. 15, 3237–3251. doi:10.1175/1520-0442(2002)015<3237:ALTHBD>2.0.CO;2

McMaster, G.S., Wilhelm, W.W., 1997. Growing degree-days: one equation, two interpretations. Agric. For. Meteorol. 87, 291–300. doi:10.1016/S0168-1923(97)00027-0

Michalakes, J., Dudhia, J., Gill, D., Henderson, T., Klemp, J., Skamarock, W., Wang, W., 2005. The weather research and forecast model: software architecture and performance, in: Proceedings of the 11th ECMWF Workshop on the Use of High Performance Computing in Meteorology. pp. 156–168.

Mitchell, K.E., Lohmann, D., Houser, P.R., Wood, E.F., Schaake, J.C., Robock, A., Cosgrove, B.A., Sheffield, J., Duan, Q., Luo, L., Higgins, R.W., Pinker, R.T., Tarpley, J.D., Lettenmaier, D.P., Marshall, C.H., Entin, J.K., Pan, M., Shi, W., Koren, V., Meng, J., Ramsay, B.H., Bailey, A.A., 2004. The multi-institution North American Land Data Assimilation System (NLDAS): Utilizing multiple GCIP products and partners in a continental distributed hydrological modeling system. J. Geophys. Res. Atmospheres 109, D07S90. doi:10.1029/2003JD003823

Mote, P.W., Hamlet, A.F., Clark, M.P., Lettenmaier, D.P., 2005. Declining mountain snowpack in western North America. doi:10.1175/BAMS-86-1-39

Nafziger, E., 2013. Illinois Agronomy Handbook now online | ACES News :: College of ACES, University of Illinois [WWW Document]. URL http://news.aces.illinois.edu/news/illinois-agronomy-handbook-now-online (accessed 2.1.16).

Nelson Co., 2014. product information and documentation [WWW Document]. URL http://www.nelsonirrigation.com/resources/ (accessed 6.19.14).

Nijs, I., Ferris, R., Blum, H., Hendrey, G., Impens, I., 1997. Stomatal regulation in a changing climate: a field study using Free Air Temperature Increase (FATI) and Free Air CO2 Enrichment (FACE). Plant Cell Environ. 20, 1041–1050. doi:10.1111/j.1365-3040.1997.tb00680.x

Ozdogan, M., Rodell, M., Beaudoing, H.K., Toll, D.L., 2010. Simulating the Effects of Irrigation over the United States in a Land Surface Model Based on Satellite-Derived Agricultural Data. J. Hydrometeorol. 11, 171–184. doi:10.1175/2009JHM1116.1

Pachepsky, Y.A., Rawls, W.J., 1999. Accuracy and Reliability of Pedotransfer Functions as Affected by Grouping Soils. Soil Sci. Soc. Am. J. 63, 1748–1757. doi:10.2136/sssaj1999.6361748x

Pala, M., Stockle, C.O., Harris, H.C., 1996. Simulation of durum wheat (Triticum turgidum ssp. durum) growth under different water and nitrogen regimes in a mediterranean environment using CropSyst. Agric. Syst. 51, 147–163. doi:10.1016/0308-521X(95)00043-5

Pannkuk, C.D., Stockle, C.O., Papendick, R.I., 1998. Evaluating CropSyst simulations of wheat management in a wheat-fallow region of the US pacific northwest. Agric. Syst. 57, 121–134. doi:10.1016/S0308-521X(97)00076-0

Parry, M., Rosenzweig, C., Livermore, M., 2005. Climate change, global food supply and risk of hunger. Philos. Trans. R. Soc. B Biol. Sci. 360, 2125–2138. doi:10.1098/rstb.2005.1751

Philip, J.R., 1957. The Theory of Infiltration [WWW Document]. URL http://journals.lww.com/soilsci/Fulltext/1957/05000/THE_THEORY_OF_INFILTRATION__1__THE_INFILTRATION.2.aspx (accessed 10.20.14).

Pielke Sr., R.A., Adegoke, J.O., Chase, T.N., Marshall, C.H., Matsui, T., Niyogi, D., 2007. A new paradigm for assessing the role of agriculture in the climate system and in climate change. Agric. For. Meteorol., The Contribution of Agriculture to the State of Climate 142, 234–254. doi:10.1016/j.agrformet.2006.06.012

Playán, E., Salvador, R., Faci, J.M., Zapata, N., Martínez-Cob, A., Sánchez, I., 2005. Day and night wind drift and evaporation losses in sprinkler solid-sets and moving laterals. Agric. Water Manag. 76, 139–159. doi:10.1016/j.agwat.2005.01.015

Pokhrel, Y., Hanasaki, N., Koirala, S., Cho, J., Yeh, P.J.-F., Kim, H., Kanae, S., Oki, T., 2011. Incorporating Anthropogenic Water Regulation Modules into a Land Surface Model. J. Hydrometeorol. 13, 255–269. doi:10.1175/JHM-D-11-013.1

Puma, M.J., Cook, B.I., 2010. Effects of irrigation on global climate during the 20th century. J. Geophys. Res. Atmospheres 115, D16120. doi:10.1029/2010JD014122

RainBird, 2014. Master Part Book:Rain Bird Manuals, Product Literature, Performance Data & Replacement Parts for Agriculture Irrigation Systems.

Rajagopalan, K, Chinnayakanahalli, K.J, Nelson, R., Stöckle, CO., Brady, M., Barber, M.E., Yorgey, G., Kruger, C., Dinesh, S.T., Malek. K., Hamlet, A., Adam, J.C., 2015. Integrated modeling to assess the impacts of climate change on agriculture in the Columbia River basin. Water Resour. Res. (in preperation).

Robertson, G.P., Swinton, S.M., 2005. Reconciling agricultural productivity and environmental integrity: a grand challenge for agriculture. Front. Ecol. Environ. 3, 38–46. doi:10.1890/1540-9295(2005)003[0038:RAPAEI]2.0.CO;2

Robinson, D.A., Campbell, C.S., Hopmans, J.W., Hornbuckle, B.K., Jones, S.B., Knight, R., Ogden, F., Selker, J., Wendroth, O., 2008. Soil Moisture Measurement for Ecological and Hydrological Watershed-Scale Observatories: A Review. Vadose Zone J. 7, 358–389. doi:10.2136/vzj2007.0143

Rosenzweig, C., Iglesias, A., Yang, X.B., Epstein, P.R., Chivian, E., 2001. Climate Change and Extreme Weather Events; Implications for Food Production, Plant Diseases, and Pests. Glob. Change Hum. Health 2, 90–104. doi:10.1023/A:1015086831467

Rost, S., Gerten, D., Bondeau, A., Lucht, W., Rohwer, J., Schaphoff, S., 2008. Agricultural green and blue water consumption and its influence on the global water system. Water Resour. Res. 44, W09405. doi:10.1029/2007WR006331

Rowan, T.S.C., Maier, H.R., Connor, J., Dandy, G.C., 2011. An integrated dynamic modeling framework for investigating the impact of climate change and variability on irrigated agriculture. Water Resour. Res. 47, n/a–n/a. doi:10.1029/2010WR010195

Sakamoto, T., Wardlow, B.D., Gitelson, A.A., Verma, S.B., Suyker, A.E., Arkebauer, T.J., 2010. A Two-Step Filtering approach for detecting maize and soybean phenology with time-series MODIS data. Remote Sens. Environ. 114, 2146–2159. doi:10.1016/j.rse.2010.04.019

Saxton, K.E., Rawls, W.J., Romberger, J.S., Papendick, R.I., 1986. Estimating Generalized Soil-water Characteristics from Texture1. Soil Sci. Soc. Am. J. 50, 1031. doi:10.2136/sssaj1986.03615995005000040039x

Scanlon, B.R., Jolly, I., Sophocleous, M., Zhang, L., 2007. Global impacts of conversions from natural to agricultural ecosystems on water resources: Quantity versus quality. Water Resour. Res. 43, W03437. doi:10.1029/2006WR005486

Schwalm, C.R., Williams, C.A., Schaefer, K., Anderson, R., Arain, M.A., Baker, I., Barr, A., Black, T.A., Chen, G., Chen, J.M., Ciais, P., Davis, K.J., Desai, A., Dietze, M., Dragoni, D., Fischer, M.L., Flanagan, L.B., Grant, R., Gu, L., Hollinger, D., Izaurralde, R.C., Kucharik, C., Lafleur, P., Law, B.E., Li, L., Li, Z., Liu, S., Lokupitiya, E., Luo, Y., Ma, S., Margolis, H., Matamala, R., McCaughey, H., Monson, R.K., Oechel, W.C., Peng, C., Poulter, B., Price, D.T., Riciutto, D.M., Riley, W., Sahoo, A.K., Sprintsin, M., Sun, J., Tian, H., Tonitto, C., Verbeeck, H., Verma, S.B., 2010. A model-data intercomparison of CO2 exchange

across North America: Results from the North American Carbon Program site synthesis. J. Geophys. Res.
Biogeosciences 115, G00H05. doi:10.1029/2009JG001229

Schwarz, G.E., Alexander, R.B., 1995. State Soil Geographic (STATSGO) Data Base for the Conterminous
United States. Open-File Rep.

5 Skamarock, W.C., Klemp, J., Dudhia, J., Gill, D.O., Barker, D.M., Duda, M.G., Huang, X.-Y., Wang, W.,
Powers, J., 2008. A Description of the Advanced Research WRF Version 3.

Smit, B., Skinner, M.W., 2002. Adaptation options in agriculture to climate change: a typology. Mitig. Adapt.
Strateg. Glob. Change 7, 85–114. doi:10.1023/A:1015862228270

Smith, B., Burton, I., Klein, R.J.T., Wandel, J., 2000. An Anatomy of Adaptation to Climate Change and
10 Variability. Clim. Change 45, 223–251. doi:10.1023/A:1005661622966

Sridhar, V., 2013. Tracking the Influence of Irrigation on Land Surface Fluxes and Boundary Layer Climatology.
J. Contemp. Water Res. Educ. 152, 79–93. doi:10.1111/j.1936-704X.2013.03170.x

Tao, F., Yokozawa, M., Hayashi, Y., Lin, E., 2003. Changes in agricultural water demands and soil moisture in
China over the last half-century and their effects on agricultural production. Agric. For. Meteorol. 118,
15 251–261. doi:10.1016/S0168-1923(03)00107-2

Thompson, A.L., Gilley, J.R., Norman, J.M., 1993. A sprinkler water droplet evaporation and plant canopy
model. II. Model application. Trans. ASAE USA.

Thornton, P.., Thornton, M.., Mayer, B.., Wilhelmi, N., Wei, Y., Cook, R.., 2012. DAYMET: Daily Surface
Weather on a 1 km Grid for North America. 1980–2008. Oak Ridge Natl. Lab. Distrib. Act. Arch. Cent.
20 Oak Ridge T N Doi 10.

Tietje, O., Hennings, V., 1996. Accuracy of the saturated hydraulic conductivity prediction by pedo-transfer
functions compared to the variability within FAO textural classes. Geoderma 69, 71–84.
doi:10.1016/0016-7061(95)00050-X

Uddin, J., Smith, R.J., Hancock, N.H., Foley, J.P., 2013. Evaporation and sapflow dynamics during sprinkler
25 irrigation of cotton. Agric. Water Manag. 125, 35–45. doi:10.1016/j.agwat.2013.04.001

USBR, 2002. Interim comprehensive basin operating plan for for the Yakima Project Washington. US Dep. Inter.
US Bureu Reclam. Yakima Field Off. Yakima WA.

Vano, J.A., Scott, M.J., Voisin, N., Stöckle, C.O., Hamlet, A.F., Mickelson, K.E.B., Elsner, M.M., Lettenmaier,
D.P., 2010. Climate change impacts on water management and irrigated agriculture in the Yakima River
30 Basin, Washington, USA. Clim. Change 102, 287–317. doi:10.1007/s10584-010-9856-z

Waha, K., Müller, C., Bondeau, A., Dietrich, J.P., Kurukulasuriya, P., Heinke, J., Lotze-Campen, H., 2013.
Adaptation to climate change through the choice of cropping system and sowing date in sub-Saharan
Africa. Glob. Environ. Change 23, 130–143. doi:10.1016/j.gloenvcha.2012.11.001

Wei, H., Xia, Y., Mitchell, K.E., Ek, M.B., 2013. Improvement of the Noah land surface model for warm season
35 processes: evaluation of water and energy flux simulation. Hydrol. Process. 27, 297–303.
doi:10.1002/hyp.9214

Wheeler, T., Braun, J. von, 2013. Climate Change Impacts on Global Food Security. Science 341, 508–513.
doi:10.1126/science.1239402

Wilson, K., Goldstein, A., Falge, E., Aubinet, M., Baldocchi, D., Berbigier, P., Bernhofer, C., Ceulemans, R.,
40 Dolman, H., Field, C., Grelle, A., Ibrom, A., Law, B.E., Kowalski, A., Meyers, T., Moncrieff, J.,
Monson, R., Oechel, W., Tenhunen, J., Valentini, R., Verma, S., 2002. Energy balance closure at
FLUXNET sites. Agric. For. Meteorol., FLUXNET 2000 Synthesis 113, 223–243. doi:10.1016/S0168-
1923(02)00109-0

Wittwer, C., Hube, W., Schossig, P., Wagner, A., Kettner, C., Mertins, M., Rittenhofer, K., 2001. ColSim-a new
45 simulation environment for complex system analysis and controllers, in: Proc. of the 7-Th IBPSA
Conference. pp. 237–244.

Yonts, C.D., Kranz, W.L., Martin, D.L., 2000. Water Loss from above-canopy and in-canopy sprinklers. Cooperative Extension, Institute of Agriculture and Natural Resources, University of Nebraska-Lincoln.

Yorgey, G, Rajagopalan, K, Chinnayakanahalli, K, Brady, M, Barber, M. E, Nelson, R., Stockle, C. O, Kruger, C. E, Dinesh, S., Malek, K, Yoder, J., Adam, J. C, 2011. Columbia River Long-Term Supply and Demand Forecast [WWW Document]. URL http://www.ecy.wa.gov/programs/wr/cwp/forecast/forecast.html (accessed 4.15.14).

Yorgey, G.G., Rajagopalan, K., Chinnayakanahalli, K., Brady, M.P., Barber, M.E., Nelson, R., Stockle, C.O., Kruger, C.E., Dinesh, S., Malek, K., 2011. Columbia River Basin Long-Term Water Supply and Demand Forecast. Wash. State Legis. Rep.

Yuan, F., Xie, Z., Liu, Q., Yang, H., Su, F., Liang, X., Ren, L., 2004. An application of the VIC-3L land surface model and remote sensing data in simulating streamflow for the Hanjiang River basin. Can. J. Remote Sens. 30, 680–690. doi:10.5589/m04-032

Zagona, E.A., Fulp, T.J., Shane, R., Magee, T., Goranflo, H.M., 2001. Riverware: A Generalized Tool for Complex Reservoir System Modeling1. JAWRA J. Am. Water Resour. Assoc. 37, 913–929. doi:10.1111/j.1752-1688.2001.tb05522.x

Zeng, X., Drewniak, B.A., Constantinescu, E.M., 2013. Calibration of the Crop model in the Community Land Model. Geosci Model Dev Discuss 6, 379–398. doi:10.5194/gmdd-6-379-2013

Zhao, G., Bryan, B.A., King, D., Luo, Z., Wang, E., Bende-Michl, U., Song, X., Yu, Q., 2013. Large-scale, high-resolution agricultural systems modeling using a hybrid approach combining grid computing and parallel processing. Environ. Model. Softw. 41, 231–238. doi:10.1016/j.envsoft.2012.08.007

Tables

Table 1- Impacts of climate change on crop yield, as discussed by Kurukulasuriya and Rosenthal, 2003; Leakey et al., 2009; Reilly, 2002; Rosenzweig et al., 2001; and Rowan et al., 2011.

Impact factors	Mechanism of impact	Direction of impact on yield	References
CO_2 concentration	More efficient photosynthesis	+	Kurukulasuriya and Rosenthal, 2003; Leakey et al., 2009
	Crop water use efficiency	+	Leakey et al., 2009
	Nutrient use efficiency	+	Ainsworth and Rogers, 2007
Temperature	Crop growing period length	-	Kurukulasuriya and Rosenthal, 2003;

			Dukes and Mooney, 1999
	Planting date	+/-	Parry et al., 2005
	Timing and rate of crop growth and phenology	+/-	Tao et al., 2003
	Pest and weed growth and development	-	Kurukulasuriya and Rosenthal, 2003
	Fruit quality	-	
Humidity	Changes in stomata functioning	+	Leakey et al., 2009; Nijs et al., 1997
Precipitation	Changes in soil moisture and irrigation water resources	-/+	Rowan et al., 2011
Frequency of climate extreme events (droughts and heat waves)	Crop productivity	-	Rosenzweig et al., 2001
Temperature + Precipitation	Water availability for irrigated agriculture over snow dominant basins	-	Adam et al., 2009; Barnett et al., 2005; Elsner et al., 2010; Mote et al., 2005

5   **Table 2 – Two flux tower stations used for evaluation of the VIC-CropSyst. Nebraska site is irrigated using a center pivot system and the Illinois flux tower station is rain-fed.**

Stations	State	Irrigated	Cropping pattern	Period	Soil type	Average Precipitation (mm)	Average Temperature (°C)

| Mead Irrigated | Nebraska (NE) | Yes | Corn | 2001-2008 | Silty clay loam | 789 | 10.1 |
| Fermi National Laboratory | Illinois (IL) | No | Corn/ Soybean | 2002-2007 | Silty clay loam | 929 | 9.2 |

Table 3–Calibration parameters used for VIC-CropSyst over the two study sites (columns 5 to 6) and over the Columbia River Basin (CRB). Column 3 represents the ranges of these parameters used for the sensitivity studies.

parameter	Description	Range	CRB	NE	IL
bs	Adjusts partitioning of precipitation to runoff and infiltration	0.001-0.4	0.1-0.3	0.2	0.31
Ds	Base flow parameter- fraction of base flow parameter	0.001-0.99	0.001-0.88	0.005	0.72
Ws	A fraction of maximum base flow indicating where the base flow curve starts	0.4-0.9	0.51-0.91	0.8	0.53
Ds-Max	Maximum daily base flow generation	0.1-30	0.2-10	10	28.61

Table 4- Estimated calendar days correspond to each of the growing stages in two study sites. Some of the information is from references listed for each site.

	crop type	planting	emergence	peak LAI	flowering	filling	maturity	reference
NE	corn	127	140	195	205	225	255	(Sakamoto et al., 2010)
IL	corn	125	137	200	208	212	250	(Nafziger, 2013)

5 **Table 5- Summary of adaptation strategies that can be handled by VIC-CropSyst: the modeling platform is able to simulate the impacts of local decisions on agricultural productivity and at the same time capture the impacts of these decisions on regional land-atmospheric interactions and hydrological water availability in the basin.**

	Adaptation strategy	Timing*	Duration**
1	**Crop-related adaptation strategies**		
	i- Crop choice and rotation	R*	L
	ii- Cropping acreage and location of cropping activities	R and A	L
	iii- Timing of planting and harvesting date	C and A	T
	iv- Using new variety of the same crop	R	L
2	**Long term strategic water management adaptations**		
	i- Irrigation system or nozzle	R and A	L
3	**Seasonal adaptations to respond to altered water deficit and temporal availability of water**		
	i- Deficit irrigation magnitude	C	T
	ii- Deficit irrigation timing in a season	C	T
4	**Short term tactical adaptation to minimize the impacts of heat stress**		
	i- Supplementary/over irrigation		T
	ii- Irrigation frequency	C	T
	iii- Irrigation intensity	C	T

*According to Smit and Skinner (2002), the timing of adaptation decision can be A-Anticipatory (proactive), C-Concurrent (during) or R-Responsive (reactive)

10 **Duration of adaptive actions can be short term-tactical (T) and long-term strategic (L)(Smit and Skinner, 2002)

15 **Figures**
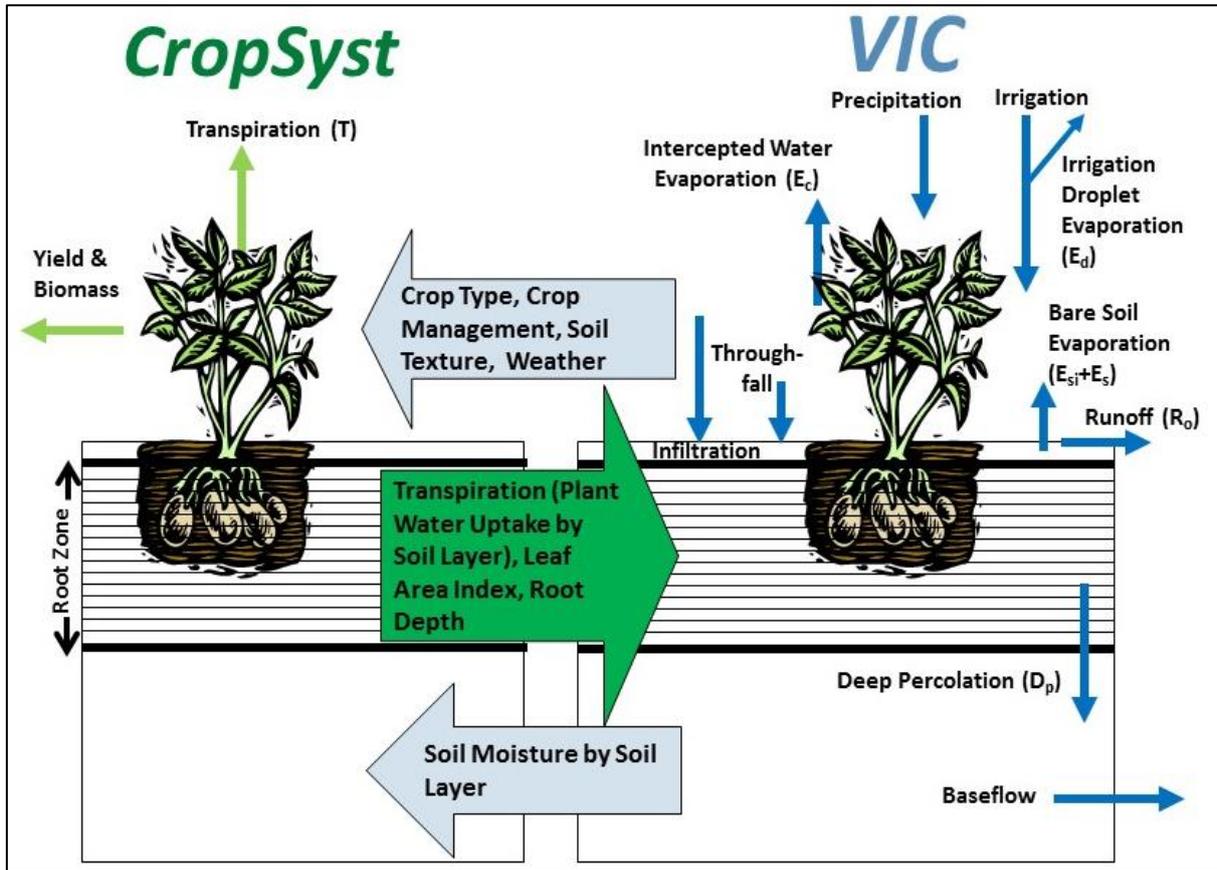
Figure 1- This schematic shows how VIC and CropSyst are coupled. VIC provides the availability of water and energy to CropSyst. CropSyst uses this information to grow the crop, produce biomass and yield, and simulate transpiration. CropSyst passes back the information that is needed by VIC (e.g., the distribution of transpiration uptake in different soil layers, LAI, and root depth) to simulate the hydrologic and energy cycle and the scheduling of irrigation.
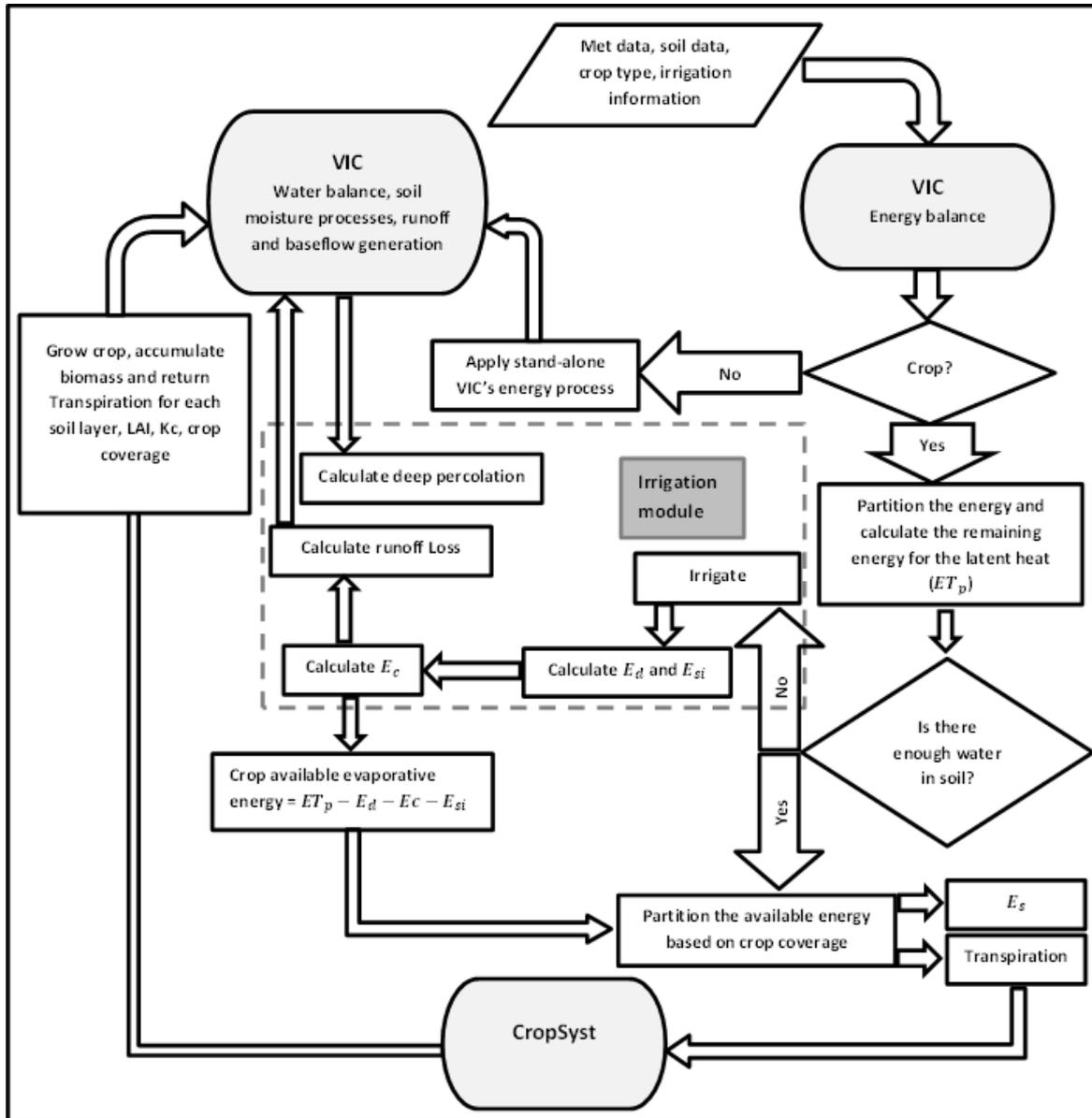
Figure 2 – Algorithm used in VIC-CropSyst to partition available energy into different evaporative components. The energy and water balances are handled by the VIC model. CropSyst receives the amount of energy available for transpiration and the availability of water in the soil to determine crop water uptake. VIC needs actual transpiration in different layers of the soil to close the water cycle. Communication between the two models happens for every time-step.
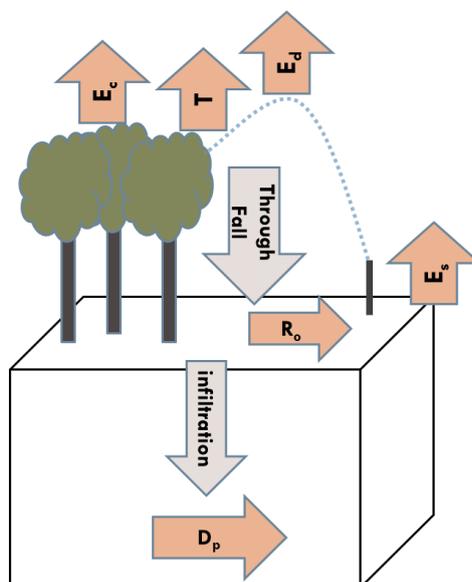
Figure 3 – Pathways of irrigation water loss simulated in the irrigation module. E_d: evaporation from irrigation droplets, E_c: evaporation from irrigation water intercepted by canopy, E_s: evaporative loss from soil surface, D_p: Deep percolation loss and R_o: Irrigation runoff loss. The efficiency of irrigation water is calculated by considering total applied water and all loss terms.

$$Ef = 100 \times \left(1 - \frac{E_d + E_s + E_c + R_o + D_p}{total\ irrigation\ water}\right)$$
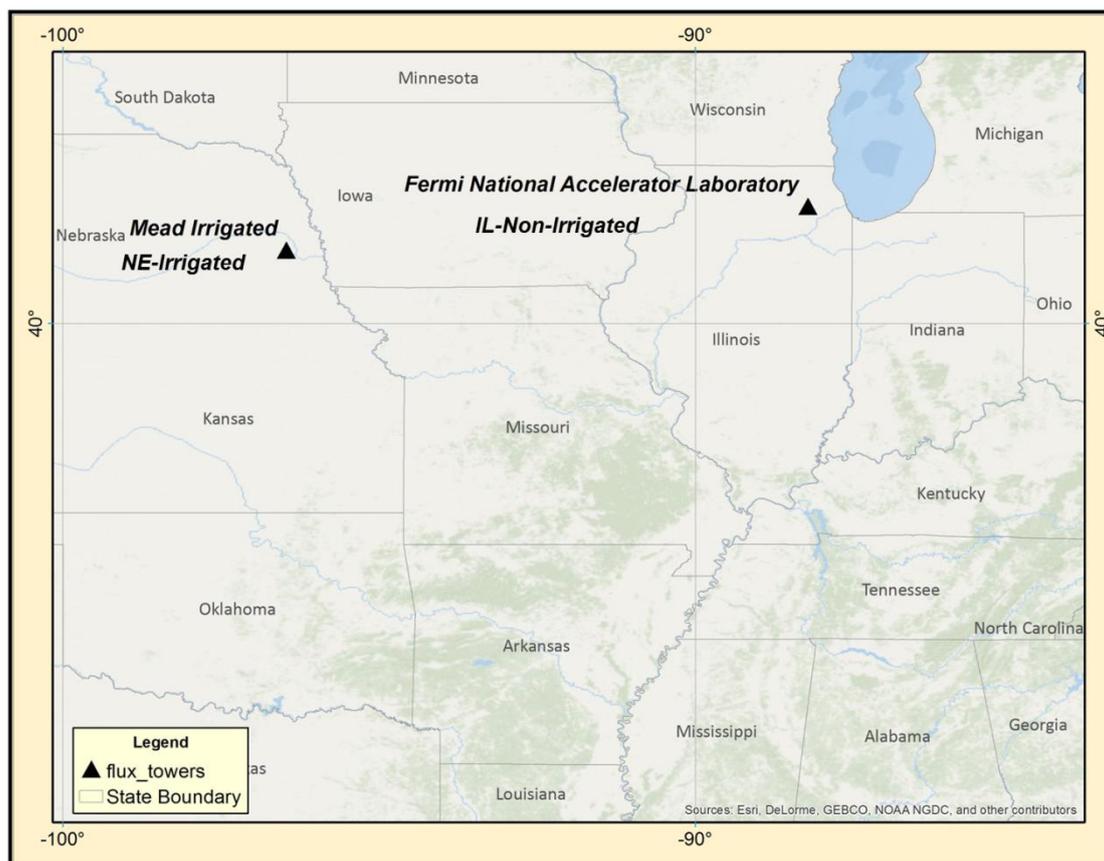
Figure 4 - Location of the two flux tower sites in the U.S. two flux tower sites are all in agricultural fields. Mead irrigated site (NE) is located in the Nebraska; Fermi National lab site (IL) is located in the Illinois; NE is irrigated and the IL is a non-irrigated agricultural site.
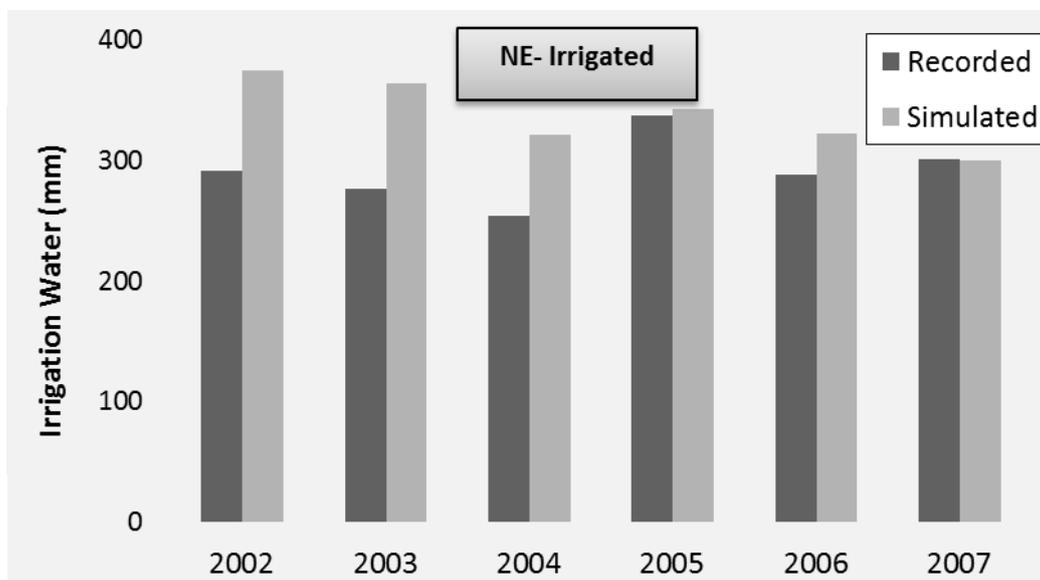
Figure 5 - Simulated versus recorded irrigated water in an irrigated corn field at the NE flux tower site.
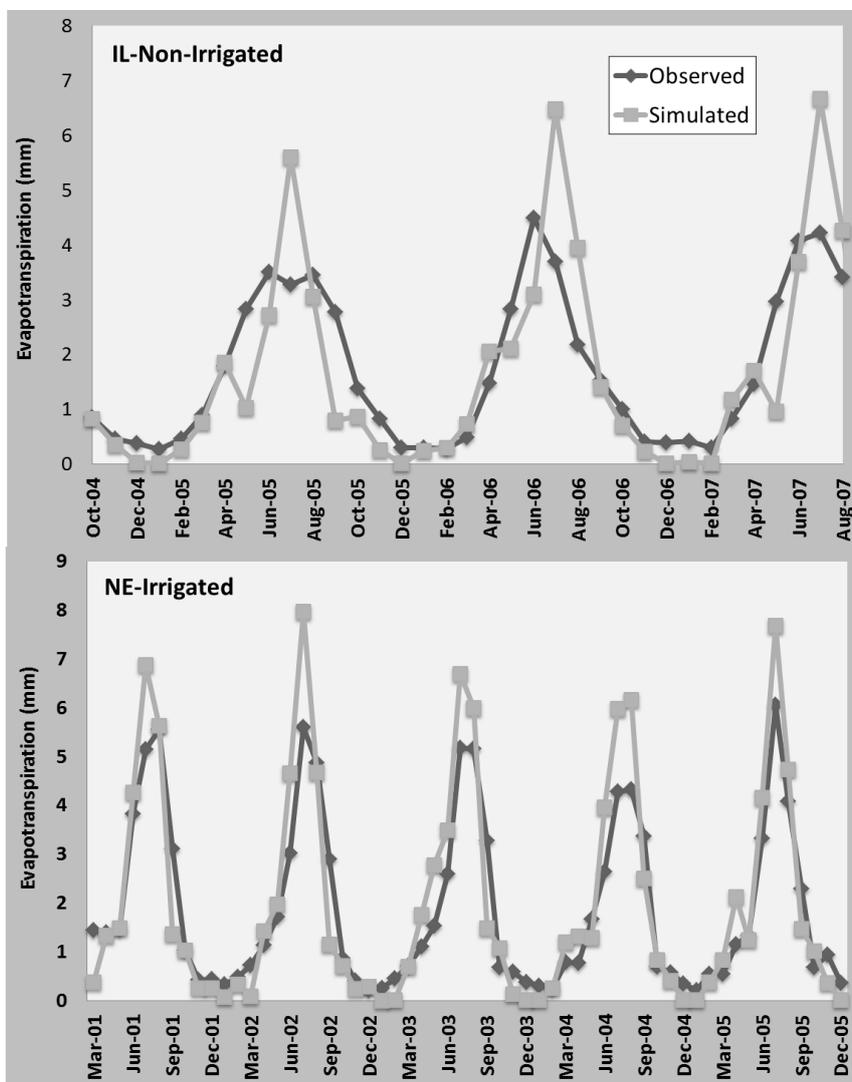
Figure 6- Comparison of simulated and observed corn evapotranspiration (ET) at two flux tower sites located in NE and IL. The NE site is irrigated while IL is a non-irrigated field.
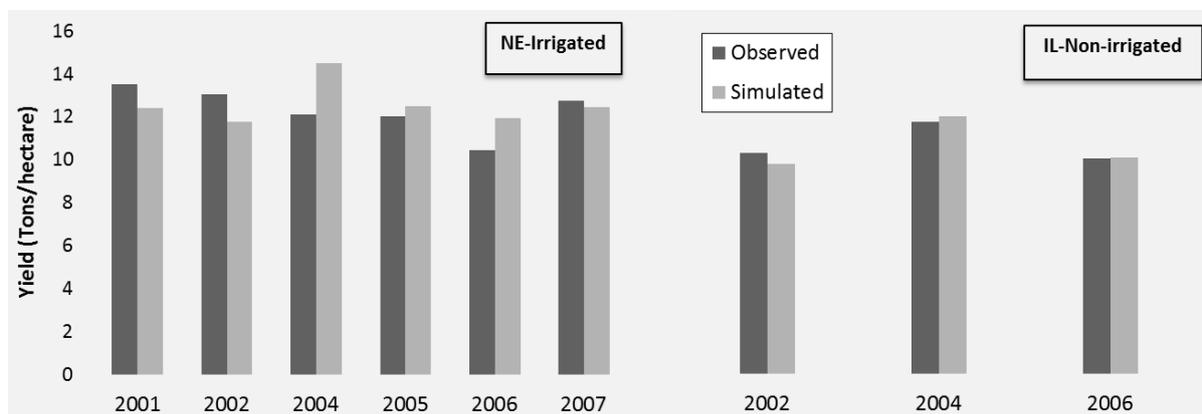
Figure 7 – Comparison of simulated and observed corn yield at two flux tower sites for the years during which yield observations were taken.
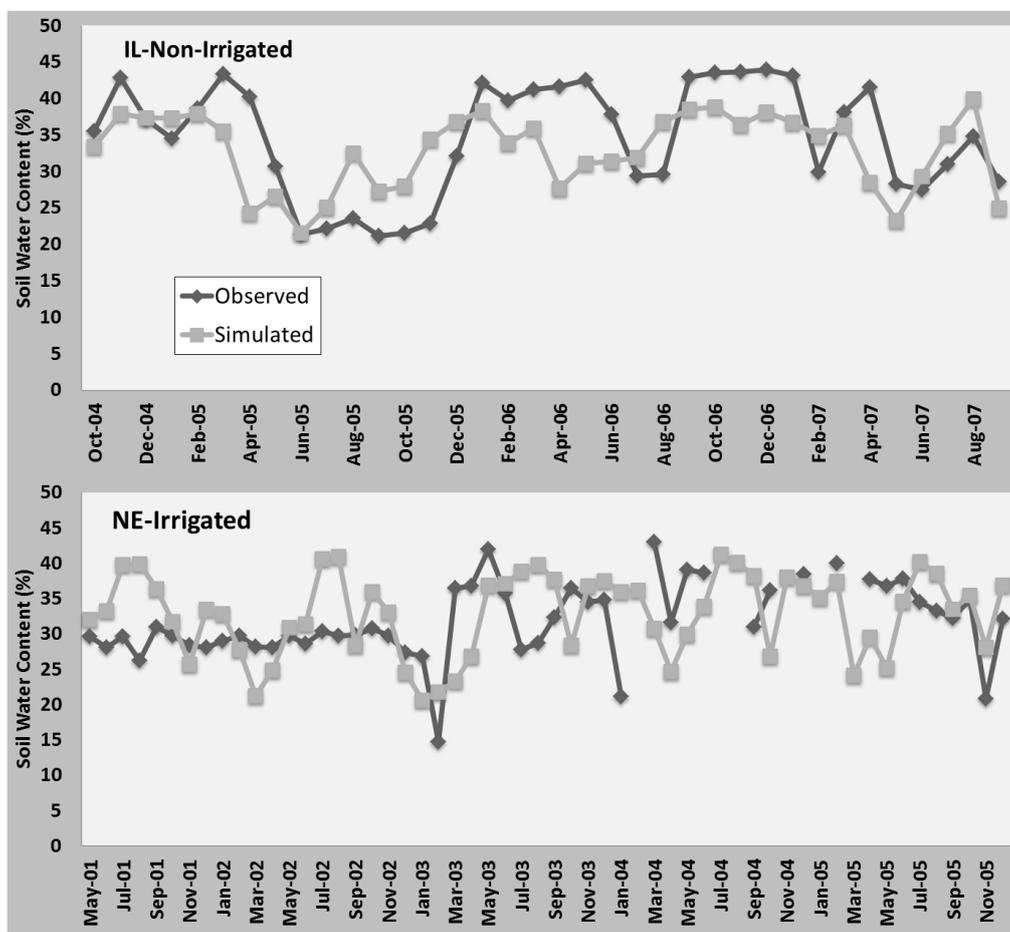
Figure 8- Comparison of simulated and observed soil moisture at the flux tower sites located in IL (top) and NE (bottom).
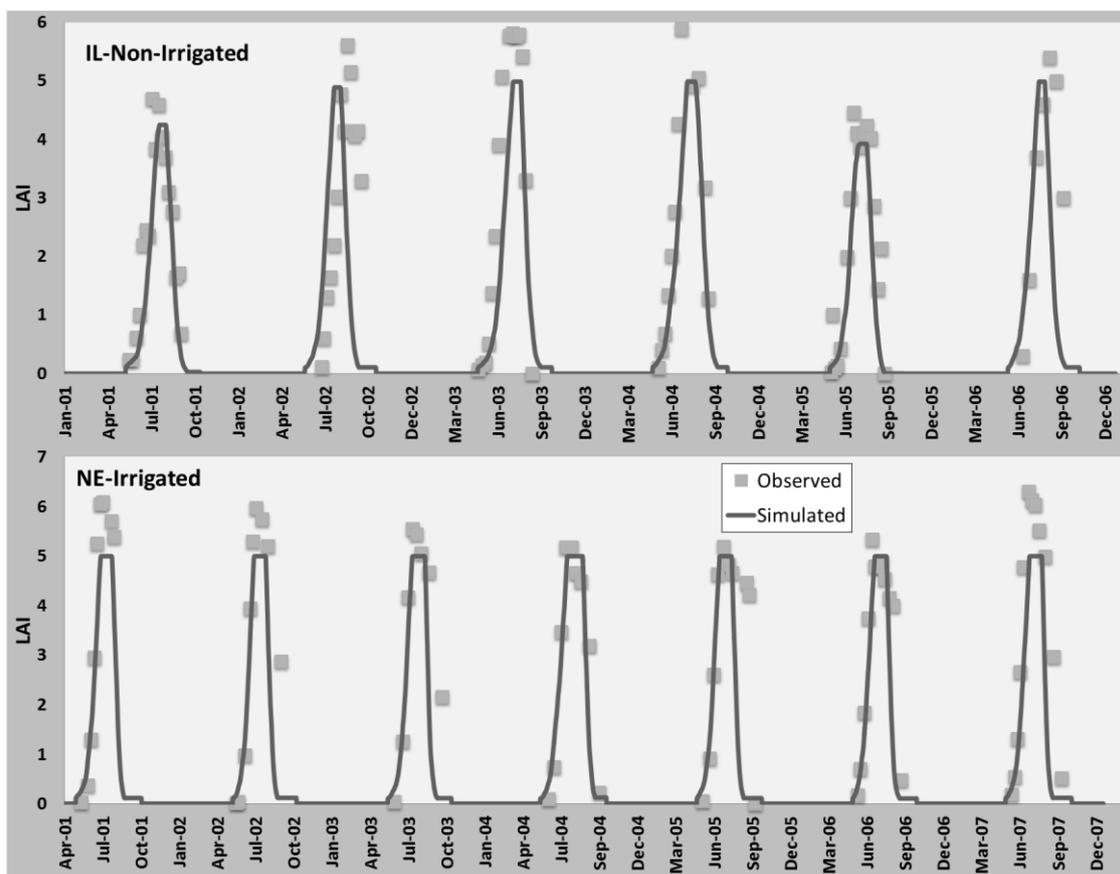
Figure 9- Comparison of simulated and observed corn LAI over two flux tower sites located in IL (top) and NE (bottom).
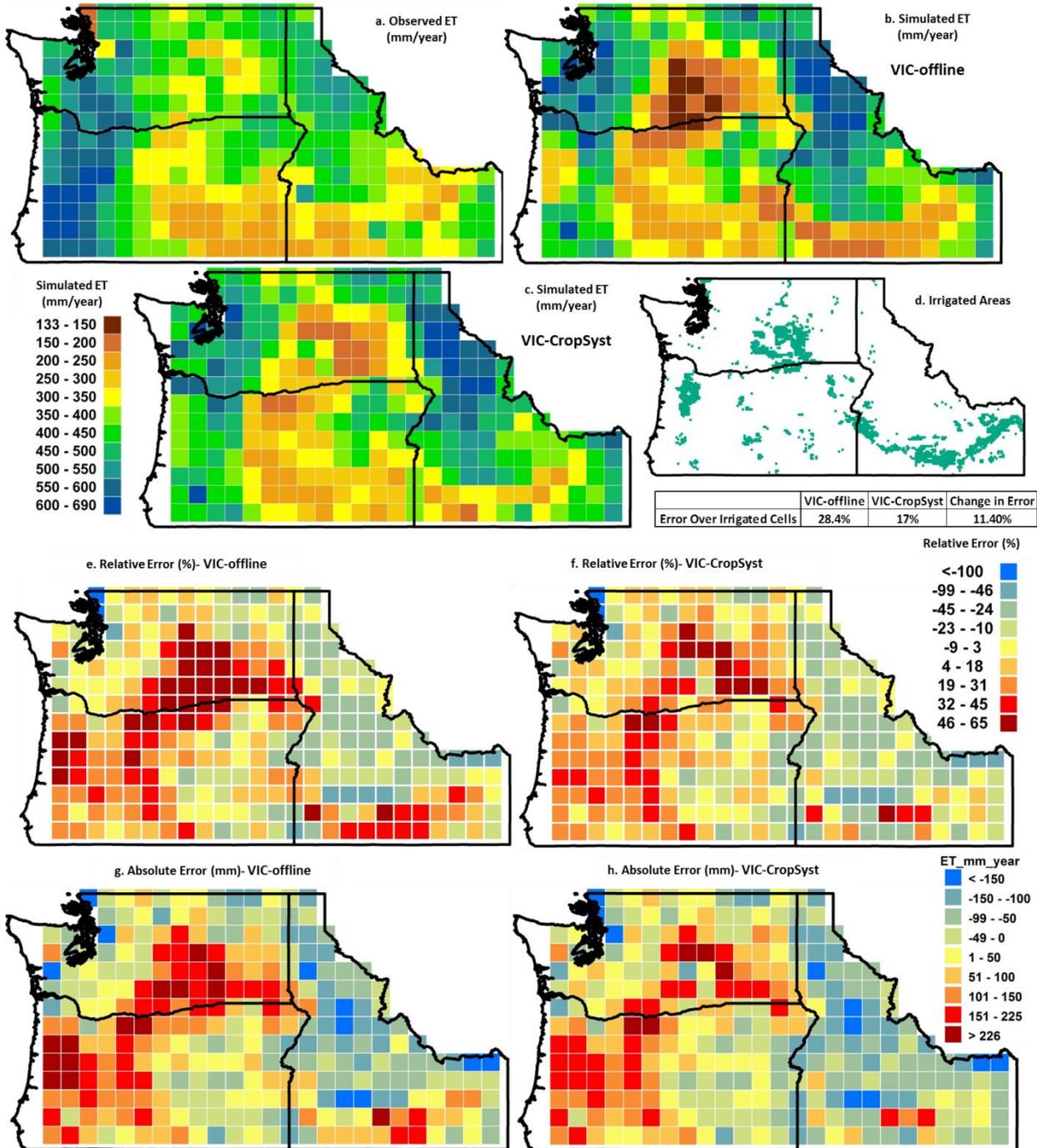
Figure 10 – Comparison of simulated and empirically-derived ET over the U.S. Pacific Northwest. The simulation and observation period is 1982-2008.
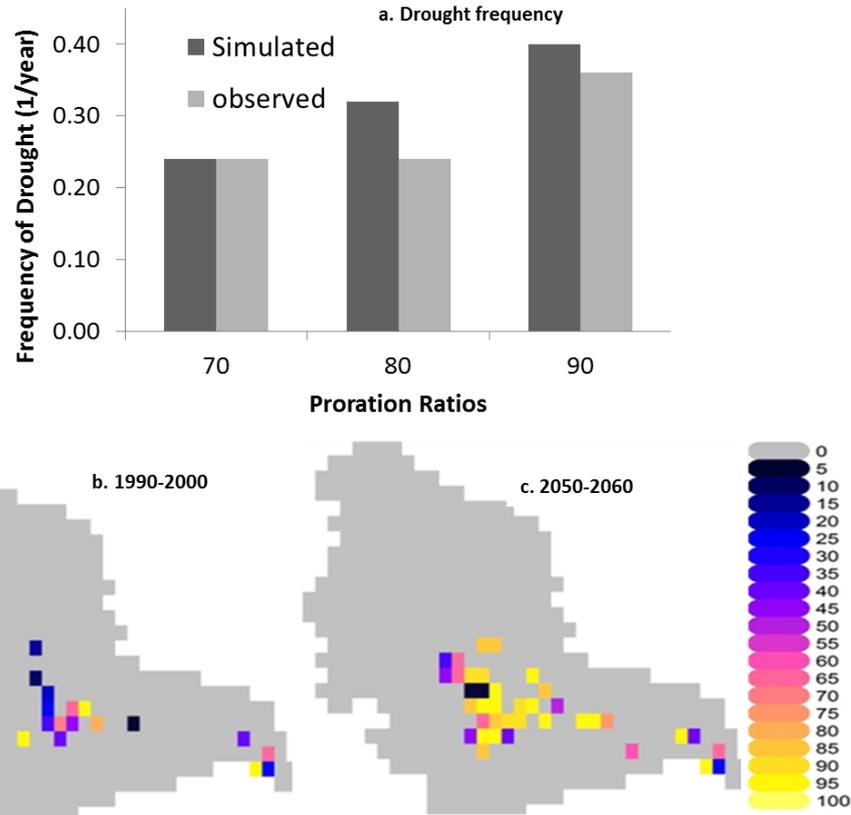
Figure 11- Regional application of VIC-CropSyst in conjunction with a river system model (YAK-RW; (Hubble, 2012; Zagona et al., 2001) and an economic model to simulate historical (1981-2006) drought frequency (panel a), when the percentage of the water right allocated for the irrigation season (i.e., proration rate) is lower than 70%, 80% and 90%. Panels b and c (Malek, K et al., 2016) show the percentage of farmers (perennial crop growers) who invest in new efficient irrigation technologies in response to simulated droughts during the two decades of 1990-2000 (panel b) and 2050-2060 (panel c).