CliCrop: a Crop Water-Stress and Irrigation Demand Model for an Integrated Global Assessment Modeling Approach

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This report is one of a series intended to communicate research results and improve public understanding of climate issues, thereby contributing to informed debate about the climate issue, the uncertainties, and the economic and social implications of policy alternatives. Titles in the Report Series to date are listed on the inside back cover.

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CliCrop: a Crop Water-Stress and Irrigation Demand Model for an Integrated Global Assessment Modeling Approach

Charles Fant[1], Arthur Gueneau[2], Kenneth Strzepek[2†], Sirein Awadalla[2], William Farmer[2], Elodie Blanc[2], and C. Adam Schlosser[2]

Abstract

This paper describes the use of the CliCrop model in the context of climate change general assessment modeling. The MIT Integrated Global System Model (IGSM) framework is a global integrated assessment modeling framework that uses emission predictions and economic outputs from the MIT Emission Prediction and Policy Analysis (EPPA) model and earth system modeling predictions from the IGSM to drive a land system component, a crop model (CliCrop) and a Water Resource System (WRS) model. The global Agriculture and Water System are dependant upon and interlinked with the global climate system. As irrigated agriculture provides 60% of grains and 40% of all crop production on 20% of global crop lands and accounts for 80% of global water consumption, it is crucial that the agricultural-water linkage be properly modeled. Crop models are used to predict future yields, irrigation demand and to understand the effect of crop and soil type on food productivity and soil fertility. In the context of an integrated global assessment, a crop water-stress and irrigation demand model must meet certain specifications that are different for other crop models; it needs to be global, fast and generic with a minimal set of inputs. This paper describes how CliCrop models the physical and biological processes of crop growth and yield production and its use within the MIT Integrated Global System Model (IGSM) framework, including the data inputs. This paper discusses the global data bases used as input to CliCrop and provides a comparison of the accuracy of CliCrop with the detailed biological-based crop model DSSAT as well as with measured crop yields over the U.S. at the country level using reanalyzed weather data. In both cases CliCrop performed well and the analysis validated its use for climate change impact assessment. We then show why correctly modeling the soil is important for irrigation demand calculation, especially in temperate areas. Finally, we discuss a method to estimate actual water withdrawal from modeled physical crop requirements using U.S. historical data.

Contents

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1. INTRODUCTION

Crop models are used to predict future yields, irrigation demand and to understand the effect of crop and soil type on food productivity and soil fertility. Many crop models have been developed over the last thirty to forty years in response to new research and more accessible computer technology. While crop simulators continue to be used primarily for academic purposes, farmers and policy makers are beginning to trust and use them. Here we describe the use of CliCrop model first introduced in Fant (2009) in the context of climate change general assessment modeling. One such application is as a component of the MIT Water Resource System model (Strzepek *et al.*, 2010).

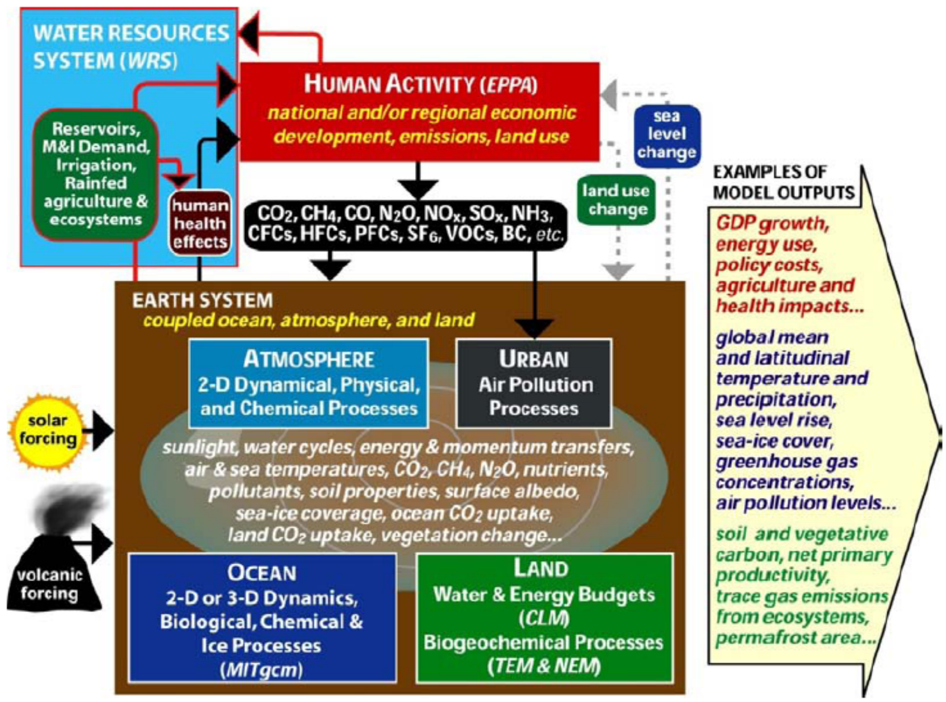

Figure 1. The IGSM Framework (Strzepek *et al.*, 2010).

Figure 1 describes the MIT Integrated Global System Model (IGSM) framework, with a particular highlight on the Water Resource System (WRS). Using emission predictions and economic outputs from the MIT Emission Prediction and Policy Analysis (EPPA) model (Paltsev *et al.*, 2005) and earth system modeling predictions form the IGSM (Sokolov *et al.*, 2005), the WRS module describes climate impacts on water demand from industrial, domestic and agricultural sectors as described in **Figure 2**. This paper describes the agriculture component of the system, which is largely based on CliCrop.

In the context of an integrated global assessment, a crop water-stress and irrigation demand model must meet certain specifications that are different for other crop models (used, for example, for yield prediction or irrigation planning at the field scale). First, we need the model to output a monthly irrigation demand (later used in the Water Simulation Model) and a rainfed yield factor (that quantifies the effects of water-stress on crop yield, and that is used in calculating the

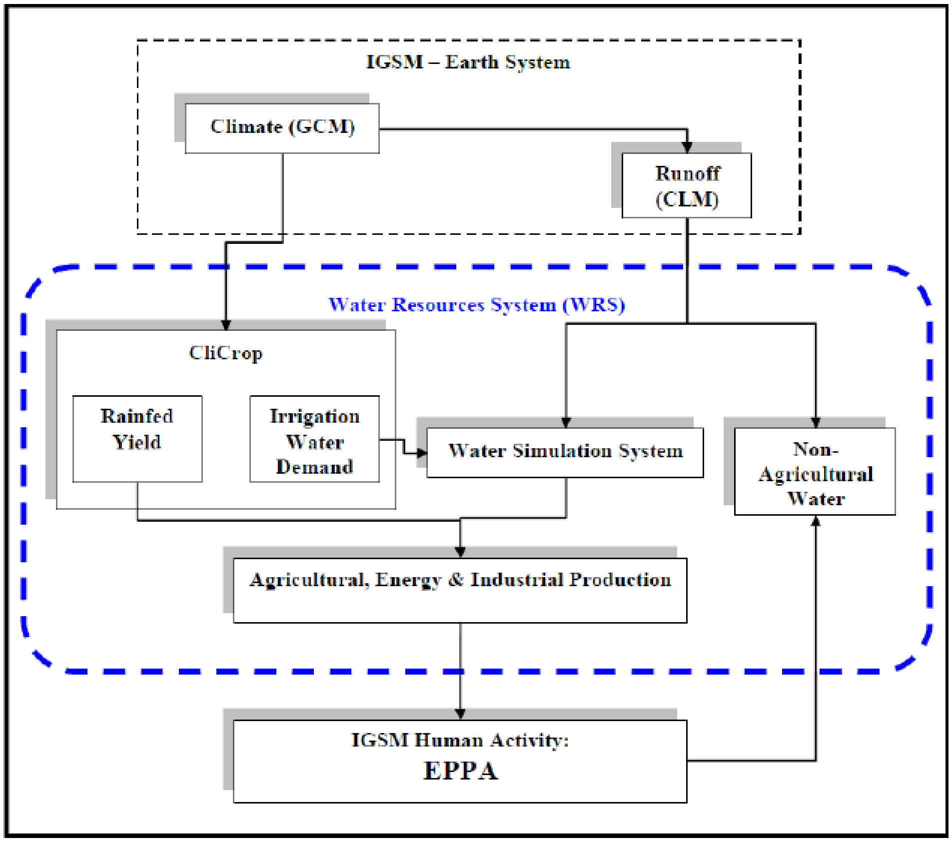

Figure 2. The WRS framework (Strzepek *et al.*, 2010).

agricultural output). Second, as we will apply the model globally, we need it to be able to run on a large grid cell and to be as computationally fast as possible. Finally, as it is hard to predict how crop characteristics will change in the future, we want this model to be a generic crop model and have a minimal set of inputs.

The biggest question surrounding crop models is whether they can reliably predict future yields and irrigation demands. Like most analysis of physical, chemical or biological processes, model accuracy is heavily dependent on input data. For crop studies these inputs include soil type, crop type and weather, which have strong effects on crop production. Soil parameters can be measured in a field one point at a time, but soil properties can change drastically on a small scale, both horizontally and vertically. The growth of different crop types, which is based on complicated biological and chemical processes, also varies by genotype, region, and the individual plant. Weather, because of its chaotic behaviour and dependence on both large-scale and small-scale changes in land and atmospheric conditions, also continues to be difficult to predict. In spite of these difficulties, research in crop simulation continues because of human dependence on cultivated food, and, in our case, the need to adapt agricultural production to climate change.

There are many existing crop models, each built to study a specific range of issues. Each models structure also depends on the inputs available and the accuracy that is required. For example CROPWAT (Smith, 1992), a model developed by the Food and Agriculture Organization of the United Nations, is a very simple crop model without soil modeling. It has been designed to plan irrigation schedules for use by farmers in developing countries; specifically in arid to semi-arid regions. CROPWAT thus requires a limited set of inputs, represents no vertical differences in soil moisture, and assumes that the soil moisture cannot exceed field capacity. It simulates water stress on crops on a monthly time-step, ignoring any nutrient stresses, solar stresses, or effects of daily precipitation patterns.

A much more sophisticated model is the Decision Support for Agrotechnology Transfer (DSSAT, Jones *et al.* (2003)) developed by the International Benchmark Sites Network for Agrotechnology Transfer. The purpose of DSSAT is to simulate as accurately as possible all the processes involved in crop growth, and it is currently one of the most widely used models in the field (Rivington and Koo, 2011). It has been calibrated for many crops and crop species using real field data from around the world. It has been used to study the impact of transferring production technology from one location to others where soils and climate were different (Jones *et al.*, 2003). The model consists of very detailed soil, crop, weather and management modules that require very accurate and numerous inputs, all of which tend to vary dramatically from one field to another.

The model we describe here, CliCrop, has been designed to explore the effect of changing daily precipitation patterns, caused by anthropogenic climate change, on crop yields and irrigation water demand. As most global climate models predict a change in temporal precipitation pattern and an increase of extreme events (Dore, 2005), CliCrop had to be a daily crop model. However, since it was developed to study agriculture on a global or continental scale for an integrated assessment, it is a generic crop model, which is not specific to any region or climate.

Originally CliCrop was to be a modification of CROPWAT with the goal of maintaining the same minimal inputs required by the earlier model while achieving more accurate yield estimates and irrigation demand. The reason for trying to keep a low number of inputs is that it is very difficult to predict future crop characteristics and how they will evolve under changing economic and climatic contexts. As CliCrop developed, however, some new features were added. For example, in order to model the negative effects of waterlogging (a pre-eminent problem in Africa) a dynamic soil profile needed to be added. Many other crop models were reviewed for guidance, and some of their methods were also borrowed for the development of CliCrop.

In Section 2, we provide an overview of the CliCrop model, including its legacy from previous models. In Section 3, we compare CliCrop against DSSAT to test the model performance against a more detailed formulation. In Section 4, we compare CliCrop water stress with USDA historic data for different crops and location in the United States. In Section 5, we highlight the importance of modeling soils to calculate the irrigation demand by comparing CliCrop irrigation demand to the widely used rainfall-evapotranspiration method. Finally, in Section 6, we compare CliCrop irrigation demand for the U.S. to the USGS water withdrawal survey statistics and provide a method to estimate the water withdrawn from streams and aquifers using CliCrop output.

2. CLICROP MODEL

2.1 Overview of the Model

The version of CliCrop described here is derived from the original CliCrop model (Fant, 2009). In CliCrop, the effects of climate on crop production are modeled by estimating water stress on crops. Water stress is related to the estimate of evapotranspiration (ET), and more specifically, the extent by which the actual ET (AET) falls short of the crop demand ET (PET). In CliCrop a yield ratio (YR) is reported as a measure of water stress. This yield ratio represents a ratio of actual yield to a theoretical maximum yield, and is based on the ratio of AET to PET. The theoretical maximum yield is the yield obtained in the complete absence of water stress. Four yield ratios are calculated, one for each of the four development stages (d): initial, crop development, mid-season, and late season (Allen *et al.*, 1998). YR is weighted using a yield response factor (K), as follows. The following equation was also used in the CROPWAT model (Allen *et al.*, 1998).

$$YR_d = 1 - K_d \left(1 - \frac{AET_d)}{PET_d} \right) \tag{1}$$

The final reported yield ratio (YR) is calculated using the multiplicative model proposed by Rao *et al.* (1988).

$$YR = \Pi_d [YR_d] \tag{2}$$

Here, Y represents the ratio of actual yield to the theoretical maximum yield due to water stress, and therefore is unitless. This value is reported by CliCrop for each year of the simulation.

A full soil moisture accounting model is used to estimate AET and PET, calculated on a daily time-step. Soil moisture is calculated using a bucket-type scheme similar to the method used in the SWAT model (Neitsch *et al.*, 2005). **Figure 3** shows a schematic of the soil moisture modeling process.

First, the model uses the soil properties of the top layer and precipitation amount to calculate the infiltration using a version of the USDA Curve Number method (U.S. Department of the Interior, 1993). The runoff is considered lost and the infiltration is added to the first layer. For all layers, starting with the first, actual ET is calculated and removed from the layer. Then, if enough water is remaining, the first layer is filled from wilting point to field capacity and a portion of the moisture over field capacity is allowed to percolate to the layer below. The model then checks if the soil moisture in the layer is above saturation. If so, the model adds the over-saturated moisture to the layer above until all moisture has found space. If the top layer is saturated and excess soil moisture remains, the excess is considered additional runoff and is lost. At the bottom soil layer, the model calculates the amount of moisture lost to the semi-impervious layer, or deep percolation. The model then checks once more for any layer whose soil moisture is above saturation. Finally, the model calculates the upward flow of soil moisture using the method described in Ritchie (1998).

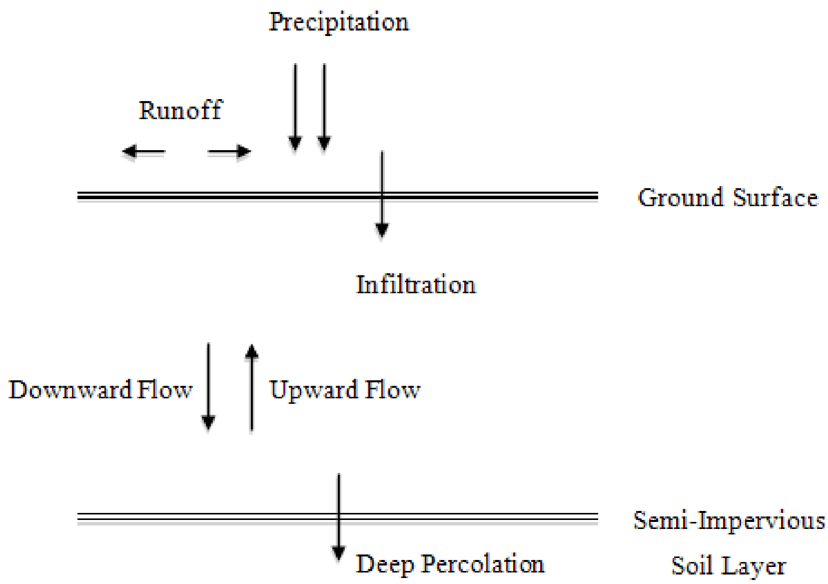

Figure 3. Schematic of the CliCrop Model Procedure.

2.2 Dormant Season

During the dormant season the above procedure is followed except that, since there is no transpiration, only evaporation is taken from the soil profile. Evaporation is removed from the top 12.5 cm of the soil profile using the following equations (Allen *et al.*, 1998). First, total evaporable water (TEW) is calculated as:

$$TEW = (FC - 0.5WP) \cdot delZ \tag{3}$$

where FC and WP are the field capacity and wilting point, respectively, of the soil layer (unitless) and $delZ$ is the thickness of the soil layer (mm). Then, the limiting coefficient of evaporation (Kr), a unitless value between 0 and 1, is calculated as:

$$K_r = \frac{SM_{t-1} - 0.5 \cdot WP \cdot delZ}{(1 - pe) \cdot TEW} \tag{4}$$

where SM_{t-1} is the soil moisture of layer l from the previous day (mm) and pe is the fraction of TEW for maximum evaporation (unitless). Then the actual evaporation ($ETSA$) removed from the layer, in mm, is calculated as:

$$ETSA = (ET_0 \cdot asm) \cdot K_r \tag{5}$$

where ET_0 is the reference ET (mm) and asm is the antecedent moisture coefficient, the fraction of reference ET that comes from evaporation. Reference ET is the rate of evapotranspiration that a hypothetical reference grass would produce as defined by Allen *et al.* (1998). CliCrop uses the Daily Modified Hargreaves equation to calculate Reference ET (Farmer *et al.*, 2011).

2.3 Growing Season

2.3.1 Actual Evapotranspiration and Crop Phenology

The dual crop coefficient method is used to calculate AET, meaning that transpiration and evaporation are calculated separately during the growing season. This method is based on a method described in Allen *et al.* (1998). The basal crop coefficient (Kcb) is used in this method (as opposed to the crop coefficient, Kc, used in many crop models (including CROPWAT). The calculation procedure used in CliCrop is described below in detail.

The crop height (h) is estimated based on the maximum crop height given in Allen *et al.* (1998) multiplied by a ratio of the crop specific demand of day t (Kcb, t) and the maximum crop specific demand:

$$h = h_{max} \frac{K_{cb\,t}}{max K_{cb}} \tag{6}$$

The crop height does not decrease, it only increases. $K_{c\,max}$ (which represents an upper limit on the evaporation or transpiration from any cropped surface) is calculated based on equation 72 in Allen *et al.* (1998), and shown below,

$$K_{c\,max} = max\left(\left\{1.2 + \left[0.04\left(RH_{min} - 45\right)\right]\left(\frac{h}{3}\right)^{0.3}\right\}, \left\{K_{cb} + 0.05\right\}\right) \tag{7}$$

where RH_{min} is the potential minimum relative humidity for the growing season calculated using a climatic classification (Lobo *et al.*, 2005).

KC_{max} is then used to calculate the fraction of the ground covered by vegetation (f_c).

$$f_c = \left(\frac{K_{cb} - K_{c\,min}}{K_{c\,max} - K_{C\,min}}\right)^{(1+0.5h)} \tag{8}$$

where $K_{c\,min}$ is the minimum K_c for dry bare soil, estimated to be 0.175 based on Allen *et al.* (1998). The fraction of soil surface that is moist, and therefore exhibits moist soil evaporation (f_{ew}) is calculated using the following equation:

$$f_{ew} = min\left(1 - f_c, f_W\right) \tag{9}$$

where f_W is taken from Table 20 in Allen *et al.* (1998), considering that no irrigation is used. Then a dimensionless evaporation reduction coefficient, K_r, is calculated using the following equation:

$$K_r = \frac{TEW - D_{e,i-1}}{TEW - REW} \text{ for } D_{e,i-1}\ REW \tag{10}$$

where REW is the readily evaporable water and is calculated using Table 19 in Allen *et al.* (1998). $D_{e,i-1}$ is the cumulative depth of evaporation, calculated from the previous day. The soil evaporation coefficient, K_e, is calculated using the following:

$$K_e = K_r\left(K_{c\,max} - K_{cb}\right) \tag{11}$$

The ET demand (PET) is the calculated as:

$$PET = \frac{(K_{cb} + K_e)\, ET_0}{nlsr} \tag{12}$$

This leads to the calculation of actual ET (AET) removed from the soil layer using the following steps. First, the soil water depletion fraction (p) is calculated as:

$$p = p_{tab} + 0.04\,(5 - PET) \tag{13}$$

where, p_{tab} is the soil water depletion fraction for the no stress case. Then the total available water (TAW) is calculated using the following equation:

$$TAW = delZ\,(FC - WP) \tag{14}$$

Then the limiting coefficient (K_s) is calculated as:

$$K_S = \frac{SM_{t-1} - WP \cdot delZ}{(1-p) \cdot TAW} \tag{15}$$

And finally, actual ET is calculated as:

$$AET = K_s \cdot PET \tag{16}$$

2.3.2 Soil Layer Percolation

Once ET is removed from the soil layer, percolation from the layer above is added based on the soil water excess equation used in SWAT (Neitsch *et al.*, 2005). This method is used for both the dormant and growing seasons. First the travel time (TT) is calculated as:

$$TT = \frac{SAT - FC}{HC} \cdot delZ \tag{17}$$

where, SAT is the moisture content at saturation. Then the amount of moisture that travels to the layer below ($Perc$) is calculated using the following:

$$Perc = (SM - FC) \cdot \left[1 - exp\left(\frac{-\Delta t}{TT}\right)\right] \tag{18}$$

where, HC is the hydraulic conductivity (mm/hr), SM is the soil moisture of the given timestep, Δt is the length of one time step (hrs). Soil moisture is moved to the layer below only if the soil layer exceeds field capacity.

After ET and percolation are removed, if the layer's soil moisture exceeds saturation, any soil moisture above saturation is added to the layer above until either all of the soil moisture has been placed or ponding occurs at the soil surface. Any ponding is considered lost (treated as runoff).

If percolation, as described above, continues to the bottom layer of the soil profile, deep percolation occurs. The maximum amount of water allowed to percolate out of the soil profile is limited to 1% of the hydraulic conductivity per day. The rest is added to the layer above until either all layers have reached saturation (in which case ponding occurs), or until all moisture has found space within the soil profile.

CliCrop also contains a mechanism to estimate the movement of soil moisture against gravity. The method, which is also used in the DSSAT model, is explained in detail in Ritchie (1998).

2.3.3 Waterlogging Module

The water table calculations are used to determine losses due to waterlogging. The height of the water table is measured from the bottom soil layer to the furthest saturated layer. If no layers are saturated, the height of the water table is considered to be zero. If the first layer is saturated, the height of the water table is equal to the depth of the soil profile. So, the height of the water table is not necessarily the height to which the soil is saturated (i.e. soil layers below the top-most saturated layer are ignored).

Using the water table calculation, the reduction in yield due to waterlogging is simulated in CliCrop using an oxygen loss reduction coefficient, SEW30. SEW30 is a method to calculate waterlogging losses based on experimental data that was proposed by Sieben (1964). SEW30 is a measurement of the magnitude and duration of the root zones saturation. The version used in CliCrop is explained in detail in Mohanty *et al.* (1994).

2.3.4 Adjustments to Crop Parameters

In CliCrop, the atmospheric CO_2 concentration affects the daily ET crop demand, which follows the methods explained in Rosenzweig and Iglesias (1998). The different crop parameters are adjusted from year to year using methods developed by Allen *et al.* (1998) – adjusting crop ET demand – and by Wahaj *et al.* (2007) – adjusting crop stage durations – which estimate the local crops reaction to deviations from average climate conditions.

3. COMPARISON OF CLICROP WITH DSSAT

In this section, outputs from the DSSAT maize model are compared to the outputs from CliCrop run in the most similar way. In a general sense, DSSAT tends to focus more on nutrient processes within crops, while CliCrop focuses more on the effects of water processes on crops.

Maize was chosen for this analysis because it is the top source of calories in many areas of the world, including Sub-Saharan Africa (Mann *et al.*, 2009). The inputs used for this model comparison were all provided with the DSSAT 4.0 package. Since the input format requirements were a bit different between the two models, not all of the soil profiles and weather files included in the DSSAT 4.0 package could be used in CliCrop. Once the incompatible files were removed, only 4 soil profiles and 287 weather files remained. These were used in the analysis.

The water module in DSSAT calculates the effect of water stresses on the final yield. If this module is turned off, water stresses are not taken into account when the final yield is calculated. DSSAT model with the water module turned on was assumed to be the rainfed crop yield. Alternatively, the output with the water module turned off was considered to be the irrigated yield, since water stresses were not taken into account in the final yield calculation. A ratio was calculated using these two yields with the following equation:

$$YR_{DSSAT} = \frac{Y_r}{Y_i} \tag{19}$$

where Y_r is the rainfed yield and Y_i is the irrigated yield. This ratio can be used to describe the water stress estimated by DSSAT and is similar to the yield ratio reported by CliCrop ($YR_{CliCrop}$). These two ratios were used to compare outputs of the two models.

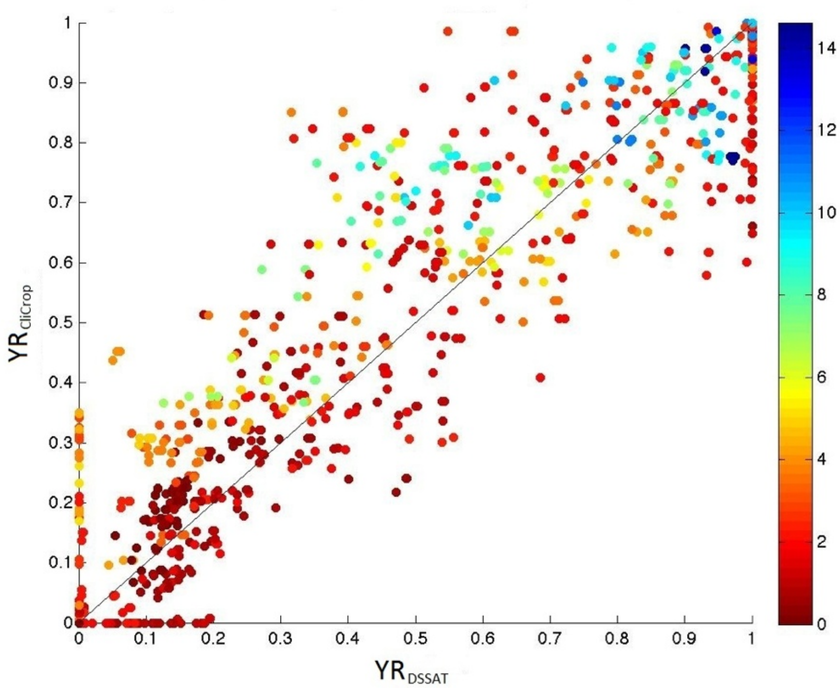

Figure 4. Scatter Plot Comparing the DSSAT yield factor (YR_{DSSAT}) with the CliCrop yield factor ($YR_{CliCrop}$). The color represents the mean precipitation (mm/day) of the weather station used.

Figure 4 shows a comparison between the two model outputs. In this scatter plot, the thin black diagonal line is the 1:1 line, and the color in the points represents the average precipitation during the growing season in mm/day. Of course, more precipitation usually means better yield ratios, but the crop growth is also sensitive to other parameters (e.g. temperature, precipitation patterns, soil...) In the upper right hand side of this plot, there are quite a few cases where DSSAT predicted a yield of 1 and CliCrop predicted a yield less than 1 (although usually close to 1). These results may suggest that the theoretical maximum yield in DSSAT (assumed to be the irrigated yield, Y_i) might be lower in some cases than the theoretical maximum yield assumed in CliCrop. In these cases, another crop stress (e.g. temperature or nitrogen stress) might be driving a decrease in the irrigated yield, while water stress is insignificant in comparison. Also, there are quite a few cases that fall in the lower left hand corner of the plot, where DSSAT yields are zero and CliCrop yields are greater than zero. These could also be attributed to one of the stresses included in DSSAT but not in CliCrop (i.e. not related to water stress directly). In spite of these outliers, this study suggests that CliCrops estimation of the impacts of water stress is comparable to the DSSAT model.

4. COMPARISON OF CLICROP OUTPUT WITH USDA DATA

CliCrop output are compared to publicly available data from the United States Department of Agriculture (USDA, 2002). Three U.S. daily weather datasets were used for this analysis: A spatially and temporally continuous global offline land-surface data set (GOLD, Dirmeyer and

Tan (2001)); NCC, Ngo-Duc *et al.* (2005); and CAS, Qian *et al.* (2006). All three datasets are reanalysis data, adjusted to fit observations. CAS is based on the National Center for Environmental Prediction (NCEP)/National Center for Atmospheric Research (NCAR) reanalysis (Kistler *et al.*, 2001) reanalysis from NCAR and the data spans from 1948 to 2000. GOLD is based on the same NCEP/NCAR dataset, corrected by the global Climate Monitoring Analysis and Prediction (CMAP; Xie and Arkin (1997)) and surface temperature data of the Climate Anomaly Monitoring System (CAMS; Ropelewski *et al.* (1985)) this dataset spans from 1958 to 2000. NCC is based on NCEP/NCAR corrected by the Climate Research Unit of East Anglia (CRU) and spans from 1949 to 2000. Planting dates for major U.S. crops were taken from the SAGE University of Wisconsin database (Sacks *et al.*, 2010) and soil data from the NCAR Land Surface Model (Bonan, 1996). CliCrop was run at a one degree by one degree scale over the continental USA with each of the three datasets.

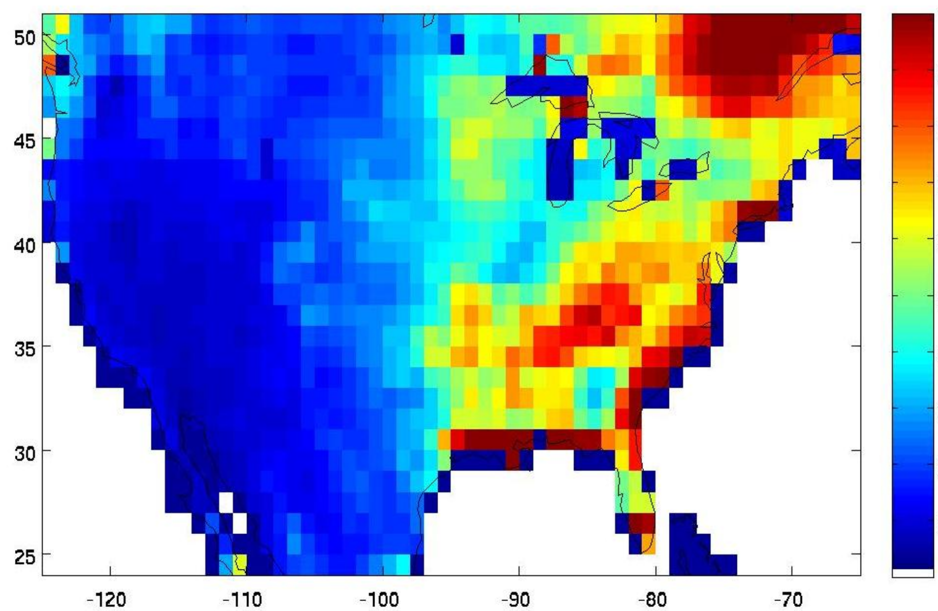

Figure 5. Yield Factor for spring wheat using NCC weather data for 1990.

Figure 5 shows an example of plots that can be made using CliCrop. This one represents CliCrop yield factor for spring wheat in the year 1990. The NCC weather dataset has been used for this plot. As expected, rainfed yields (and consequently the yield factor) are higher on the East Coast that receives more rainfall.

A good indication of whether CliCrop is relevant to spot droughts and water stress is to compare the water stress factor output to actual measured yields. The Agriculture Survey that is administered every year by USDA provides this exact information, broken down by rainfed and irrigated area. Let us note here that any land that receives water once from a source other than rain, independent of the technique used, is considered irrigated in this dataset.

Figure 6 shows CliCrop yield factor output plotted versus rainfed yield for maize aggregated for Nebraska from 1980 to 2000. The actual rain-fed yields are shown using the left axis and the

CliCrop yield ratio values are shown on the right axis.

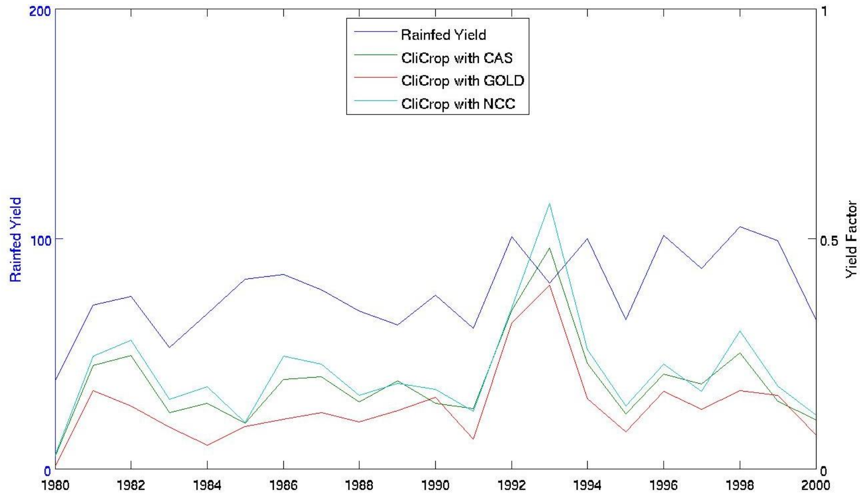

Figure 6. Time series of USDA rainfed yield (left axis) and of CliCrop yield factor using the three different datasets (right axis) for maize aggregated over Nebraska by cultivated area.

We can see that CliCrop catches most of the drop in yields due to dry years, in 1991 or 1995 for example. However, CliCrop does not include fertilization or the impact of modern agricultural techniques; as a consequence, the slow upper trend in yields due to the rise in capital invested into farms does not appear in the model. Another point is that CliCrop does not model the impacts of pests or extreme events like thunderstorms. To overcome these shortcomings, we construct another index from USDA data by dividing rainfed yield by irrigated yield, called the yield ratio:

$$YR = \frac{Y_{rainfed}}{Y_{irrigated}} \tag{20}$$

This new indicator is expected to solve some of the shortcomings of the previous one as extreme events, as well as the capital invested in agriculture, usually affect both irrigated and rainfed crops. **Figure 7** shows USDA ratios as well as the three CliCrop yield factors for maize from 1980 to 2000 in Nebraska as a time series.

These new plots show improved correlation. However, CliCrop yield factor usually lies below the yield ratio calculated from USDA. Two main reasons explain this outcome. First, since irrigation is usually not perfect (for economic reasons), there is still some kind of water stress on irrigated crops; the theoretical maximum yield is thus rarely achieved. Second, in a one-by-one grid cell, irrigated crops tend to lie in the most water-stressed areas (especially for supplemental irrigation), consequently rainfed yield reported to USDA for the area tends to be higher than what would be expected by considering only the average water-stress factor.

Thus, CliCrop is a good indicator of the relative impact of weather on crops, but needs to be calibrated to output the actual rainfed yield. Section 6 goes more in depth into these calibration issues.

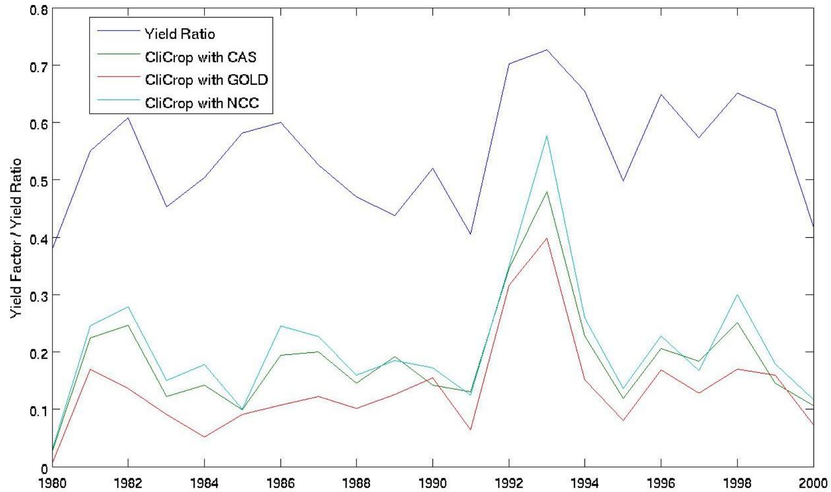

Figure 7. Time series of CliCrop Yield factor (using the three weather datasets) and USDA-based yield ratio for maize in Nebraska from 1980 to 2000.

5. IMPACT OF SOIL MODELING ON CALCULATED IRRIGATION NEED

In this section we look at the impact of adding the multi-layer soil feature of CliCrop model on the irrigation demand. Most models use a simple method where monthly irrigation demand is equal to the difference between monthly effective precipitation (which stands for the precipitation when surface runoff has been deduced) and monthly potential evapotranspiration of the plant (Nelson *et al.*, 2009).

$$IRR_{simple} = PET - P_{eff} \tag{21}$$

where PET is calculated using the same method described in Section 2 and P_{eff} is calculated using the USDA Curve Number method for infiltration (U.S. Department of the Interior, 1993). CliCrop's irrigation need is derived from the difference between the potential evapotranspiration and the actual evapotranspiration:

$$IRR_{CliCrop} = PET - AET \tag{22}$$

Figure 8 shows a comparison between this simple method and the full CliCrop model method. Irrigation needs for maize are aggregated to IFPRIs Food Producing Unit (FPU) level (Nelson *et al.*, 2009) and we plot the simple method versus CliCrop, using an average annual irrigation demand over the period 1991-2000. The blue line is the 1:1 line. The black line represents the mean-square method regression and shows that on average standard method irrigation needs are 12% higher than CliCrop irrigation needs.

We see that if the two methods are comparable on very dry climates (for high irrigation demand), the simple method strongly overestimates the irrigation need in more temperate climate. **Figure 9** shows the geographic repartition of the difference in irrigation need when soil is taken into account. For each FPU we plot the ratio simple method over CliCrop, except for very wet

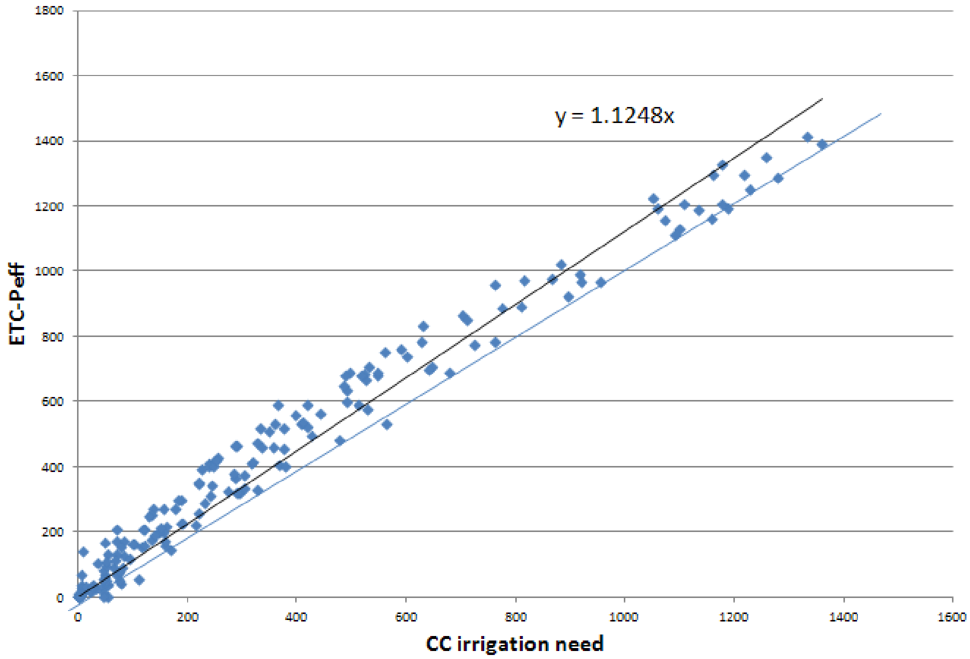

Figure 8. CliCrop irrigation need versus the PET/Peff method averaged over 1949-200 for maize using NCC weather data.

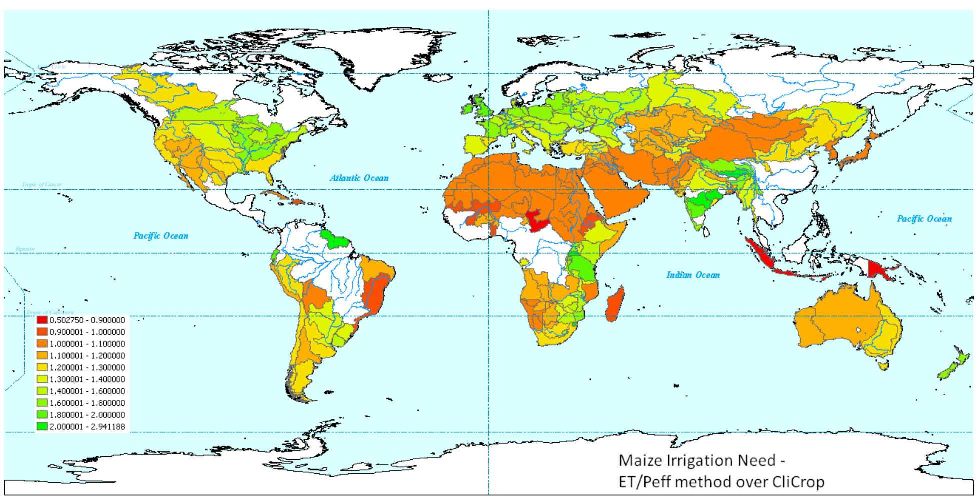

Figure 9. Global impact of using CliCrop versus the PET/Peff method, plot of the ratio of the two methods irrigation need for maize averaged annually over 1949-2000 using NCC weather.

areas where irrigation demand is low. As previously predicted, very dry areas in Northern Africa and Central Asia, for example, show a ratio very close to one. The fact that it is a little less than one can be explained by the fact that the little rain they get does not even reach crop roots on a dry soil. However on temperate regions like North America, Southern South America, Europe, Northern China, Southern Africa or Australia, where most crops are grown, the difference is very important and the simple method can lead to fifty percent higher crop irrigation demand than with CliCrop.

This analysis proves that for the main agricultural regions – which are in temperate latitudes – it is very important to account for soil in the model to accurately represent irrigation demand. Thus CliCrop seems to fit our need for a crop model that gives irrigation demand for a global integrated assessment.

6. ESTIMATING IRRIGATION WATER WITHDRAWAL FROM CLICROP

6.1 Methodology

CliCrop estimates irrigation needs at the roots of the plant. However, the important information for a water planner, and by extension for the WRS basin management module (Strzepek *et al.*, 2010), is the water withdrawal from the stream. For a set of different reasons, we do this work on the continental U.S.

According to the USDA 2002 Census, the following crops make up approximately 98% of total area of raw crops irrigated within the U.S.:

- Forage/Alfalfa, includes all types of forage such as hay, tame and wild hay (43% of the total)
- Cotton
- Grains or barley
- Ground nuts, including peanuts and popcorn
- Maize or corn (grain and silage)
- Potatoes
- Pulses, such as grasses and legumes
- Rice
- Sorghum
- Soybeans
- Sugar Beets
- Sugar Cane
- Wheat, spring and winter

From FAO data (Allen *et al.*, 1998) we obtain the crop parameters used in CliCrop and from SAGE-University of Wisconsin, we have their planting dates, so we can successfully run CliCrop for these crops. In addition to the above list, CliCrop irrigation demands were later estimated for Vegetables, Orchards, Berries, Pastureland, and Other Crops based on CliCrop results for the first set of crops and other factors researched independently.

CliCrop results are produced for a $2^\circ \times 2^\circ$ spatial grid, and remapped to the U.S. county level, state level and to 99 Assessment Sub-basin Regions (ASR) within the continental USA. ASR are demarcated along water catchment borders and are the USGSs 4-digit Hydrologic Unit Code (HUC-4) (USGS, 2011). Special importance is given to validating CliCrop at this latter level. ASR values are obtained by aggregating over county level data. Irrigated areas per State and per crop are given by the USDA Census of Agriculture of 2002 (USDA, 2002).

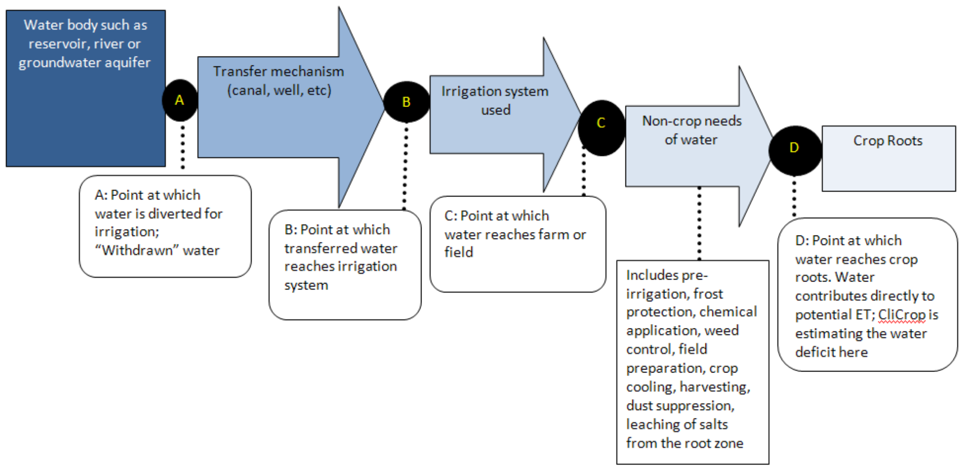

Figure 10. Points A, B, C and D are where water measurements data can refer to; water losses occur between each two points.

Figure 10 shows the different efficiencies to be considered while going from the stream to the roots of the plants. Working backwards, between C and D, water is lost in the field: it is the irrigation inefficiency. The main reason is that an efficiency of less than 100% is needed in order to prevent the soil from containing too much salt. Other uses comprehend pre-irrigation, frost protection, chemical application, weed control, field preparation, crop cooling, harvesting, dust suppression, and leaching of salts from the root zone (Kenny, 2004). Between B and C is the irrigation system inefficiency: furrows are, for example, less efficient than sprinklers or drip irrigation. This is usually called water application efficiency. Finally, there are losses in water transport between the stream and the field (A and B) which are usually called conveyance inefficiencies. This efficiency depends on the conveyance system. **Figure 11** shows the average irrigation and conveyance efficiencies combined in the continental U.S. using the 2003 Farm and Ranch Irrigation Survey (USDA, 2003) and using standard irrigation efficiencies for each technique (Kenny, 2004).

Applying these efficiencies to the FRIS water withdrawal from the stream (interpolated from the irrigated area declared in the survey to the total irrigated area declared in the Census), we get the theoretical amount of water applied to the roots for each crop per state. **Figure 12** shows the difference between CliCrop's output and the estimated value of irrigation for the 19 most important states in the U.S. in terms of total irrigation. Overall CliCrop values are higher than FRIS values which suggests that farmers do not irrigate as much as what would be needed to get an optimal yield. **Figure 13** shows a scatter plot of this difference for all 48 continental states. It is interesting to note that there is a high correlation coefficient between CliCrop output and FRIS data as $R^2 = 81.8\%$. This shows that CliCrop captures climate variability across the states. The following section discusses the reason for the important differences in results.

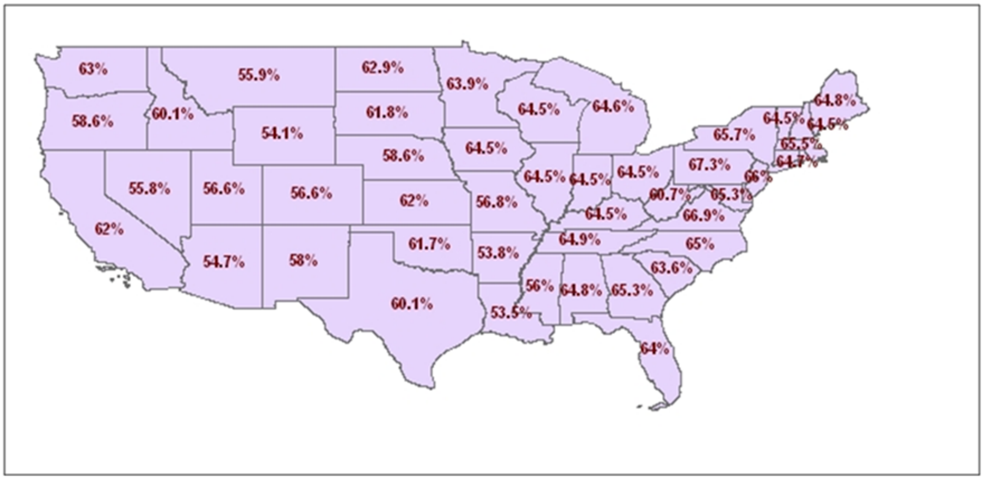

Figure 11. Irrigation systems efficiency in percentage per state.

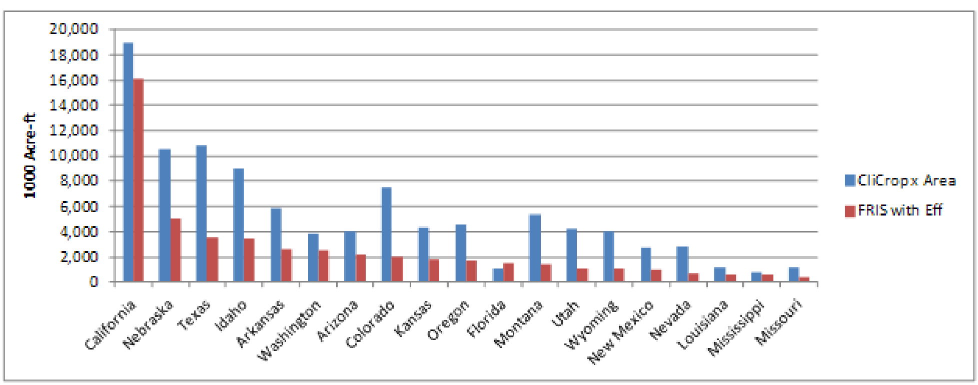

Figure 12. Comparison of FRIS water consumption (with all irrigation efficiencies applied) and CliCrop x Area Irrigated, in 1000 Acre-ft per state.

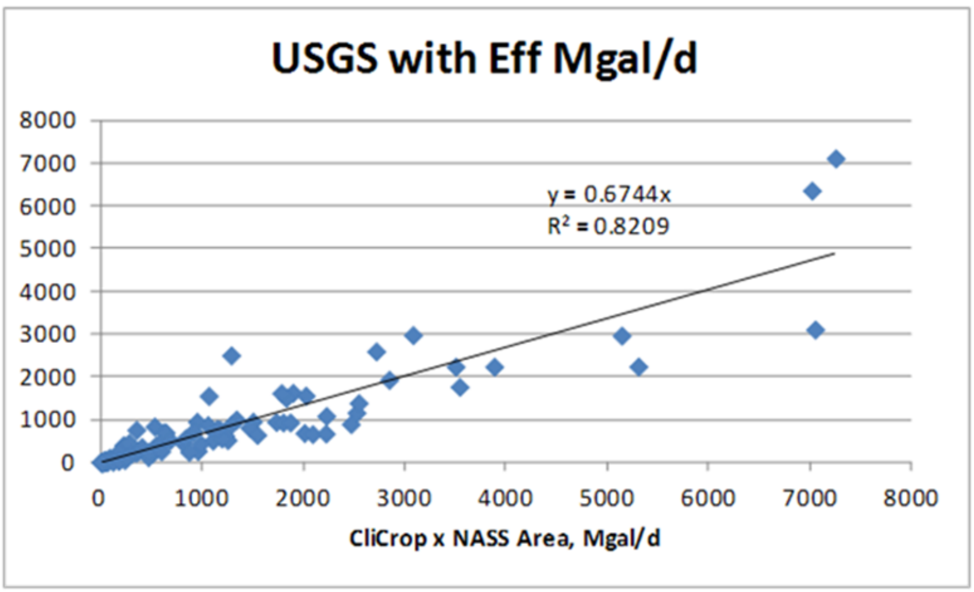

Figure 13. Scatter plot comparing FRIS water consumption and CliCrop x Area Irrigated, in 1000 Acre-ft. The R-square value as well as the slope of the linear regression is also indicated.

6.2 Management Options and the Need for a J-factor

How much water is applied to the farm (Point C) in irrigation for a particular crop in a particular location is a consequence of a combination of several factors, which can be summarized in the following way:

- *Climate:* precipitation, temperature and other meteorological variables determine both how much of the crop growth can be sustain by rain only as well as the actual crop evapotranspiration;
- *Soil conditions:* soil moisture is a component of crop water intake. Also, soil conditions determine non-crop water needs of the soil such as leaching and crop-cooling. For example, the amount of nutrients present in the soil has an impact on water used for fertilization and chemigation;
- *Water availability:* whether in stream, aquifer or reservoir, a water-stressed catchment affects the ability of farmers to obtain it, either as a pure quantity constraint or as an economic constraint;
- *Crop water needs:* crops such as rice and berries (paddies for rice, use of water flooding for cranberries harvesting) have a higher demand for irrigation than others like maize and hay for management reasons. Occasionally, crops are irrigated at rates higher than what is required for maximum yield (e.g. for orchards, as the additional water results in larger fruit size);
- *Crop economic value:* high-value crops, such as vegetables, are more irrigated than cheaper counterparts like hay. On the other hand, a crop could be irrigated more in one location than it is in another location, depending on the specific financial return. This is especially true for hay, when it is used to feed high-value cattle.

The above factors combined contribute to determine how much water a farmer will use for irrigation.

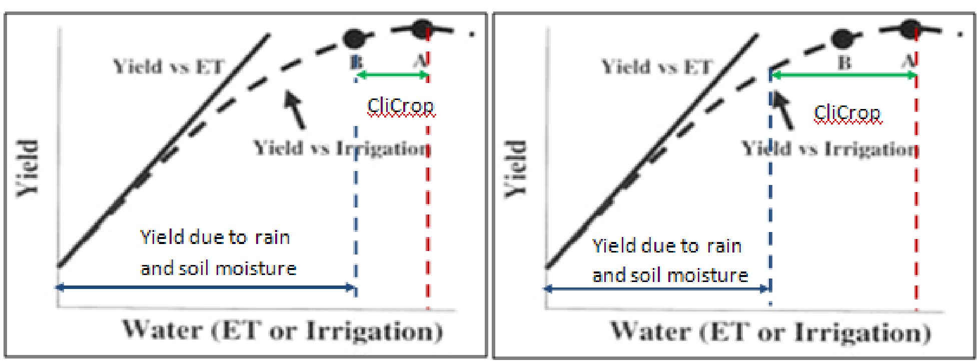

Figure 14. CliCrop result can be different for the same crop as a result of different climate and soil conditions. Point A and red vertical line are point of maximum yield; blue vertical line is the yield due to naturally available water; the blue arrow indicates this naturally available water, while the green arrow indicates CliCrops results. Adapted from Schneekloth and Andales (2009).

The schematics of **Figure 14** demonstrate how different climate and soil conditions can lead to different amount of water required to obtain maximum yields (CliCrop results). Because farmers irrigate only up to a fraction of this maximum yield (a fraction that is determined according to a combination of the above factors) the relationship between CliCrop results and the actual rate of irrigation combines the factors listed above. The J-factor is defined here as the ratio between the actual water supplied to the crop by farmers (taking into account inefficiencies in the irrigation system) and CliCrop's irrigation need to obtain maximum yields.

The scenarios shown in the following schematics demonstrate examples of situations for J-factor values to vary. In these examples, assignments of high and low values are given for demonstration purposes and do not have a meaning in absolute terms. Scenario 1 (**Figure 15**) represents a situation where naturally available water (rain and soil moisture) is high. As such, the relative CliCrop result or water stress for this crop/climate is low. The value of the crop (labeled Crop economic viability and represented with purple arrow) is high, so the J-factor is high. In Scenario 2 (**Figure 16**), naturally available water is low, so the water stress is high. With a similar crop economic viability, this produces a medium J-factor. In this scenario, the cost of obtaining water is the limiting factor. In Scenario 3 (**Figure 17**), both available water and crop economic viability are low. As the water stress is high, the associated J-factor is lower than the previous two scenarios; the cost of water is high compared to the benefits of a higher yield.

The scenarios demonstrate examples of the underlying logic of the J-factor, albeit simplified. Actual J-factors were computed and the results for selected states are presented below.

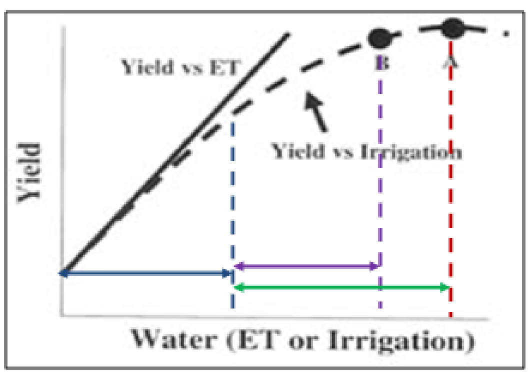

Figure 15. Scenario 1: Naturally available water: high; Crop economic viability: high. Adapted from Schneekloth and Andales (2009).

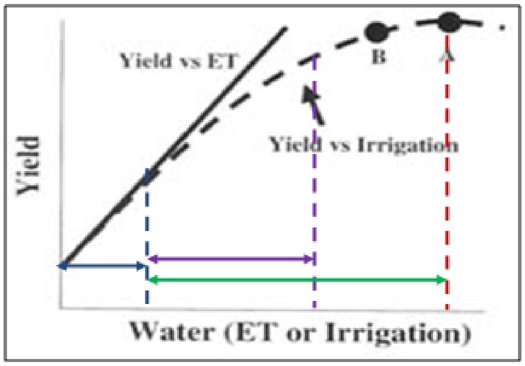

Figure 16. Scenario 2: Naturally available water: low; Crop economic viability: high. Adapted from Schneekloth and Andales (2009).

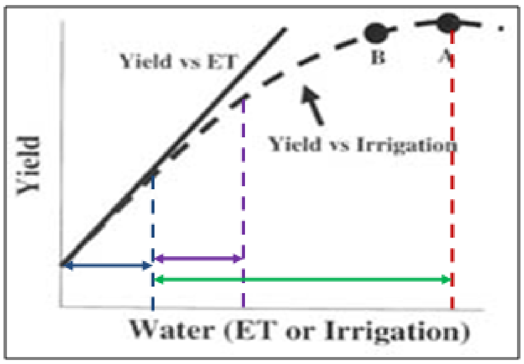

Figure 17. Scenario 3: Naturally available water: low; Crop economic viability: low. Adapted from Schneekloth and Andales (2009).

6.3 Analysis of J-factor Patterns for Some States

The J-factor, which summarizes farmer management decisions, was computed for every crop and every state as the ratio of FRIS output to CliCrop output according to the following relationship:

$$J_{Crop,State} = \frac{FRIS_{Crop,State}[Depth/Time]Efficiency_{State,(Transport,SystemandFarm)}[\%]}{CliCrop_{Crop,State}[Depth/Time]} \tag{23}$$

Figure 18 shows the value of the J-factors for four states (California, Idaho, Nebraska and Washington). We propose here some reasons why J-factors may be different between states.

- *Economic Value of Different Crops within the Same State*

  The graphs show that in California, orchards are irrigated at 128% of what CliCrop reports. This can be explained by a conjunction of facts: fruits are high valued commodities, they require large amounts of water, the part of California where orchards are grown has a dry climate, and usually more water is applied to orchards than what is

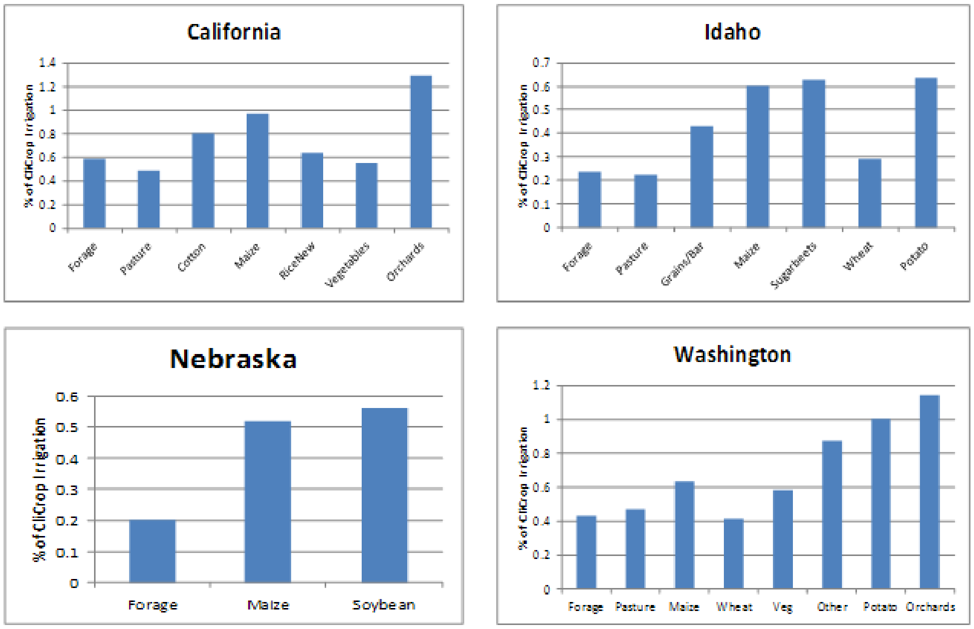

Figure 18. Calculated J-factor for selected states California, Nebraska, Idaho and Washington and the significant crops grown.

needed for the maximum yield because the surplus water increases fruit size. On the other hand, hay (forage) is less valued economically than orchards in California so it is irrigated at only 60% of what CliCrop calculates as needed for maximum yields. This shows the influence of economic factors as a driver of the irrigation rate within a state. A similar analysis can be made for potatoes and pastureland in Idaho; the former has a J-factor of 65%, whereas the latter has a J-factor of 22%, reflecting the high economic value of potatoes in Idaho. Similarly, in Washington, maize is irrigated at 63% while orchards are irrigated at 114%, reflecting orchards high economic value as well as their high water needs.

- *Climate Variations between Different States for the Same Crop*

  The climatic variations between states also dictate how much irrigation is applied for the same crop in different states. Wheat in Washington is irrigated at 42% of its water stress, while it is irrigated at 29% only in Idaho. This is a reflection of a wetter climate in Washington, making water more easily available for farmers, rather than of a difference in the price of wheat between these states.

- *Economic Value of Same Crop in Different States*

  Contrary to what could be expected from the previous point, California's J-factor for hay is larger than that of Nebraska and that of Idaho although the state is more prone to water-stress. The likely explanation for this fact is that hay in California is more valued economically as it is used to feed high-value livestock.

7. CONCLUSIONS

Predicting crop yield is a very difficult task. In general, it seems that CliCrop predicts water stresses efficiently and in a way that makes sense to the ones involved in its development. One danger in taking pieces of multiple models and fitting them together to make a new model is that, although the pieces work by themselves in other models, the pieces may not work well together. However, as seen in this exercise while comparing it to DSSAT or even to USDA yields, CliCrop appears to avoid these risks and provides a reasonably good estimate of the ratio of rainfed yield to optimal yield as well as irrigation needs to obtain these optimal yields.

First, looking at the results comparing CliCrop with DSSAT (Figure 4), there are some cases where yield factors predicted by DSSAT are 0.4 higher than the yield factor predicted by CliCrop, and in some cases the predicted yield ratio is 0.5 higher with CliCrop than DSSAT. In general, Figure 4 seems to suggest that CliCrop tends to estimate slightly higher yield than DSSAT. Although we were able to adapt the outputs from DSSAT to resemble the output from CliCrop, the yield ratios used for comparison are still slightly different in nature. Nevertheless, there is a strong correlation between DSSAT and CliCrop outputs so we are confident that CliCrop catches most of the climate and weather variability impacts.

Second, looking at the results comparing CliCrop with USDA yields from the census of Agriculture, CliCrop's yield factor calculated using reanalysis weather appears to be consistently smaller than the ratio between rainfed and irrigated yield calculated from USDA statistics. However, as explained in Section 4 and in greater detail in Section 6, this systematic error can be explained by a set of economic and management option considerations. The main take-away here is that CliCrop efficiently represents dry and wet year impacts on crops showing respectively smaller or higher yield factors.

Section 5 shows the importance of using a crop model with a multi-layer soil that allows water storage when looking at temperate climate regions. Thus, CliCrop is adapted to be used in intensive agriculture areas, like Europe or North America, contrary to some more simple models based on a CROPWAT framework.

Finally, this study explores the reason why CliCrop's yield factor is systematically higher than the observed ratio between rainfed and irrigated yield and why the irrigation demand that one can compute using CliCrop (taking into account all efficiencies in the irrigation chain) is systematically superior to actual water withdrawals from streams and aquifers. This study was made for the U.S. using multiple data sources. Depending on the economic value of crops and on other factors listed in Section 6.2 farmers will irrigate differently than what is theoretically needed to get optimal crop yields.

Using these data, a factor can be derived for each state and each crop to represent the impact of crop economic value and of management techniques on the irrigation effectively supplied to the crop. These factors can then be used in an integrated modeling framework as the IGSM-WRS framework (Strzepek *et al.*, 2010) to study the impact of a changing climate on water resources.

Future work will focus on three directions. First, CliCrop and the J-factors will be used in a study of the U.S. water system under climate change. Second, as data is very limited outside of the U.S., the relationship between J-factor and economic and climatic situations will be explored so as to come up with an endogenous way to produce it in the Integrated Assessment Framework. Finally, these tools will be used for a global assessment of the impact of proposed policies on the water supply and on food prices.

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