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Bio-Physical Crop Land Atmosphere Water Simulator

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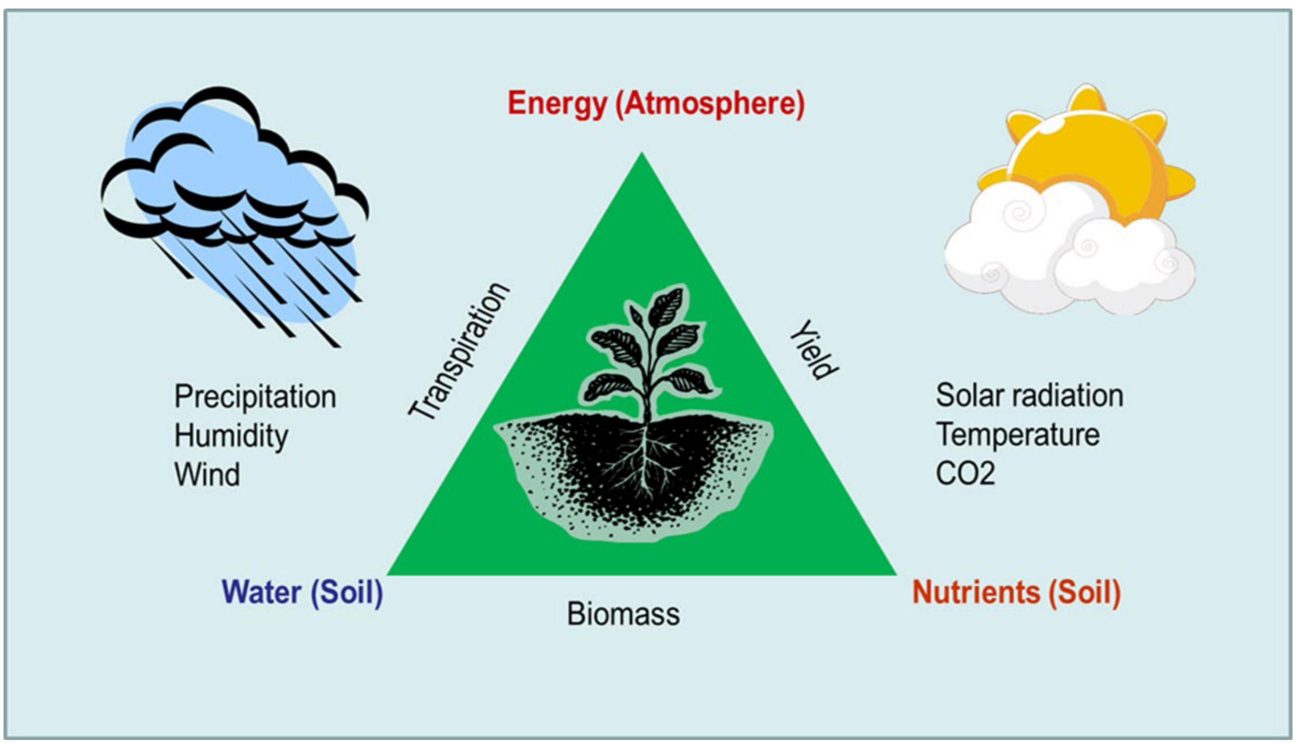

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14. ABSTRACT The Bio-Physical Crop Land Atmosphere Water Simulator (BPCLAWS) model was developed to address research needs identified by Reclamation, U.S. Army Corp of Engineers and other Federal and Non-Federal Partners. Specifically, the need to better understand how climate and CO_2 changes impact plant physiology and how impacts vary by crop type and affect irrigation demand and crop yield were identified as a high priority research needs. To address these research needs, the BPCLAWS project developed a crop model combining physiologically based plant growth and transpiration processes with physical processes affecting water and nitrogen content in the soil.						
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Bio-Physical Crop Land Atmosphere Water Simulator

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prepared by

California Great Basin Regional Office
Division of Planning
Decision Support Analysis Branch
Sacramento, California

Michael Tansey, Regional Climate Change Coordinator
Sacramento, California

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MICHAEL TANSEY

Digitally signed by MICHAEL TANSEY
Date: 2021.12.20 17:30:57 -08'00'

Prepared by: Michael Tansey, Ph.D.
Climate Change Coordinator, California Great Basin Region, MP-740

12/20/21

Peer Review by: Troy Peters, P.E., Ph.D.
Professor and Irrigation Engineer, Washington State University

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Acronyms and Abbreviations

A	API	Application Programming Interface
B	BPCLAWS	Bio-Physical Crop Land Atmosphere Water Simulator
C	CO_2	Carbon dioxide
	CER	Carbon dioxide exchange rate
E	ET	Evapotranspiration
H	H_20	Water
N	N	Nitrogen
R	RUE	radiation use efficiency
S	SSM	Simple Spreadsheet Model
	SSM-iCrop2	SSM iCrop2 version
	SSM-iCrop2N	SSM iCrop2N version
T	TEC	Transpiration Efficiency Coefficient
	TUE	Transpiration Use Efficiency
V	VPD	Vapor Pressure Deficit
W	WEAP-PGM	Water Evaluation and Planning - Plant Growth Model

Measurements

°C	degree Centigrade
cm	centimeter
g	gram
ha	hectare
m	meter
mg/L	micrograms per liter
mm	millimeters

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Executive Summary

The Bio-Physical Crop Land Atmosphere Water Simulator (BPCLAWS) was developed to address research needs identified by Reclamation, U.S. Army Corp of Engineers and other Federal and Non-Federal Partners. Specifically, the need to better understand how climate and CO_2 changes impact plant physiology and how impacts vary by crop type and affect irrigation demand and crop yield were identified as a high priority research needs. To address these research needs, the BPCLAWS project developed a crop model combining physiologically based plant growth processes with physical processes affecting water and nitrogen content in the soil using freely distributable, open-source code in Python.

The BPCLAWS model was developed based on the well-known, peer reviewed Simple Spreadsheet Model. The most recent version of the model (SSM-iCrop2N) was converted from Visual Basic for Applications (VBA) code to Python. The BPCLAWS model was verified by simulating a variety of major crop types grown in Reclamation regions of the western United States and comparing crop water use, bio-mass production and yield with the SSM-iCrop2N model results. In addition, new daily and annual summary graphical capabilities were developed to provide users with high quality graphics improving capabilities efficiently analyze simulation results and effectively compare scenarios with multiple crop management options.

The BPCLAWS model is a necessary step in the development of an agricultural water management system. In its present development stage, it can be used for seasonal and multiyear planning studies focused on agricultural water demands and economic crop yields. However, the longer-term goal of developing a robust forecasting system for irrigation scheduling and crop management will require additional effort.

Background

Project Purpose, Needs and Objectives

The Bio-Physical Crop Land Atmosphere Water Simulator (BPCLAWS) project addresses multiple priority research gaps identified by Reclamation (2011), the US Army Corp of Engineers along with other Federal and Non-Federal partners. These gaps include a better understanding of how climate change impacts evapotranspiration and how it is represented in watershed hydrologic models - 4.02; understanding how climate and CO_2 changes impact plant physiology and how impacts vary by crop type and affect irrigation demand – 4.11.

To address these research needs, the BPCLAWS project developed a crop model combining physiologically based plant growth processes with physical processes affecting water and nitrogen content in the soil. Based on plant physiological responses to daily meteorological and soil conditions, the BPCLAWS model simulates crop evapotranspiration, biomass production and economic yield. It can used to simulate a large variety agricultural crop types including field, orchard and vineyard crops as well as pasture and native vegetation. The model also allows users to specify a variety of crop management options including weather conditions affecting planting, irrigation scheduling and nitrogen fertilizer applications.

Beyond addressing these research needs, BPCLAWS can be used for a variety of planning applications. As a decision support tool, it can be used to evaluate seasonal and long-term crop water demands, biomass production and yield projections. In its current configuration, BPCLAWS is a daily time step model intended for simulations of annual growth periods over user specified multi-year time periods. These capabilities provide opportunities for planners to evaluate the effects of different management options on crop water needs, biomass production and economic yields. When combined with scenarios of projected weather conditions, BPCLAWS can assist managers in the evaluation of appropriate responses for reservoir operations as well as irrigation scheduling and fertilizer management to optimize crop yield.

The BPCLAWS project also developed a framework for users to obtain ensemble based weather forecasts through an Application Program Interface (API) that was developed by another Reclamation research project (Tansey et al, 2020). By providing these capabilities in an open source and freely distributable Python code, BPCLAWS is decision support tool that can grow its capabilities over time.

Project Development

Overview of Crop Modeling

Like other types of modeling, crop models range from simple to complex. The simplest are often single purpose models using statistical methods (e.g. regression) to estimate a particular output (e.g. yield) for a specific crop (e.g. corn) using a limited number of variables (e.g. temperature, precipitation, fertilizer application rates etc.). However, such models have limitations because the included regression variables (e.g. temperature and precipitation) are likely to be correlated with other variables (e.g. CO_2, solar radiation etc.) which were not explicitly represented but are important represent the physiological processes affecting crop water use, bio-mass production and economic yield. Furthermore, transferability to areas outside the region where the input variables (e.g. soil types, water table depth, etc.) have dissimilar characteristics is another problem limiting applicability.

However, simple models often have advantages in terms of the level of effort necessary to obtain data for inputs, develop the model and interpret the results. Consequently, these models can provide important information especially for assessments at the local to regional scales. As the objectives of the crop modeling become more multi-purpose, more comprehensive and longer term, modeling approaches that explicitly account for multiple factors are desirable. Typically, these ecophysiological models include to varying degrees representations of meteorological conditions, biogeochemical processes occurring in various plant organs, soil-plant-water interactions and management practices with explicit temporal scales ranging from minutes to days and spatial scales ranging individual plants (m^2) to fields (~100 ha). Regional and even global scale crop simulations using these models are typically performed by extrapolation of smaller scale results based on externally developed land use data.

These models are often applied to better understand the effects of a wide range of external factors such as climate, soil conditions and management actions for a variety of applications including agricultural productivity, soil and water conservation, surface and groundwater quantity and quality and ecosystem sustainability and biodiversity. In general, these models represent physical and biological processes deterministically but empirical relationships are also used when scientific knowledge and/or parameterization data are lacking or computational efficiency is necessary to accomplish study objectives. Although these models overcome various limitations of the simpler models, it must be recognized that the data requirements, expertise needed and level of effort to develop and apply them is correspondingly greater.

In ecophysiological models, plant responses to climate are typically simulated by model components that represent to varying extents plant phenology; photosynthesis and respiration; biomass accumulation, partitioning and organ growth; water balance; N-uptake and translocation and other factors (Tubiello and Ewert, 2002). Phenology is generally simulated as a function of accumulated daily temperature and day length. Photosynthetic response to light is often computed using exponential or rectangular hyperbolic functions along with various methods to determine how much of the incident solar radiation is intercepted by the canopy. Some crop models use more detailed biochemical equations. Simpler models calculate net biomass production by multiplying intercepted light by the radiation use efficiency (RUE) which is usually assumed to be constant throughout the growth period but may change as a function of CO_2 and VPD. In some models, biomass production may affect transpiration due to crop specific transpiration use efficiency (TEC) to account for the differences in the diffusion of CO_2 into and water vapor out of stomatal cells. In models that compute maintenance and growth respiration, CO_2 may affect photosynthesis and respiration rates indirectly through changes in growth rates.

The modeling of meteorological conditions on crop transpiration has been simulated using several different approaches. In some simpler models (Richie, 1972), actual crop transpiration is computed based on the minimum of potential evapotranspiration, which may be computed by a variety of methods, and root water uptake which is computed as a function of soil water content and the root abundance. In such models, the effects of CO_2 may be simulated by reducing the stomatal conductance which reduces the ET rate. However, stomatal closure has been observed to elevate leaf temperature which increases water vapor diffusion rate. In simpler models, this effect may be empirically simulated by increasing air temperature which is generally assumed to equal leaf temperature. In more complex models, the simulation of photosynthetic carbon uptake is linked with calculations of stomatal conductance. In these models, the algorithms that optimize carbon fixation and transpiration reduce stomatal conductance under water stress conditions which reduces the diffusion of CO_2 into the leaf. Increasing the atmospheric CO_2 concentration has a similar effect on stomatal conductance. In more complex models, reduced stomatal conductance also directly affects leaf temperature and associated phonological stage development rates. In some models, the effects of elevated CO_2 on increased optimum photosynthetic temperature can be simulated. However, comparisons between simple and more complex models did not show significant differences due to this effect (Tubiello and Ewert, 2002).

Biomass partitioning among roots, stems, leaves, and grain or fruit is simulated in simpler models by using constant allocation fractions that may change with crop phonological stages. More complex models dynamically allocate carbon among organ groups. In these models, CO_2 may dynamically modify partitioning and biomass accumulation through feedbacks between photosynthesis and organ growth known as source-sink relations. In simpler models, harvest yield is computed from final above-ground biomass using a harvest yield index coefficient that may also depend on accumulated water and heat stress. In more complex models, harvest yield is based on the dynamic feedbacks used in computing grain or fruit growth.

Other important factors that can affect crop responses to meteorological conditions include air pollutants especially ozone, soil quality, weeds, pests and diseases. Ozone effects the assimilation of CO_2 by reducing stomatal conductance and/or decreasing biochemical activity due to cell damage (Tubiello and Ewert, 2002). Some or all of these effects are simulated to varying extents in both simple and complex models.

White et al. (2011) described three general modeling approaches that have been implemented in crop models to simulate the effects of climate changes crop water use and yields.

1. Models that use RUE and/or TUE with various adjustments depending on the model to account for effects of CO_2, temperature, water, nutrients and other environmental or physiological factors affecting daily bio-mass production.

2. Models that simulate the processes of photosynthesis and respiration at the leaf-level, scaled to canopy level considering losses through respiration and senescence. Plant temperature affects multiple processes and is either assumed equal to air temperature or obtained from simple

submodels. CO_2 effects photosynthesis and stomatal conductance. Depending on the model, other environmental and physiological factors affecting growth and yield such as soil nutrients and water availability and management practices are frequently included.

3. Models that explicitly simulate the physiological effect of CO_2 on reduced stomatal conductance and increased canopy temperature. Processes of photosynthesis and respiration are simulated in ways similar to the second class of models. Other environmental and physiological factors affecting growth and yield are also included.

Typically, these models include sub-modules to represent the effects of meteorology, hydrology, plant physiology and management factors. Brief descriptions of the major data requirements and processes included in these models are provided below. In Appendix 3, model specific information is provided for some of the most commonly used models in crop studies.

Meteorology requirements typically include temperature, precipitation, solar radiation, humidity and wind speed at daily to monthly time scales. Weather data requirements for computing ET by the Penman-Montieth method are greater than for other methods such as Preistly-Taylor, Hargreaves-Semani, Blaney-Criddle and others. Because many weather stations do not collect the required solar radiation, humidity and wind speed data, some models employ estimation procedures that provide the needed weather inputs from temperature, precipitation, elevation, and latitude. For modeling studies, atmospheric CO_2 concentrations are also employed.

Hydrology modules typically provide the means to represent interactions between soil-plant-climate factors. Input data requirements include soil characteristics affecting soil evaporation, erosion, surface runoff, soil infiltration, redistribution of soil moisture within the soil profile, actual crop transpiration, and deep percolation from the root zone. Some models have the ability to simulate shallow water table effects on ET. For models that include plant - soil nutrient interactions, soil organic matter, nitrogen and phosphorus mineralization, speciation and volatilization, specific parameters representing relationships between soil concentrations and plant requirements during various life cycle stages are required. Models that include capabilities to simulate nutrients, pesticides, herbicides and bacteria may require various types of soil and constituent transport parameters.

Plant modules typically include processes that represent plant growth, biomass production and yield. Plant growth is commonly simulated based on plant specific life cycle stage dependent responses to temperature, radiation, humidity, photoperiod, plant available soil water and nutrients and CO_2. Some models directly simulate the effects of photosynthesis and respiration on carbohydrate and protein contents within various plant organs. In these models, yield is computed based on the availability of these substrates during the specific growth stages and may include re-translocation of substrates and nutrients between plant organs in response to environmental stresses. In other models, crop yields are computed as a function of a temperature based harvest index. Plant growth is usually partitioned into above and below biomass based on plant specific characteristics. In some models, the vertical distribution of roots includes the effects of layer specific soil water content during the growing season.

Management modules generally include capabilities to represent field operations affecting water use, crop yields, soil erosion, runoff, accumulation and transport of sediment, nutrients, herbicides and pesticides in surface and ground water. Typical management activities include crop specific dates for planting single, multi-crops and crop rotations; tillage; fertilization, herbicide and pesticide applications; plant residue management and irrigation scheduling. Most of these models allow both user defined and automated scheduling of crop management practices based on dynamic temperature and moisture conditions.

Model Selection

As the preceding overview of crop modeling demonstrates, there are many approaches to modeling crops ranging from simple empirical, single purpose models to highly complex physiological process based, multiple purpose management models. Therefore, the selection of modeling approach should be based on the applications for which the model will be used. Soltani and Sinclair (2012) describe three major categories of crop model applications including:

- Management
    - Evaluating the effects of various management practices such as sowing and harvesting dates, planting density, irrigation and fertilization management, crop type and cultivar selection.
    - Simulations of crop yields and optimal management practices for farm operations.
    - Identification of management practices to increase yields, reduce water consumption and environmental impacts from fertilizers.
    - Forecasting crop yields.
- Education
    - Crop models can be used as a tool to educate farmers and students.
- Research
    - Integration of research knowledge obtained from independent studies of different processes when little information is available.
    - Assessment of crop genetic improvements.
    - Developing needs for new experimental data collection.
    - Assessment of yield potential across regions of variable climate and soil factors.
    - Climate change and variability assessments of yield and water use.
    - Environmental impacts and benefits of crop production
    - Cross disciplinary studies

The major applications intended for the BPCLAWS model primarily include longer term water management planning studies with an emphasis on irrigation water management and economic yields of major crops grown in the western United States. Typically, these studies involve climate change effects and the development of adaptation strategies. Additionally, the BPCLAWS model can be used for annual water supply allocations based on meteorological projections encompassing one or more growing seasons as well as agricultural water demands based reservoir operations.

These applications require a crop model that can simulate a wide variety of crops with variable climate and soil conditions occurring in Reclamation's service areas. These areas encompass large regional watersheds with differing climatic conditions where a large variety of field, orchard, vineyard, pasture, rangeland and native vegetation types are found. Similarly, soil physical characteristics such as depth, texture, organic matter, water holding capacity, runoff, drainage as well as biological and chemical properties are diverse.

As the largest supplier of irrigation water supply in the United States, the capability to simulate a wide range of irrigation management options is an important model consideration. Similarly, flexibility in fertilizer applications is important both respect to economic yield as well as environmental considerations.

A physiologically process based is model is also deemed essential to meet the requirements of this project. In a previous Reclamation research project, Tansey (2018) performed a detailed study of the effects of 21st century projected climate changes on water use and yield of major crops grown in the Central Valley of California. Like many previous studies, this study demonstrated the importance of representing physiological processes in evaluating the effects of changing climate conditions and increasing atmospheric CO_2 concentrations on crop water use and yields. However, the WEAP-PGM crop model used in the study has relatively simple parameterizations of the physiological processes found in more biologically based crop models. In this study, these limitations are addressed by more fully representing the physiological processes affecting crop water use, biomass production and economic yield.

Practical considerations are also important. The model needs to be reasonably simple with respect inputs of weather, crop and management parameters. Computational efficiency is also deemed an important consideration in the selection of a suitable model because simulations of multiple crops over multi-year periods can become time consuming as model complexity increases. Finally, the proposed project specifications included the development of open source, freely distributable Python code to encourage others to participate in future improvements of the model.

Tansey (2018) provides a relatively comprehensive summary of major crop model capabilities and parameterization requirements (see Appendix 3). Largely due to complexity of most of these models and the objective of developing a Python based code, these models are not really good candidates for this study. However, developing a completely new crop model in Python is deemed beyond the scope of the project.

Fortunately, a publicly available and well documented crop model was identified. This model was originally developed by Sinclair (1986) and subsequently more fully developed by Soltani and Sinclair (2012) and described in detail in their book “Modeling Physiology of Crop Development Growth and Yield”. This model referred to as the Simple Spreadsheet Model (SSM) was programmed in Visual Basic for Applications (VBA) in Excel. It simulates the physiological processes representing crop phenology, canopy development, biomass production and economic yield development based on climate and soil characteristics. It also includes the effects of soil available nitrogen and biological fixation and provides users with options to manage irrigation scheduling and amounts of applied water and nitrogen fertilizer.

Further development to provide regional capabilities to simulate diverse crop species was described in Soltani et al (2020). This model (SSM-iCrop2) was calibrated and evaluated by comparison with 32 crops species using data from numerous field experiments from areas in Iran having Arid, Semi-arid and Mediterranean similar to conditions in the western United States. The results demonstrated that the model was robust in its simulations of crop yield and water use. Its root mean square of error as percentage of observed mean of yield was 18% for grain field crops, 14% for non-grain crops 14% for vegetables and 28% for fruit trees.

Recently, the SSM-iCrop2 model was further modified to include the effects of soil available nitrogen on canopy development, biomass production and yield. This Excel model (SSM-iCrop2N) was provided to the author by Afshin Soltani (personal communication) on January 21, 2021. It is the basis for the BPCLAWS Python code developed for this project.

Model Development

The development of the BPCLAWS model was performed by "translating" the VBA code in the SSM-iCrop2 Excel spreadsheet into Python version 3.8.5 code. This conversion was intended to represent the VBA code as closely as possible in Python. Thus, input weather, management, soil and crop, inputs parameters as well as the daily and summary outputs variables have nearly identical names. The organization of the codes is also the same except that the logic controlling the flow of the model occurs at the end of the Python code instead of at the beginning as in the VBA code. This difference is the result of differences in how programs are structured in Python and VBA. There are also differences in how variables are initialized. In VBA, variables may be used which have not been previously defined. This is not the case in Python. Therefore, in the BPCLAWS code, there is additional code to explicitly initialize variables associated with different methods.

Another major difference is the use Object Oriented Programming in Python. This technique allows programmers to develop "Classes" which have properties and methods that are similar to variables, parameters and subroutines in VBA. Additionally, Python has rich library of modules that can be used to organize and efficiently perform mathematical operations and logical tests on large collections of suitably organized data. These capabilities were used extensively in the development of the BPCLAWS code. Also employed in the BPCLAWS code are other Python modules that provide capabilities to create high quality graphics in various commonly used formats. Such graphical capabilities are not part of the SSM-iCropN model.

Along with the code development, a considerable amount of documentation was included with the Python code. This documentation includes descriptions of the purpose of each of the Class methods, variables and initialization values as well as commentary associated with the purpose of the algorithms employed in the code.

Research Methodology

In this section, an overview of the BPCLAWS model is provided along with descriptions of the physiological and hydrological processes that are included in the simulations. The organization and setup of simulations as well as verification of the model are also discussed.

Overview of BPCLAWS Model

Like the SSM-iCrop2N model, BPCLAWS provides users with the capability to setup scenarios which are executed in a specified sequence. Each scenario occurs at a user defined location over a given number of years in which daily weather conditions including precipitation, maximum and minimum temperature and solar radiation data are provided. A description of the BPCLAWS methods, input and output variables is presented in Appendix 1.

In addition to specifying meteorology, each scenario includes a particular soil and crop type. Soil properties include depth, water holding capacity, drainage and runoff characteristics. For simulations involving soil nitrogen mineralization, bio-fixation, denitrification and leaching, additional soil properties such as bulk density, organic matter content, soluble nitrogen content are required. A large variety of crop types can be simulated (Soltani et al, 2020). These include grain and non-grain crops both non-legumes and legumes; orchards and vineyards both deciduous and non-deciduous; vegetables and tubers as well as pasture and rangeland. The model also provides capabilities to simulate ponding of rice and multiple cuttings of alfalfa crops.

For each scenario, the user can specify a variety of management options. A variety of weather conditions can be specified to determining when sowing occurs. There are also a variety of options for how water and nitrogen influence the crop's water use, growth and yield. These water management options may include rain only simulations or irrigation based on soil water content as well as irrigations applications based on crop growth stage, day of the year or days after planting. When only the effects of temperature and solar radiation are included without water and nitrogen effects, the crop's potential production can be simulated. When soil water is included, the effects of soil water content both high and low on crop development and yield are simulated. When simulating soil water, the effect of nitrogen may also be simulated in a variety of ways. These include simulating the effects of nitrogen mobilization and transfer on the development of crop vegetative matter and seed (fruit) formation. The effects of soil nitrogen availability and bio-fixation for legume crops may also be simulated. Applications of nitrogen fertilizer may also be simulated based either crop growth stage, day of the year or days after planting.

Phenology

Modeling of phenology simulates the time of occurrence of different crop developmental stages including emergence, beginning of seed growth, termination of seed growth, senescence and maturity. Simulating crop development is important for management decisions such as pesticide, herbicide and fertilizer application and the timing of harvest. It can also be important in cultivar selection to optimize yield under different climatic conditions. In climate change studies, global warming will affect plant phenology resulting in changes growing season length, planting and harvest dates. Phenology is affected by multiple factors including temperature, photoperiod, drought and nutrition. Therefore, calendar dates are not a good predictor of phenological development.

The cumulative "temperature unit" (aka heat unit, thermal unit and thermal time) concept has been used extensively to quantify phenological development. The daily temperature unit is quantified as the difference between the mean daily temperature minus a crop specific basal temperature. By summing the daily heat units, the cumulative temperature units indicate the progress in the development from one stage to another. A limiting upper rate of development occurs as temperature increases which under high temperatures may result a decreased rate of development.

Although various representations are possible, phenological stage progression can be simulated using a 3-piece segmented linear function (Soltani and Sinclair, 2012) as shown in Figure 1.

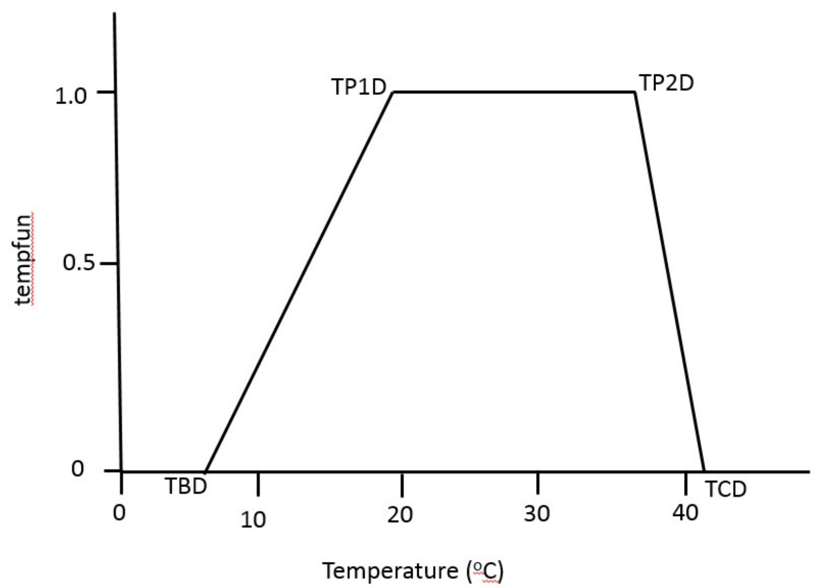

Figure 1. Phenological Development Temperature Function.

The rate of development is represented by the temperature response function (tempfun) which remains zero at mean daily temperatures (TMP) below the crop's base temperature (TBD). Between TBD and the lower optimum temperature (TP1D), the rate of development increases linearly with increasing temperature. The rate of development continues to be maximum in the optimum range between TP1D and the upper optimum temperature (TP2D). At temperatures above TP2D but less than the ceiling temperature (TCD), the rate of development declines linearly. At temperatures above TCD, the rate of development is zero. These temperature parameters are referred to as cardinal temperatures and tend to be fairly stable within a species.

The daily temperature unit (DTU) is calculated using the crop specific tempfun by assuming an optimal phenological growth rate (TP1D – TBD) and correcting for the actual growth using the tempfun. The phenological development up to the current day is obtained by summing the daily temperature units (CTU). Experimentally determined temperature units (tu) for the following phenological stages are parameters in the BPCLAWS model.

- Sowing to emergence (EMR)
- EMR to beginning of seed growth (BSG)
- BSG to termination of seed growth (TSG)
- TSG to harvest maturity (HAR).

Similarly, phenological stages including the beginning of leaf senescence (BLF) and nitrogen fixation (BNF) can be expressed in terms of CTUs. For forages with multiple cuttings temperature units from beginning of regrowth to harvest are inputs, For rice, harvest is expressed as temperature units from transplanting to harvest and for trees, temperature units from bud burst to harvest or leaf fall are inputs.

In the BPLAWS model, the crop development stages are expressed as a ratio of CTU to the total temperature units at harvest (tuHAR). This normalized development stage is expressed as:

NDS = CTU / tuHAR

In addition to photoperiod which is not represented in BPCALWS, phenological development can be affected by soil water content. In some crops, low water content may accelerate crop development while in others development may be retarded. In the BPCLAWS model, these effects are represented by adjustments to the DTU. These water stress factors are described in the Soil Water section below.

Canopy Development

Crop leaf area is an important determinant of crop yield and water use. There are three basic approaches of simulating crop leaf area development including carbon based methods, temperature based methods and hybrid methods. The carbon based methods assume that the rate of increase in plant leaf area depends on the amount of dry matter available for leaf growth on a daily basis. The leaf area is computed as the amount of dry matter portioned for leaf growth times the specific leaf area. In contrast, temperature based methods assume leaf development is not generally limited by the availability of assimilates but depends on linking leaf area to temperature. The hybrid methods assume solar radiation determines the amount of photosynthate available and temperature determines the rate of cell division and expansion.

In BPCLAWS, a temperature based method is employed with the normalized development stage (NDS) representing the effects of temperature on canopy development. The canopy development is expressed in terms of the Leaf Area Index (LAI). A multiple part exponential function is employed to represent canopy LAI (Soltani and Sinclair, 2012). This function is employed in growth stages from emergence (EMR) to the beginning of leaf senescence (BLS) expressed in terms of NDS. It requires the specification of 4 parameters (X1, Y1, X2, Y2) and the maximum crop LAI. After BLS, a power function based on NDS and a user specified senescence rate parameter (SRATE) determines how the canopy senescence occurs. If SRATE = 0, there is no senescence; SRATE =1, senescence is linear; SRATE < 1, non-linear upward curvature; and SRATE > 1, non-linear with downward curvature. Like phenological development, canopy development can also be affected by low soil water content.

Figure 2 is an example of a soybean crop with parameters X1=0.15, Y1=0.05, X2=0.5, Y2; SRATE=1.0; LAIMAX = 4; and senscence beginning at NDS=0.95. Also shown is the fraction of solar radiation intercepted by the canopy (FINT) during the growing season.

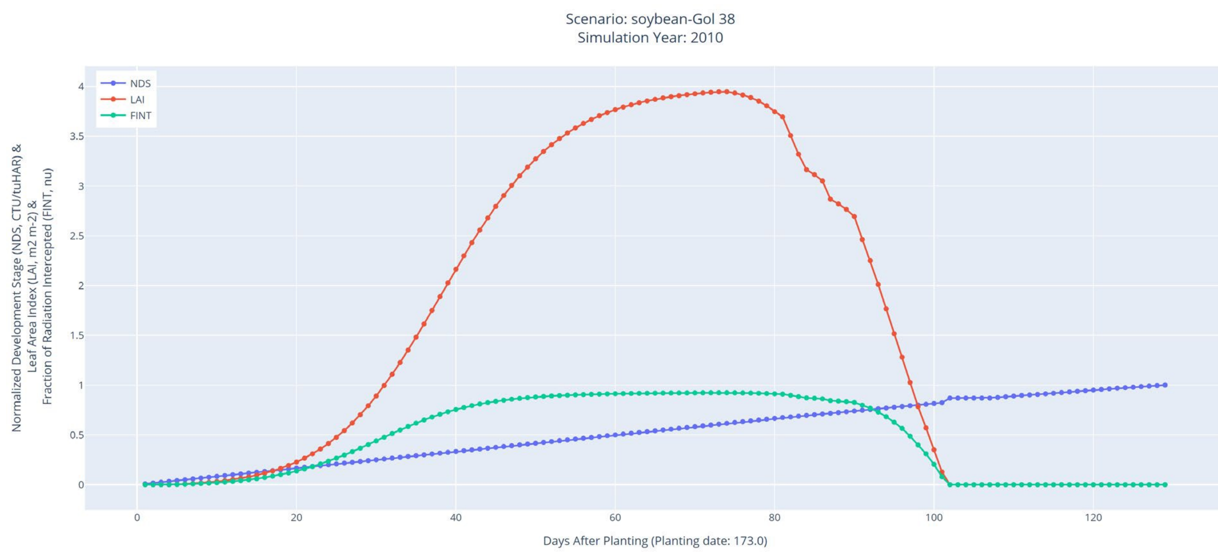

Figure 2. Canopy Development and Senescence as a function of Normalized Development Stage and Days After Planting.

When the effects of nitrogen are simulated, the rate of canopy senescence is increased in proportion to ratio of the nitrogen mobilized from the leaves and the difference in user specified nitrogen content of green and senescenced leaves. This is discussed in more detail in the Plant Nitrogen section.

In BPCLAWS, the effects on the daily rate canopy senescence by either maximum or minimum daily temperatures exceeding user defined thresholds are also simulated. When minimum temperature is below the threshold, the rate of senescence is decreased in proportion to the difference by a user specified fractional reduction factor. When maximum temperature exceeds its threshold value, the rate of senescence is increased in proportion to the difference by a user specified reduction factor.

Dry Matter Production, Distribution and Yield

Several methods are commonly used to simulate daily dry matter production (DDMP). In some models, DDMP is based on detailed modeling of photosynthesis, growth and maintenance respiration. Radiation intercepted by the leaves is calculated first, then gross photosynthesis, and finally dry matter after subtraction of maintenance and growth respiration from gross photosynthesis.

Other models like BPCLAWS simulate dry matter production based on the concept of radiation interception and radiation use efficiency (RUE). Photosynthetically active radiation (PAR) is about 48 % of the total solar radiation. To calculate DDMP it is necessary to determine the amount of PAR that is intercepted by the canopy. The fraction of intercepted PAR (FINT) is a function of the extinction coefficient (KPAR) and the LAI. KPAR can vary with respect to leaf angle and time of day. There are a variety of methods to estimate KPAR. In this model, KPAR is assumed to be constant throughout the crop life cycle.

$$FINT = 1 - \exp(-KPAR * LAI)$$

RUE is a summary variable that represents the processes of photosynthesis, maintenance and growth respiration. RUE is defined in terms of above ground crop dry matter. Each crop is represented by a unique potential RUE reflecting its maximum photosynthetic capacity (IRUE) and biochemical composition of dry matter produced. In general, C4 plants (eg. corn) have a higher RUE than C3 species (eg. wheat). Typically, plants producing mainly carbohydrates have higher RUE than plants producing proteins and lipids. Several factors can affect the potential RUE including temperature, soil water and carbon dioxide concentration.

In BPCLAWS, the effect of mean daily temperature on RUE is obtained from a three-segment linear function, tcfrue, defined by crop specific temperature parameters TBRUE, TP1RUE, TP2RUE, and TCRUE The tcfrue function remains zero at mean daily temperatures below the TBRUE temperature. Between TBRUE and the lower optimum temperature (TP1RUE), the function increases linearly with increasing temperature. The function continues to be maximum (tcfrue = 1) in the optimum range between TP1RUE and the upper optimum temperature (TP2RUE). At temperatures above TP2RUE but less than the ceiling temperature (TCRUE), the function declines linearly. At temperatures above TCRUE, the funtion is zero.

An example of the tcfrue function is displayed on Figure 3. The daily RUE is computed by multiplying the radiation use efficiency under optimal conditions (IRUE) by the tcfrue function.

$$RUE = IRUE * tcfrue$$

RUE is also a function for CO_2 concentration and can be adjusted by the following equation (Penning De Vries et al, 1989).

$$RUE = RUE * (1 + b * Ln(CO_2 / Co))$$

Where CO_2 is the current atmospheric concentration in parts per million (ppm) and Co is the BPCLAWS reference concentration (350 ppm). The parameter b = 0.4 in C4 crops and 0.8 in C3 crops.

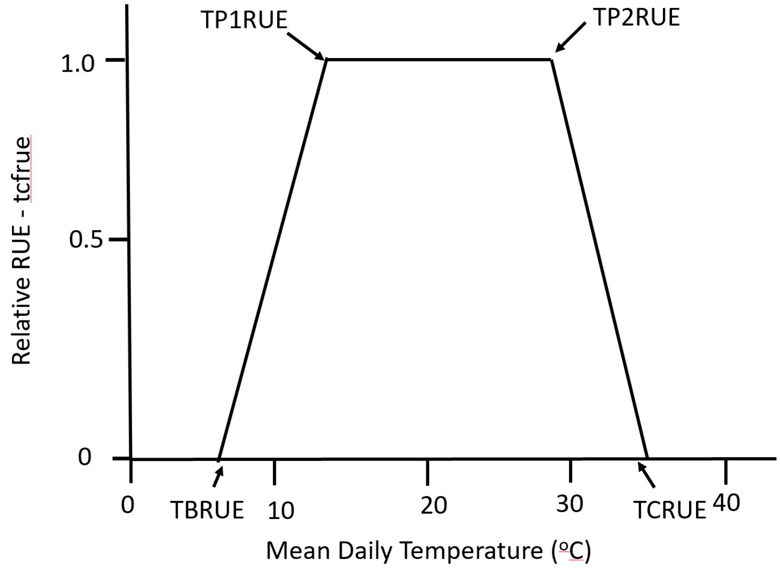

Figure 3. Radiation Use Efficiency Function of Mean Daily Temperature.

The DDMP is calculated as:

DDMP = PAR * FINT * RUE

Dry matter distribution has been simulated by a variety of methods. In the simplest case, the distribution of dry matter between grain and other organs is based on the concept of the harvest index (HI) which is the ratio of the grain mass to the total above ground plant mass. In this approach, total DMP is calculated first and grain yield is obtained as the product of HI and DMP. Another similar approach is to simulate yield formation based on a linear increase in HI during seed growth. This method is based on the observation that a linear increase on HI occurs during the seed formation period (Speath and Sinclair, 1985). In this approach, the calculation of seed yield intrinsically combines the contributions of both current and stored assimilates.

In more complex methods, the distribution of dry matter into each organ is based on organ specific partitioning coefficients. Additional considerations in calculating yield formation is the relationship between the supply of assimilates and the demand from the grains. In the source limited approach, grain growth and yield is only limited by the capacity of the leaves and other organs to provide assimilates to the grains. In sink-limited approaches, it is assumed that assimilate production is sufficient and grain growth is limited by the ability of these sinks to absorb assimilates. In combined approaches, the production of assimilates and the demands are calculated separately and the minimum value is used.

In the BPCLAWS model, the distribution of assimilates and the formation of yield are simulated during the development stage starting at the beginning of seed growth (BSG) and ending at the termination of seed growth (TSG). At the beginning of the seed formation phenological stage, the accumulated DDMP (BSGDM) is in crop vegetative organs (stems + leaves). After seed growth begins, a crop specific assimilate fraction (HIMIN) is available for translocation to seeds. The amount of translocable assimilate is calculated as:

TRLDM = BSGDM * HIMIN

During seed formation, the daily increase in seed weight (SGR) is related to both accumulated dry matter and DDMP production. Determining SGR is accomplished by specifying the linear increase in HI per DTU (PDHI). The PHDI parameter is computed by specifying a maximum production of seed formation per unit DMP production (HIMAX) along with the total temperature units to harvest (tuHAR) and the NDS values occurring when seed growth begins (frBSG) and terminates (frTSG).

PDHI = HIMAX / (tuHAR * (frTSG – frBSG))

As has been observed experimentally, PHDI remains reasonably constant during seed formation. Therefore, the daily harvest index (DHI) as a function of basal temperature units (DTU) can be computed as:

DHI = PDHI * DTU

The daily increase in seed weight (SGR) is calculated from the previously accumulated total above ground vegetative matter (WTOP) including stems, leaves and seeds; the current day's DDMP and the product of DDMP and the current day (DHI) and cumulative HI based on accumulated weight of the grains (WGRN) divided by WTOP.

SGR = DHI * (WTOP + DDMP) + DDMP * HI

However, the weight of seeds with high protein or lipids content crops can be less than the weight of potentially translocable assimilate. Therefore, amount of translocable dry matter needs to be adjusted by a crop specific grain conversion coefficient (GCC) relating the weight of seeds to the weight of plant dry matter. When the corrected seed weight (SGR/GCC) is in excess of the DDMP, translocation (TRANSL) from the vegetative tissue to the seeds occurs in the amount:

TRANSL = (SGR/GCC) – DDMP

and the reservoir of translocable assimilate (TRLDM) is reduced by the amount of the transfer.

TRLDM = TRLDM – TRANSL

Otherwise, there is no translocation.

Plant Nitrogen

Leaves require nitrogen (N) as a critical component of the enzymes that carry on photosynthesis and sugar production. Nitrogen deficit limits leaf area development. The implementation of this effect in BPCLAWS was discussed in the Canopy Development section. Both carbon dioxide exchange rates (CER) and RUE are sensitive to leaf N content especially at low leaf N content but become increasing less sensitive as leaf N content increases and reach maximum CER and RUE values at high leaf N content. Experimental studies have shown that leaf N content at the top of mature canopies is substantially greater than in the lower canopy. At the top of mature canopies, leaf N content is such that these leaves approached maximum photosynthetic rates. This non-uniform distribution of N content enhances the canopy RUE and CER by ensuring that the leaves which receive the most solar radiation have the highest N content.

In general, N demand is computed based on biomass and N concentration in plant tissues. Prior to emergence and after the termination of seed growth, there is no demand for N. In order to simulate genotypic and environmental control of crop N dynamics, it is necessary to account for both the metabolic (leaves) and structural (stems) demands for N. In this approach, N demand (NUP) is set by the need to maintain target concentrations in new leaves. Stems act as reservoirs for extra N between the stem minimum and target N contents. During seed development, the N stored in the leaves and stems is translocated from the leaves and stems to the developing seeds (fruit).

In BPCLAWS, the daily dry matter production (DDMP) includes the weight of all plant organs. Therefore, the weight of the seeds (SGR * GCC) must be subtracted from DDMP to obtain weight of the non-seed plant tissue.

DDMC = DDMP - SGR * GCC

The daily increase in LAI (GLAI) must also converted to weight by the specific leaf area per unit weight (SLA).

GLF = GLAI/SLA

The daily increase in stem weight (GST) is computed as the difference.

GST = DDMC - GLF

During the vegetative growth stages, the daily demand for NUP is product of the target N contents in the leaves (SLNG) and stems (SNCG) with the corresponding organ weights.

NUP = (GST * SNCG) + (GLAI * SLNG) + NSTDF

The term NSTDF represents previous deficiencies in the stem N content due to insufficient N availability in the soil. It may be computed as:

NSTDF = (WST * SNCG) – NST
For non-legume crops, NUP is limited by the availability of soil nitrogen (SNAVL) which is described in the Soil Nitrogen section.

NUP = SNAVL

If soil water content is near saturation (WXFS = 0), NUP is zero.

NUP = NUP * WXFS

For legume crops in the vegetative development stages after entering the bio-fixation growth stage (NDS > frBNF), NUP may also be adjusted low soil water content (WSFN < 1).

NUP = NUP * WSFN

However, NUP is not limited to SNAVL as biological fixation of nitrogen (BNF) provides additional N meet the crop demand.

BNF = NUP – SNAVL

On a daily basis, a biological fixation coefficient (NFC) is computed based on NUP and the accumulated crop vegetative weight (WVEG).

NFC = NFC * 3 / 4 + NUP / WVEG * (1 / 4)

In the vegetative phase, N is preferentially allocated to the leaf demand. This allocation continues until yesterday's accumulated N in the stems (NST) becomes less than the minimum needed for stems which is the product of the accumulated stem dry matter (WST) and the minimum stem nitrogen concentration in senesced stems, SNCS. This condition can be expressed as:

NST <= WST * SNCS

When the N content of stems is above its minimum requirement, this condition is false and the daily increase in leaf nitrogen (INLF) will meet its target N demand based on the daily rate of canopy increase (GLAI) and the target N content of green leaves (SLNG).

INLF = GLAI * SLNG

There will also be no mobilization of nitrogen from the leaves to the stems (XNLF = 0) because the stems still have N greater than their minimum requirement. However, if INLF is not greater than NUP, the remaining NUP is stored in the stems (INST).
.
INST = NUP – INLF

Under these conditions, there will also be no mobilization of N from the stems to leaves (XNST = 0).

If INLF is greater than or equal to NUP, there is a need to mobilization N from the stems to the leaves (XNST). Therefore, there is no increase in stem N (INST = 0). The amount of N transferred from the stems (XNST) is the lessor of either the difference between target N rate in leaves (INLF) and NUP.

XNST = INLF – NUP

or the difference between N in stems (NST) and the minimum stem N requirement WST * SNCS.

XNST = NST – (WST * SNCS)

The final daily N leaf N content is given by the sum:

INLF = NUP + XNST

When the accumulated N content of the stems (NST) becomes less than its minimum target (SNCS), N will be supplied to the stems in preference over the leaves.

NST <= WST * SNCS

The needed daily increase in stem N (INST) is calculated as the difference between the minimum target stem (WST * SNCS) and the existing stem nitrogen content (NST).

INST = WST * SNCS – NST

And no mobilization of N from the stems occurs (XNST = 0)

Next, it is necessary to determine how much mobilization from the leaves (XNLF) to the stems is necessary. If INST is greater than or equal to the whole plant demand (NUP), then no N is supplied to the leaves (INLF =0) and N is mobilized from the leaves to the stems (XLNF) in the amount of the difference between the stem demands and the total N demands

XLNF = INST – NUP

This transfer of N from leaves to stems results in the senescence of leaves which is described in the Canopy Development section.

However, if NUP is greater than INST, there is no mobilization of N from the leaves (XNLF = 0) and the daily increase in leaf N (INLF) is computed as the lessor of the target leaf demand

INLF = GLAI * SNLG

Or the difference between total N demand and existing stem N content (NST).

INLF = NUP – NST

Finally, the daily increase in stem N is computed as the difference between NUP and the increase in leaf N content.

INST = NUP – INLF

These physiological N processes are illustrated in the flow chart below.

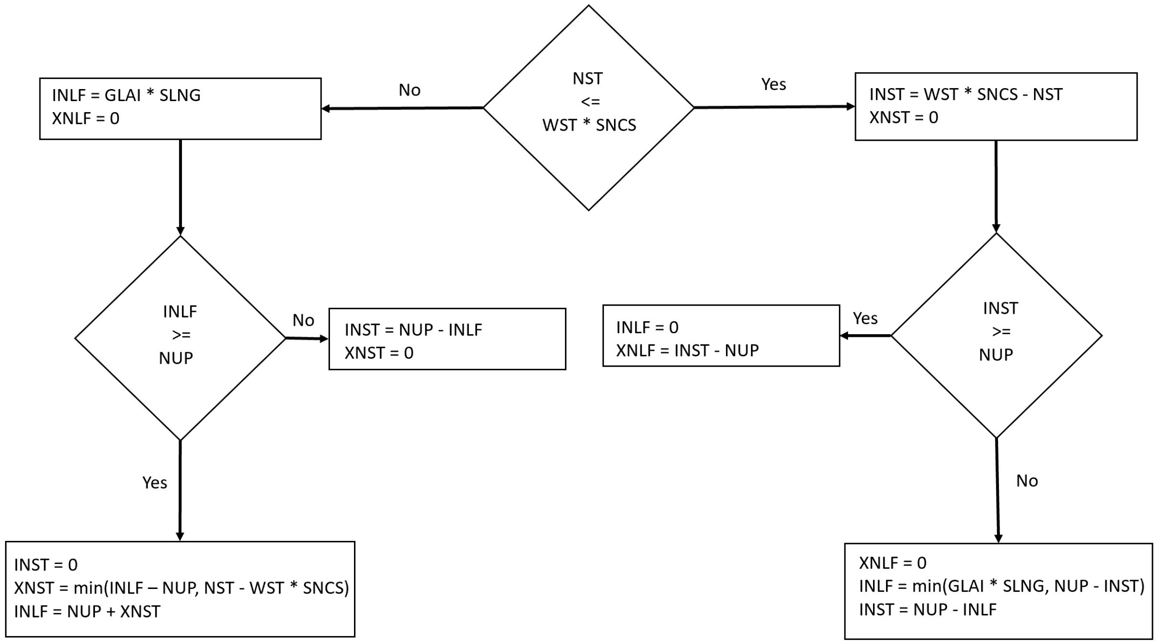

Figure 4. Flow chart of Nitrogen Mobilization in Leaves and Stems during the Vegetive Growth Stage.

In general, there is a direct relationship between LAI and grain yield. After BSG, N accumulation is negligible. Therefore, seed growth is very dependent on translocation of N from leaves and stems to the seeds. This translocation results in leaf senescence. However, N supply from roots continues which also contributes to the final grain yield.

In the seed (fruit) development stage (BSG to TSG), all seed demand for N is supplied by N mobilization from leaves and stems. The fraction of N supplied by leaves and stems is proportional to their relative mobilization which is accompanied by leaf senescence resulting from mobilization from leaves. During this period, seeds become the primary sink for N. The daily N demand by seeds (INGRN) is calculated as the product of SGR and the N content of the seeds, GNC.

INGRN = SGR * GNC

The daily N demand, NUP is the sum of INGRN plus the target accumulation rates in the stems and leaves.

NUP = INGRN + (GST * SNCG) + (GLAI * SLNG)

For legume crops during seed development, the potential daily rate of bio-fixation (PDNF) is computed from NFC and WVEG (Sinclair et al. 2003).

PDNF = NFC * WVEG

PDNF may be adjusted for soil water content affecting bio-fixation. The water stress factor for nitrogen fixation (WSNF) only decreases to less than 1 at low water contents as described in the Soil Water section. The adjusted daily rate of bio-fixation (DNF) is given by:

DNF = PDNF * WSNF

Subject to the constraint that DNF <= NUP, legume NUP can be as large as the sum of available soil nitrogen and bio-fixation.

NUP = SNAVL + DNF

with bio-fixation providing the difference between NUP and SNAVL.

BNF = NUP – SNAVL

If NUP is greater the N demand of seeds (NUP > IGRN), the translocation of N between leaves and stems occurs in the same way as described for the vegetative stages (See Figure 4) except that the seed N demand must be removed from NUP.

NUPC = NUP - IGRN

Otherwise, when NUP <= IGRN, translocation of N to the seeds is needed. The amount of translocatable N (TRLN) is the sum of leaf and stem N content above their minimum values.

TRLN = LAI * (SLNG - SLNS) + (NST - WST * SNCS)

The fraction of translocatable leaf N (FXLF) is the ratio of translocatable leaf N to the total translocatable N.

FXLF = LAI * (SLNG - SLNS) / TRLN

The amount of N translocation for leaves is given by:

XNLF = (INGRN - NUP) * FXLF

The amount of N translocation from the stems is given by:

XNLF = (INGRN - NUP) * (1 – FXLF)

Crop models are different with respect to the effect of the decrease in leaf N on LAI and RUE. Some models simulate the effects on both LAI and RUE and other models on only one or the other. In this model, it is assumed that the transfer reduces the LAI but has no effect on RUE because SLNG remains a constant throughout the simulation. The main reason for this assumption is that changes in leaf N throughout the canopy are not uniform. The N content of leaves near the top of the canopy remain high so RUE in these leaves remains nearly optimal during seed filling. Under limited N conditions, the accelerated transfer of N from the leaves to the seeds results in a loss of crop productivity because of the leaf senescence caused by the transfer (XNLF).

Soil Water

When crops experience limitations in their water supply during the growing season, their productivity is affected. This can occur when there is either to little water (water deficit) or too much (flooding). In the BPCLAWS model, soil is considered as a reservoir (WSTORG) for plant growth. When the soil pores are completely filled, the soil is at saturation (SAT). In BPCLAWS, field capacity is termed the drained upper limit (DUL) Not all water in the soil is available to plants. The lower limit of soil water available to a crop is defined as LL. The total extractable water available for transpiration by the crop (EXTR) is the difference between DUL and LL multiplied by the thickness of the root zone (DEPORT). Because different crops extract transpirable water down to different soil water contents both EXTR and LL vary with both soil and crop type.

In BPCLAWS, the total soil depth (SOLDEP) is subdivided into 4 functional layers. Soil evaporation (SEVP) occurs from a user specified fixed depth upper layer (DEP1), soil nitrogen processes occur the HYDDEP layer which extends from the soil surface to a user specified soil depth. The depth of soil water extraction increases with root growth (GRTD) as the initial rootzone increases in depth at crop emergence to a maximum root depth from which the crop can extract soil water (MEED). The soil profile also includes a soil water storage layer which occurs below the advancing root zone. These soil layer are illustrated in Figure 5.

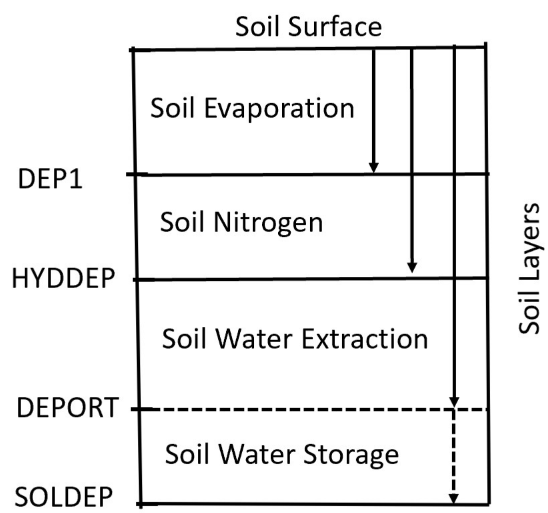

Figure 5. Soil Layers included in the BPCLAWS Soil Water Budget.

A daily soil water balance is computed for each of these layers. The hydrologic components include the following:

- Extractable soil water content – ATSW*
- Precipitation - RAIN
- Irrigation water applied – IRGW
- Available soil water increase to due to root growth – EWAT

- Drainage – DRAIN*
- Runoff – RUNOF*

- Soil evaporation – SEVP
- Transpiration – TR*

Except for the rootzone layer, hydrologic variables followed by * indicate the layer name is added to the variable name. The daily hydrologic layer balance equation is given by:

$ATSW_i* = ATSW_{i-1}* + RAIN + IRGW + EWAT – DRAIN* - RUNOF – TR* – SEVP$

Today's and yesterday's soil water available content for crop transpiration ($ATSW_i$ and $ATSW_{i-1}$) are given by the product of the user specified extractable soil water, EXTR, and the layer's thickness. For the rootzone layer, the amount is given by:

ATSW = DEPORT * EXTR

Adding to available soil water on a daily basis are 4 hydrologic components. Precipitation occurs on a daily basis and may be either rain or snow (SNOW) depending on whether the maximum temperature (TMAX) is greater or less than 1 ^{o}C.

SNOW = SNOW + RAIN

When TMAX is greater than 1 ^{o}C and SNOW is present, snowmelt (SNOMLT) is also calculated, added to RAIN and SNOW reduced.

SNOMLT = TMAX + RAIN * 0.4

RAIN = RAIN + SNOMLT

SNOW = SNOW – SNOMLT

Applied irrigation water is also accounted for on a daily basis. In BPCLAWS, there are a variety of ways that irrigation water can be applied based on user selected options. One method is to specify a fraction of the available soil water content (FTSW) that can be depleted (IRGLVL). When IRGLVL is exceeded, irrigation water is applied in the amount necessary to refill the rootzone to field capacity (TTSW).

FTSW = ATSW / TTSW

TTSW = DEPORT * EXTR

IRGW = TTSW – ATSW

In BPCLAWS, multiple irrigations may also be scheduled based on user specified days of the year (DOY), days after planting (DAP) or the normalized growth stage, NDS. For these options, the user specifies the amount of water applied. An option is also available to irrigate to field capacity at user specified NDS stages.

In BPCLAWS, rootzone depth (DEPORT) increases from a user specified depth at crop emergence. The root growth per DTU is computed as the difference between the maximum depth of water extraction (MEED) and the initial DEPORT at emergence per DTU where frTRG is the NDS at the termination of root growth; frBRG is the NDS value at the beginning of root growth; and tuHAR is the total DTUs required to reach harvest (tuHAR).

GRTDP = (MEED - DEPORT) / ((frTRG - frBRG) * tuHAR)

The daily root growth (GRTD) is computed as the product root growth per degree and the daily temperature units.

GRTD = GRTDP * DTU

As the roots grow deeper into the soil at a daily rate, GRTD, the rootzone depth increases.

DEPORT = DEPORT + GRTD

This rootzone increase makes additional soil water available for extraction in the amount of EWAT.

EWAT = GRTD * EXTR

There are 4 hydrologic components reducing ATSW in each layer. Drainage from a layer occurs when ATSW is greater than TTSW. The daily drainage rate factor (DRAINF) for each layer is used to compute the daily drainage (DRAIN)

DRAIN = (ATSW – TTSW) * DRAINF

The storage of soil water below the rootzone (WSTORG) is adjusted for drainage and increase in rootzone available soil water,

WSTORG = WSTORG + DRAIN - EWAT

Surface runoff (RUNOF) is also computed for each layer. In irrigated scenarios, runoff occurs when the total soil water content (WAT) minus drainage of the HYDDEP layer exceeds saturation (WSAT). Except for rice, the daily rate of runoff under these conditions is the product of this difference and DRAINF.

RUNOF = (WAT - WSAT – DRAIN) * SDRAINF

For irrigated rice, there is no runoff.

For rainfed simulations, runoff is calculated using a user specified curve number (CN2) and slope land surface (Slope). This curve number is adjusted for Slope and canopy cover (COVER) computed from LAI. The internally computed soil retention parameter (SMAX) is adjusted for the fraction of available soil water in the HYDDEP layer.

S = SMAX * (1 - ATSW / (1.12 * TTSW))

If S is greater than 0.2 * S, runoff is computed by:

RUNOF = ((RAIN - 0.2 * S) ^ 2)/(RAIN + 0.8 * S)

Otherwise, there is no RUNOF.

Crop transpiration (TR) also reduces the available soil water in each layer. In BPCLAWS, daily crop transpiration is computed as a function of the daily dry matter production (DDMP), the vapor pressure deficit (VPD) and the transpiration efficiency coefficient (TEC). A discussion of DDMP is provided in the Dry Matter Production, Distribution and Yield section of this report.

VPD represents the difference between the saturated vapor pressure in the stomatal cells of the crop and the vapor pressure in the surrounding the crop canopy. These vapor pressures VPTMAX and VPTMIN are functions of daily TMAX and TMIN. VPD represents the local canopy scale water vapor gradient driving diffusion out of the canopy leaves. VPD is computed as the product of their difference and a user specified vapor pressure deficit factor (VPDF).

VPD = VPDF * (VPTMAX – VPTMIN)

VPDF represents fraction of the day when transpiration is high. Typically, it ranges from 0.65 to 0.75 and increases with increasing climatic aridity.

In BPCLAWS, TEC represents the ratio of CO_2 flux into stomatal cells driven by the CO_2 concentration gradient to water vapor loss driven by the VPD gradient as the production of metabolic sugars by photosynthesis is occurring. Described as the “kd” coefficient, its derivation is presented in Tanner and Sinclair (1983). The magnitude of TEC is related to atmospheric CO_2 concentration, the crop’s photosynthetic pathway (C3, C4), types of plant tissue produced (protein, lipids, carbohydrate) by the crop, canopy leaf area exposed to direct solar radiation (L_D) and effective transpiring leaf area (L_T) of the canopy. In BPCLAWS, TEC is a user specified parameter and daily transpiration is computed by:

TR = DDMP * VPD / TEC

Soil evaporation (SEVP) is another water budget component that reduces the crop available soil water. In BPCLAWS, The daily SEVP is computed as function of weighted daily temperature TD,

TD = 0.6 * TMAX + 0.4 * TMIN

daily albedo (ALBEDO) based on crop albedo (CALB), soil albebo (SALB) and the extent of the canopy covering the ground surface given by a function of LAI intercepting incoming solar radiation (SRAD).

ALBEDO = CALB * (1 - Exp(-KET * ETLAI)) + SALB * Exp(-KET * ETLAI)

A potential soil evaporation (PET) is calculated and adjusted for TMAX greater than 35 ^{o}C or TMAX less than 5 ^{o}C. Evaporation from the soil (EOS) is reduced from PET as a function of canopy shading.

EOS = PET * Exp(-KET * ETLAI)

A minimum soil evaporation (EOSMIN) may also be specified by the user. If PET is greater than EOSMIN and EOS is less than EOSMIN, then EOS equals EOSMIN, the EOS = EOSMIN. The daily soil evaporation (SEVP) is calculated by:

SEVP = EOS

SEVP may also be reduced as a function of the days since the last rain or irrigation event (DYSE) that is greater than a use specified total amount of WETWAT. If DYSE is greater than 1 day or the fraction of transpirable soil water (FTSW) less than 0.5 or ASTW of the DEP1 layer less than or equal to 1, then SEVP is calculated by:

SEVP = SVP * ((DYSE + 1) ^ 0.5 - DYSE ^ 0.5

until rain and irrigation events exceed WETWAT which resets DYSE to 1 day.

In BPCLAWS, water stress factors affecting crop phenology, canopy development, dry matter production and nitrogen fixation are computed based on the fraction of transpirable soil water.

FTSW = ATSW / TTSW

Water stress factors for canopy development (WSFL) and dry matter production (WSFG) are based on user specified crop threshold parameters. As illustrated on Figure 6, when FTSW is greater than the values WSSL, WSFG for canopy LAI and daily dry mater production DDMP respectively, there is no reduction in either of these physiological processes until FTSW becomes less than these thresholds.

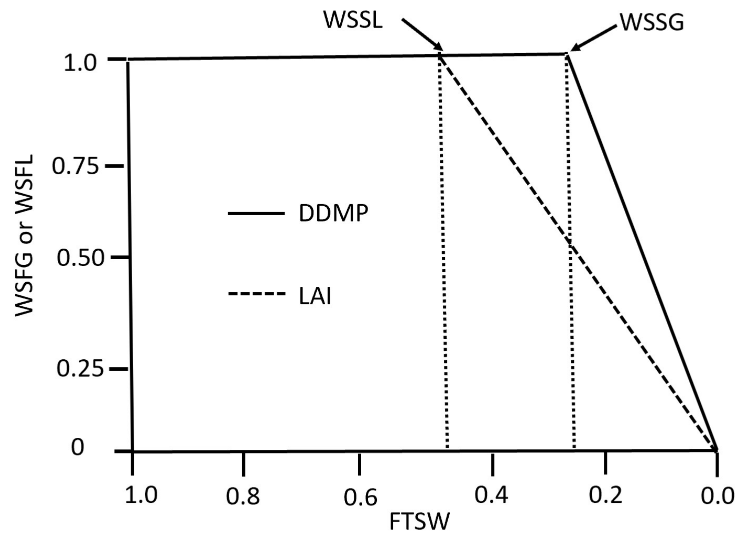

Figure 6. Water Stress Factors for Canopy Development (LAI) and Dry Matter Production (DDMP).

Likewise, the water stress factor for nitrogen fixation (WSFN) which is equivalent to WSFG is reduced when FTSW becomes less than WSSG.

The water stress factor for phenological development (WSFDS) is unity until FTSW becomes less than the absolute value of the user specified threshold parameter WSSD. When FTSW is less than WSSD, WSFDS is multiplied by WSSD which if positive increases the phenological development rate or if WSSD negative the phenological development rate decreases.

WSFDS = (1 - WSFG) * WSSD + 1

These changes in the rate of phenological development are illustrated in Figure 7 below.

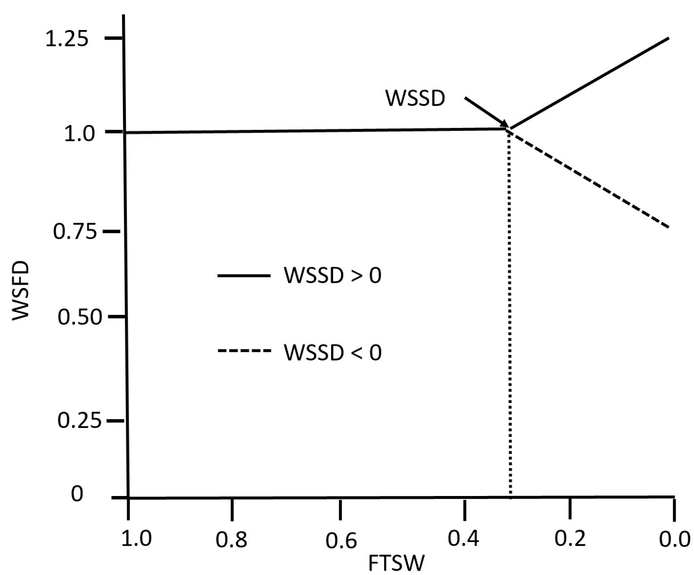

Figure 7. Water Stress Factor for Phenology Development.

Excessive soil water content also has a negative effect on physiological processes. When soil moisture exceeds 99% of saturation, canopy and phenological development as well as nitrogen fixation in legumes ceases until sufficient drainage occurs.

Soil Nitrogen

The nitrogen (N) balance in the soil is important for the simulation of crop growth and yield because it is the nutrient required in the greatest amounts by plants. Nitrogen fertilization is also a major expense in crop production. In addition, the release of soil nitrogen into surface and groundwater affects water quality and its gaseous forms affect air quality.

In BPCLAWS, the soluble nitrogen (NSOL) in the soil is determined by the balance between N inputs and N removal. The N inputs include mineralization of organic matter (NMIN) and fertilizer applied (NFERT). Nitrogen removal includes N volatilization (NVOL), leaching (NLEACH), denitrification (NDNIT), plant uptake (NUP) and bio-fixation (BNF). The $NSOL_i$ balance is computed on a daily basis in the HYDDEP layer by the following equation:

$$NSOL_i = NSOL_{i-1} + NMIN + NFERT – NVOL – NLEACH – NDNIT – NUP - BNF$$

$NSOL_i$ and $NSOL_{i-1}$ are the current day and previous day soluble N content of nitrate (NO_3) plus ammonium (NH_4) in the HYDDEP layer. Mineralization of N contained in organic matter is an important source of soluble N in natural environments as well as in croplands. The mineralization of organic N is a function of potentially mineralizable organic soil N (MNORG), soil temperature (TMPS) and fractional water content (FTSW) in the HYDDEP layer. In BPCLAWS, MNORG is computed from the total organic soil N (NORG) and the user specified fraction of soil organic N available for mineralization (FMIN).

MNORG = NORG * FMIN

The effect of temperature on the rate of N mineralization is represented by the soil temperature coefficient of N mineralization (KN) which is a function of the temperature dependent N mineralization exponent (KNMIN).

KN = 1 - Exp(-KNMIN)

The effect of soil water content on N mineralization is represented by the soil moisture coefficient for N mineralization (RN). When FTSW is less than 0.9, RN is computed by:

RN = 1.111 * FTSW

Otherwise, RN = 10 – 10 * FTSW

NMIN is computed by:

NMIN = MNORG * RN * KN

Since mineralization is a biological activity, high concentrations of N in the soil water (NCON) can inhibit the rate of mineralization. In BPCLAWS, NMIN decreases linearly to zero as NCON increase from 0 to 200 mg/L where 0.0002 is the g N g^{-1} H_20 equivalent of 200 mg/L.

NMIN = NMIN * (0.0002 - NCON) / 0.0002

Where NCON is the soil solution concentration (g N g^{-1} H_20) of NSOL.

In BPCLAWS, multiple applications of fertilizer may also be scheduled based on user specified days of the year (DOY), days after planting (DAP) or the normalized development stage, NDS. For these options, the user specifies the amount of fertilizer applied (NFERT). The volatilization of applied fertilizer (NVOL) occurs on the day of application in a user specified fraction (VOLF) of NFERT.

NVOL = VOLF * NFERT

Leaching of N from the HYDDEP layer occurs during drainage. It is computed as a function of the NSOL and the fraction of drainage from the total soil water content (WAT) of the HYDDEP layer.

NLEACH = NSOL / (DRAIN / (WAT + DRAIN))

However, NLEACH only occurs when is NCON is greater than 1 mg/L.

In BPCLAWS, denitrification (NDNIT) occurs when anaerobic conditions exist in the HYDDEP layer (FTSW > 1). Like mineralization, NDNIT is a function of TMPS and NCON. This function is expressed as:

NDNIT = NCON * (1 - Exp(-KDNIT))

where KDNIT is a temperature dependent parameter.

In BPCLAWS, the amount of NDNIT is limited to the upper 30 cm of the soil profile if the HYDDEP layer has a greater depth. There is also no denitrification when the crop is rice.

The calculations of N uptake (NUP) and biological N fixation (BNF) are described in the preceding Plant Nitrogen section.

The soil N available for crop growth (SNAVL) is computed from NCON. This requires determining the fraction of the HYDDEP layer in which are roots are growing (FROOT).

FROOT = DEPORT / HYDDEP

If DEPORT is greater than HYDEP, FROOT is limited to unity implying that all SNAVL occurs in the HYDDEP layer.

It is also assumed that only soil N above a concentration of 1 mg/L (0.000001 g N g^{-1} H_20) contributes to crop growth. The conversion of NCON to SNAVL also requires the inclusion of the available soil water in the HYDDEP layer (ATSW) and a unit conversion factor of 1000 g H_20 / mm depth per m^2 to obtain SNAVL in units of g N m^{-2}.

SNAVL = (NCON - 0.000001) * ATSW * 1000 * FROOT

Model Organization

The BPCLAWS model organization follows that of the SSM-iCrop2N model with the exception of that the control of the simulations (SimMain) occurs near the end of the code rather than at the beginning. A detailed description of the BPCLAWS modules and input parameters is presented in Appendix 1 In this section, the overall flow of the simulations and control options are discussed.

In the SSM-iCrop2N model, model scenarios, parameters and timeseries inputs are obtained from the Run, Location, Management, Soil and Crop worksheets. In BPCLAWS, these inputs are obtained from similarly named files with comma separated values (CSV) which are located in a user specified input folder (eg ..\Model_Inputs). In this folder, the following csv files are required:

scenario_inputs.csv – identifies one or more scenarios which will be simulated and where the location, management, soil and crop data for each scenario occur in the following four files.

location_inputs.csv – provides information about the locations of simulations and the name of the weather files which correspond with the locations. The daily weather data files must be in the Weather subfolder of the input folder (eg ..\Model_Inputs\Weather). These weather files are also csv files.

manage_inputs.csv – provides information about which management options may be included in the simulations. Management choices include a variety of water and nitrogen simulation options.

soil_inputs.csv – provides information about the soil characteristics needed for simulations.

crop_inputs.csv – provides information about the crop characteristics needed for simulations.

As an example of the setup of a scenario, Figure 8 shows a scenario_inputs file displayed in an Excel spreadsheet

	A	B	C	D	E
1	Scenario	LocRowNo	MangRowNo	SoilRowNo	CropRowNo
2	soybean-Gol 38	5	38	46	57

Figure 8. Example of a scenario_nput File.

In the Scenario column (A) is the scenario name "soybean-Gol 38". In the LocRowNo column, the number 5 is the identifier for the location data in the location_inputs.csv file. As illustrated in Figure 9, the location identifier (5) is found in row 2 of the #Loc column in the location_inputs file. This row contains additional parameters that are inputs for the "soybean-Gol 38" scenario. Of interest is the entry in the Weather column. It is the name of the weather file (GOL_hashemabad_99241.csv) which must be present in the Weather subfolder.

	A	B	C	D	E
1	#Loc	Location	Latitute	VPDF	Weather
2	5	GOL_hashemabad_99241	36.85	0.63	GOL_hashemabad_99241

Figure 9. Example of a location_inputs File

In the MangRowNo column (C) of the scenario_inputs file is the identifier of management data (38) which will be read from the manage_inputs.csv file. As illustrated in Figure 10, the management inputs will be read from row 48 which contains the identifier 38 in the #Manag column.

	A	B	C	D	E
1	#Manag	Manag	FixFind	Fyear	yrno
47	36	Rice_Irr1_N0	0	2010	5
48	360	Rice_PP	0	2010	5
49	38	Soybean_irr1_N0	0	2010	5

Figure 10. Example of a management_inputs File

The management_inputs file also contains information regarding irrigation and N fertilization options. This information is read from the irrigation_inputs and nferti_inputs files respectively. These options are described in the Soil Water and Soil Nitrogen sections.

Similarly, the soil data for this scenario will be read from the row in the soil_inputs file which has the value 46 in #Soil column. Likewise, the crop data will be read from the row in crop_inputs file which has the value 57 in the #Crop column.

The organization of the code is illustrated as a flowchart in Figure 11. Execution of program in the SimMain function begins with the LocManagInputs method which reads data from the location and management input files. Using these inputs, the FindSimSowDate method find the planting day based on user specified date, weather and soil conditions. The Weather method reads the weather variables. The PhenologyBD method obtain crop parameters from the crop_inputs file and computes the daily temperature units and growth stages. If the parameter nitrogen equals 1 or 2, N availability effects on canopy development are simulated in the CropLAIN method. Otherwise, the CropLAI method is used. The DMProduction method reads data for the crop_input file and computes dry matter production and distribution. If nitrogen effects on crop growth are simulated, the PlantN method simulates the effects of nitrogen on crop growth and yield. It reads additional N parameters from the crop_input file.

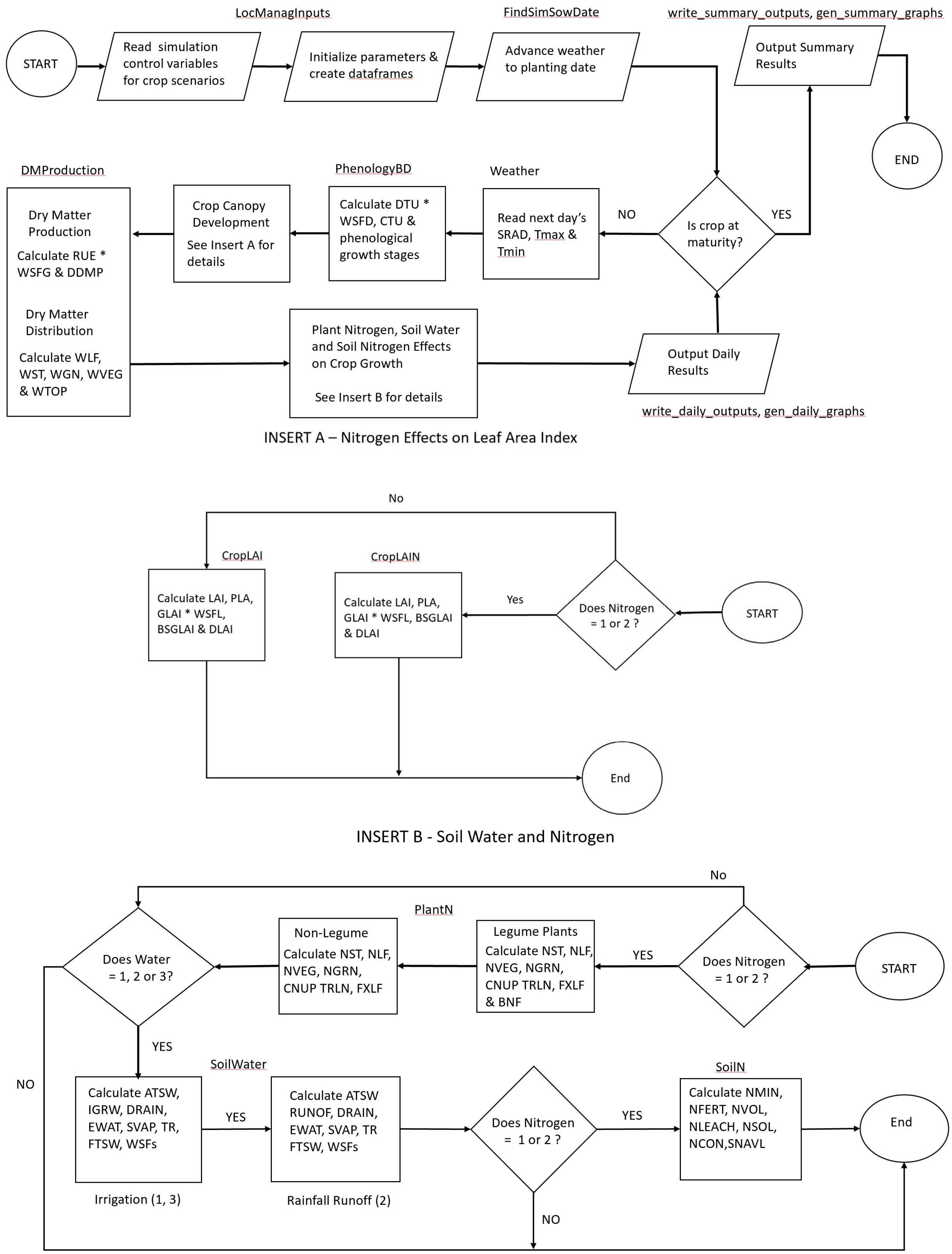

Figure 11. Flow Chart of the BPCLAWS model organization.

It is important to note that simulation of N effects requires the inclusion of the SoilWater and SoilN methods. This is accomplished by setting the parameter water equal to 1, 2 or 3. These methods read soil parameters from the soil_inputs file. When water equals 1, irrigation is simulated based on the rootzone soil water content. When water equal 2, a rainfed crop is simulated and runoff is computed. When water equals 3, multiple irrigations may be simulated based of day of the year, days after planting or growth stage. Application amounts may be specified by the user or based on rootzone water content when growth stage specified.

Like SSM-iCrop2N, BPCLAWS writes csv files of daily and annual summary outputs for each year included in the scenario to a user specified output directory. These outputs include many variables computed during the simulation. In addition, BPCALWS generates custom groupings of daily and annual summary variables in both html and png graphical formats. Examples of these graphs are presented in the Results section below.

Results

In this section, simulations of major crop types of interest in the western United States are presented and compared to the SSN-iCrop2N model results in order to verify the BPCLAWS code successfully reproduced the same results as the SSM-iCrop2N model. The SSM-iCrop2 model for regional scale simulation was parameterized and validated by comparison with numerous field experiments for more than 30 crop species in grown in climatic regions in Iran that are similar to the western United States (Soltani et al, 2020). These results indicated the model was robust in the predictions of crop yield and water use with a root mean square of error as percentage of observed mean for yield of 18% for grain field crops, 14% for non-grain crops 14% for vegetables and 28% for fruit trees.

Ideally, a similar validation of the BPCLAWS model would be performed by developing parameterized models for each of the major crops in the Reclamation regions. Unfortunately, this objective could not be accomplished in this study. However, there is no reason that with adequate resources BPCLAWS has the capabilities to accomplish this result. In the following sections, the capabilities of BPCLAWS to model major crop types grown in the western United States is demonstrated along with selected daily and annual summary graphs that generated for each year included in the simulation.

Small Grains – Non Legume

Wheat is a major food crop grown worldwide and also in the Reclamation regions. It is annual cool season, non-legume field crop that uses the C3 photosynthetic pathway. To demonstrate the capabilities of BPCLAWS to simulate management of wheat and other similar crop types, an irrigated and fertilized winter wheat crop was simulated in which planting occurred on last day of a 5-day rain free period with a moving average temperature less user specified 16 ^{o}C after a user specified initial planting date of approximately August 22nd (Julian day 234). During the 5-years included in this simulation (2010 – 2014), these conditions were met in the month of November. The BPCLAWS models generates 17 daily output graphs which include groupings of many of the variables affecting the crop's growth, water consumption and yield. Figure 12 illustrates the range of temperatures that occurred during the 2010 growing season including average daily (TMP), maximum (TMAX), minimum (TMIN) and thermal units (DTU).

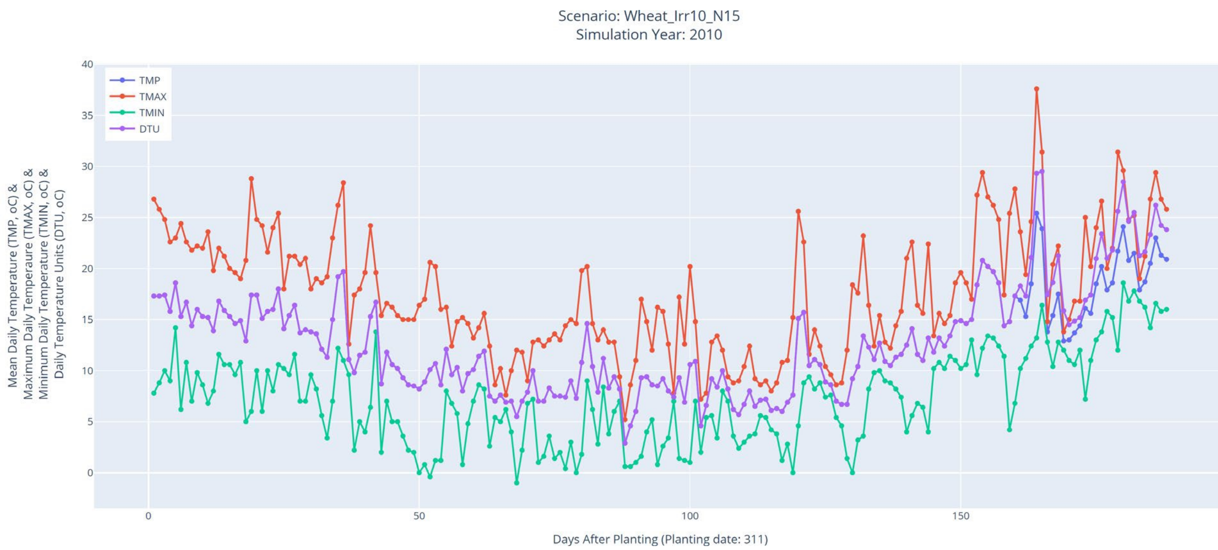

Figure 12. Wheat - Average Daily, Maximum, Minimum and Daily Thermal Units during the 2010 Growing Season.

Figure 13 illustrates the daily development of the crop canopy (LAI), the normalized development stage (NDS) as well as the fraction of solar radiation intercepted by the growing canopy (FINT).

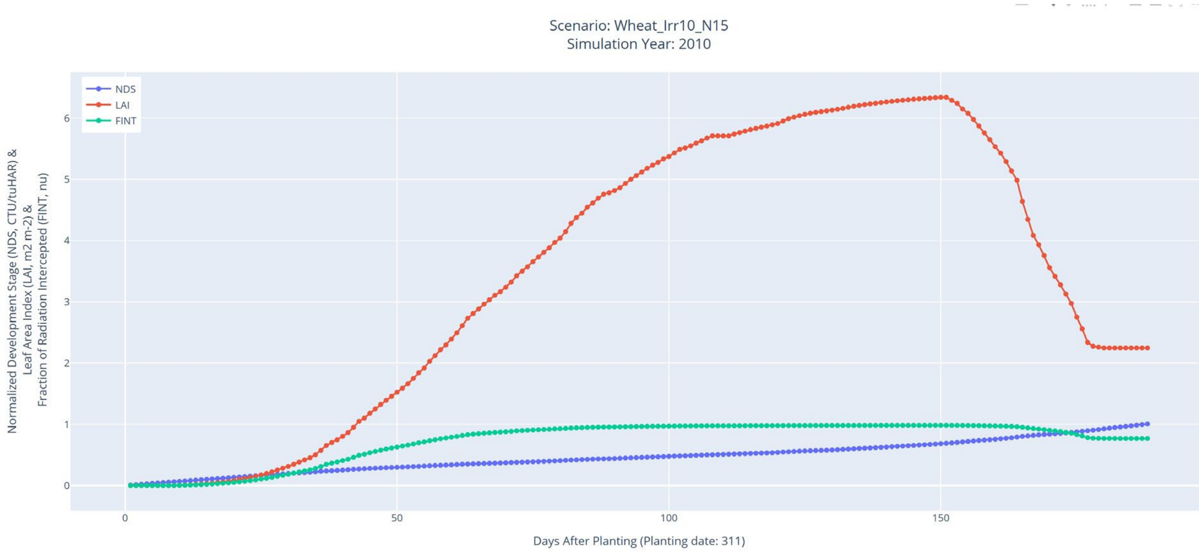

Figure 13. Wheat - Average Daily, Maximum, Minimum and Daily Temperature Units during Growing Season.

Figure 14 provides insight into the daily hydrologic balance of the surface layer including

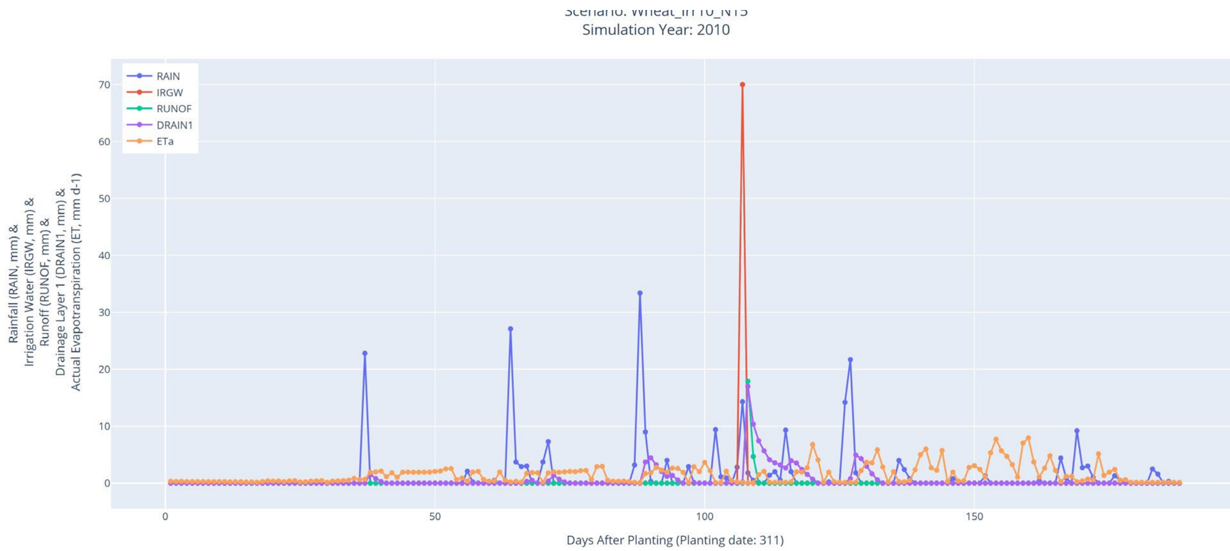

Figure 14. Wheat - Rainfall, Irrigation, Runoff, Drainage and Evapotranspiration.

precipitation (RAIN), applied irrigation water (IRGW), runoff (RUNOF), drainage from the DEP1 (DRAIN1) and evapotranspiration (ETa). Of note, this wheat crop was irrigated with 70 mm of water on the 107th day after planting which corresponded with its phenological growth stage (NDS) exceeding the user specified value of 0.5. However, rainfall also occurred simultaneously in the amount of 14 mm resulting in surface runoff occurring for 2 subsequent days in the amounts of 17 and 4 mm. Figure 15 illustrates several of useful features of the Plotly html graphs generated by BPCLAWS. In this figure, the zoom feature has been used along with labeling of the timeseries data to focus on the results for the day after the irrigation and rain events.

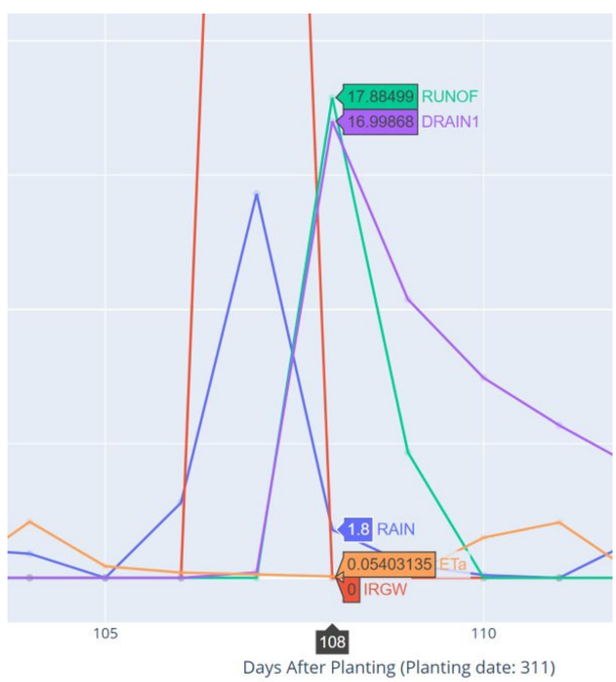

Figure 15. Example of Plotly html Zoom and Labelling features.

As shown on Figure 16, cumulative hydrologic timeseries are also computed for the growing season including cumulative crop transpiration (CTR), soil evaporation (CES), evapoptranspiration

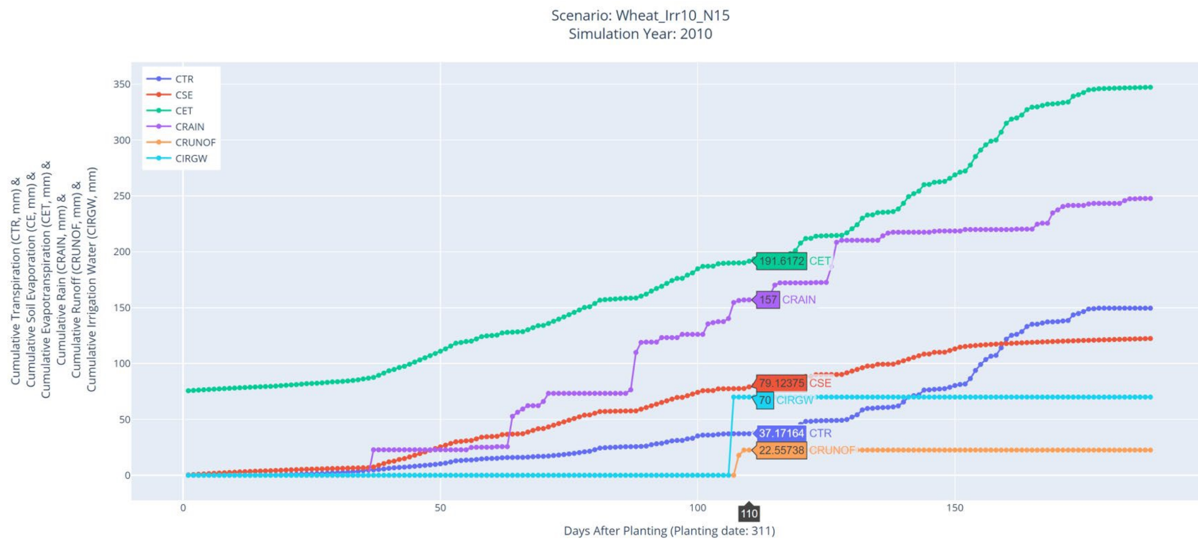

Figure 16. Wheat - Cumulative Hydrologic Water Budget Components Timeseries.

(CET), precipitation (CRAIN), runoff (CRUNOF) and applied irrigation water (CIRGW).
The wheat scenario includes 3 applications of nitrogen fertilizer of on days 1, 43, 95 after planting. BPCLAWS generates a cumulative daily nitrogen balance graphic for each growing season of the simulation period. Figure 17 illustrates the components of soil nitrogen budget including organic

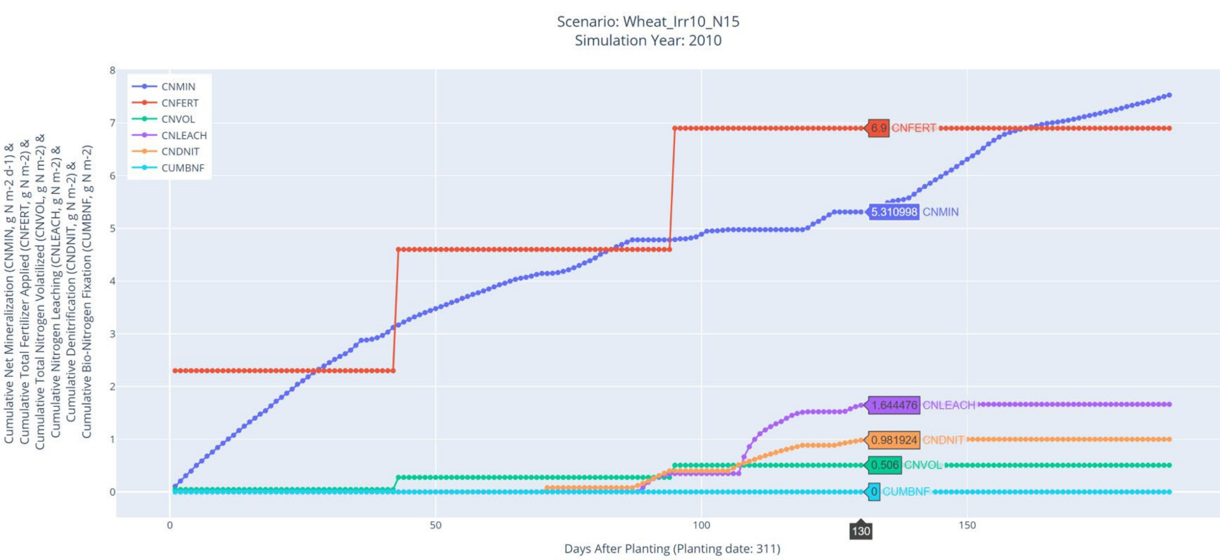

Figure 17. Wheat - Cumulative Daily Soil Nitrogen Budget Components Timeseries.

nitrogen mineralization (CMIN), applied nitrogen fertilizer (CNFERT), volatilization of applied nitrogen fertilizer (CNVOL), nitrogen leaching (CNLEACH), denitrification (CNDNIT) and biological nitrogen fixation (CUMBNF). Another example of the usefulness of the BPCLAWS graphs for analysis is illustrated in Figure 18. This graph shows that both leaching of nitrogen and denitrification occur in the HYDDEP layer during the rainy period from approximately 80 to 120 days after planting which also includes the irrigation event on day 107.

BPCLAWS also generates a variety of daily timeseries data associated with crop growth and seed formation. Figure 18 illustrates the daily dry matter production (DDMP) and seed growth (SGR).

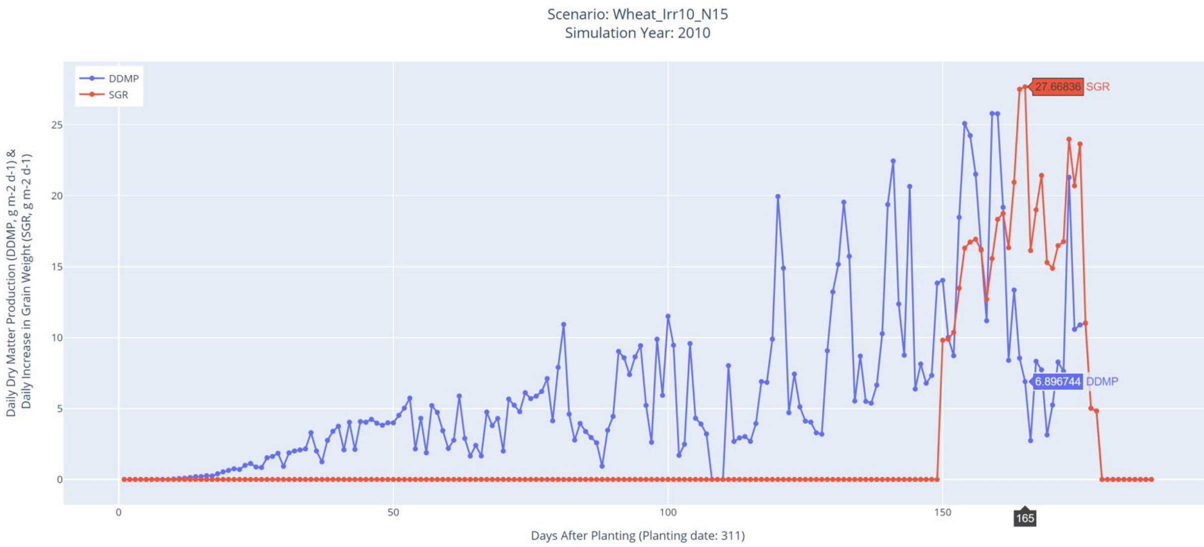

Figure 18. Wheat - Cumulative Daily Dry Matter Production and Seed Growth Timeseries.

The increasing trend in DDMP and its daily variability correspond well with changes in solar radiation (not shown) during the growing season. The SGR daily formation begins on the 149 day after planting and reaches it peak on day 165. The graph also shows the rapid decline in DDMP starting on day 160. This occurs as a direct consequence of the priority for seed growth over dry matter production during this stage of phenological development.

BPCLAWS also produces 8 annual summary graphs for a variety of groupings of hydrologic, nitrogen and crop growth and yield variables. Figure 19 illustrates the annul volumes of hydrologic components affecting the rootzone water balance during the 5-year simulation period for the wheat crop.

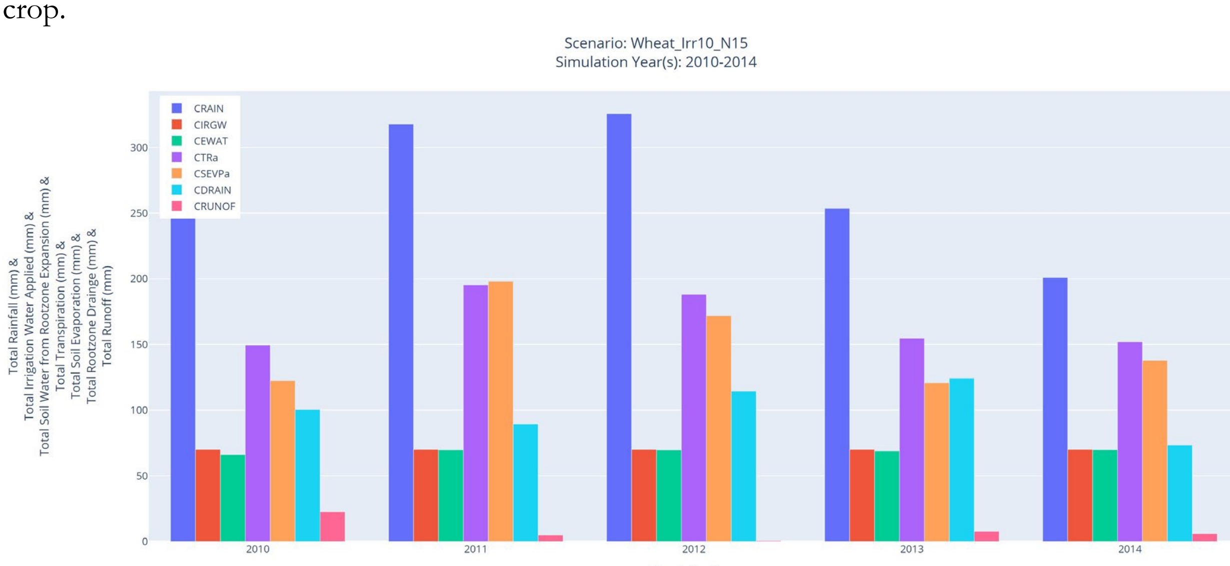

Figure 19. Wheat - Annual Summaries of Precipitation, Applied Irrigation Water, Soil Water Increase from Storage, Crop Transpiration Soil Evaporation, Drainage, and Runoff from the Rootzone Layer.

The figure illustrates annual totals of precipitation (CRAIN), applied irrigation water (CIRGW), soil water increase due to the increase in rootzone depth after emergence (CEWAT), crop transpiration (CTRa), soil evaporation (CSEVPa), rootzone drainage (CDRAIN) and runoff (CRUNOF). In the simulated wheat scenario, CITGW and CEWAT are the same every year. The interannual variability in CRAIN is reflected in proportional changes in CTRa, CSEPa, CDRAIN and CRUNOF.

BPCLAWS also generates annual summaries of the nitrogen budget components. As illustrated in Figure 20, these components include organic nitrogen mineralization (CMIN), biological nitrogen fixation (CBNF), applied nitrogen fertilizer (CNFERT), nitrogen leaching (NLEACH), denitrification (CNDNIT) and nitrogen fertilizer volatilization (CNVOL) from the HYDDEP layer. In the wheat simulations, all years have the same CNFERT and CNVOL. CBNF is zero as wheat is not a legume crop. Warmer years without excessive precipitation will have more nitrogen mineralization and less leaching and denitrification (eg 2010 and 2014).

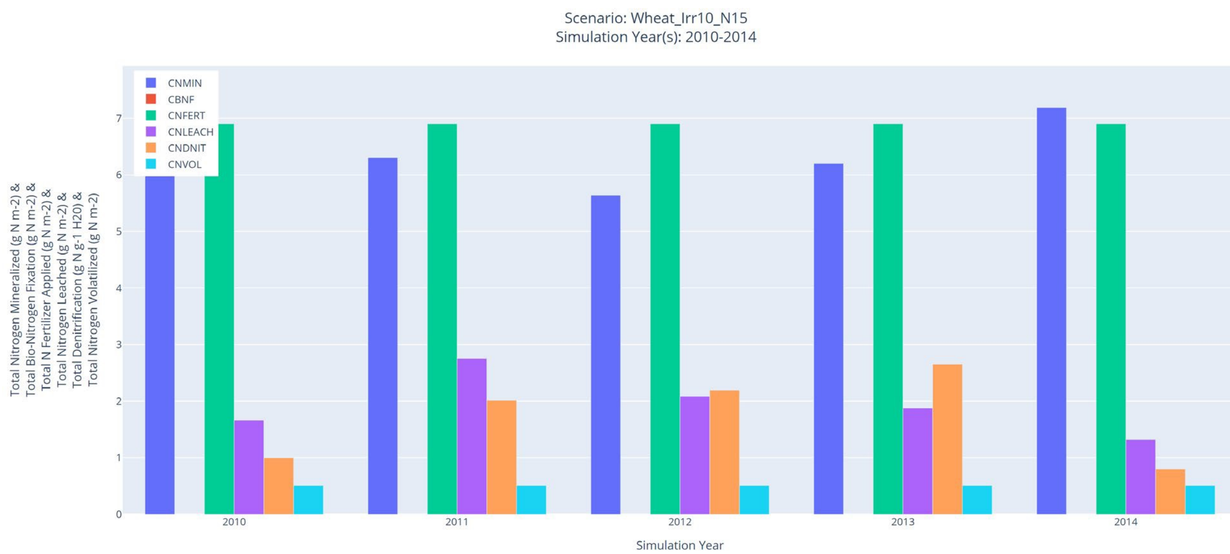

Figure 20. Wheat - Annual Summaries of Nitrogen Mineralization, Biological Nitrogen Fixation, Applied Nitrogen Fertilizer, Nitrogen Leaching, Denitrification, and Nitrogen Volatilization from the HYDDEP Layer.

Annual summaries of the total amounts of above ground plant weight (WTOP), vegetative weight of stems and leaves (WVEG), weight of seed (fruit) yield (WGRN) and the harvest index (HI) which is the ratio WGRN/WTOP expressed as a percentage are presented as shown on Figure 21.

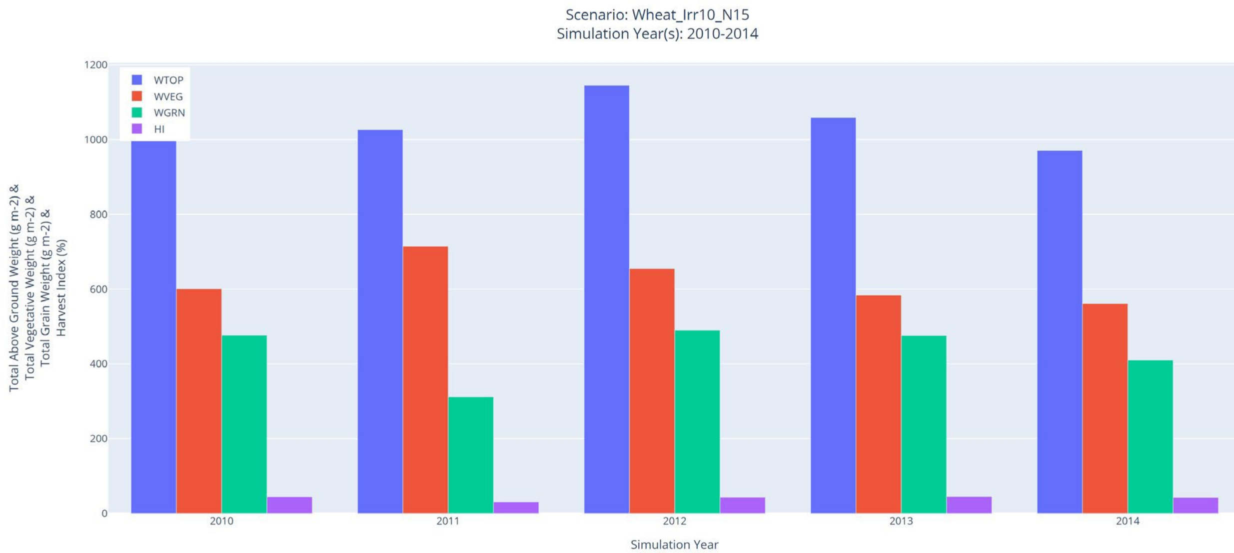

Figure 21. Wheat - Annual Summaries of Total Above Ground Plant Weight, Vegetative Weight of Stems and Leaves, Weight of Grain yield and the Harvest Index.

In this wheat simulation, the weight of grain yield ranged from 312 g m^{-2} in 2011 to 490 g m^{-2} in 2012 (3.12 metric tons per hectare to 4.9 metric tons per hectare) with corresponding HI's ranging from 30 to 42%.

Corn (aka Maize) is a major crop grown throughout Reclamation regions in the western United States. It is annual warm season, non-legume field crop that uses the C4 photosynthetic pathway. In the BPCLAWS scenario, a 5-year period from 2010 to 2014 is simulated with the same weather conditions as the wheat crop. Planting of the crop occurred on June 19 (Julian day 170). The crop was managed by irrigating whenever the fraction of plant available soil water content in the rootzone became less than 0.5 by an amount necessary to fill the rootzone to field capacity. It was also fertilized twice during the growing season. Nitrogen fertilizer was applied at the time of planting in the amount of 2.3 g N m^{-2} and mid-way through the growing season in the same amount of which 2% volatilized in both instances.

The daily crop transpiration, soil evaporation and evapotranspiration during the growing season are shown on Figure 22.

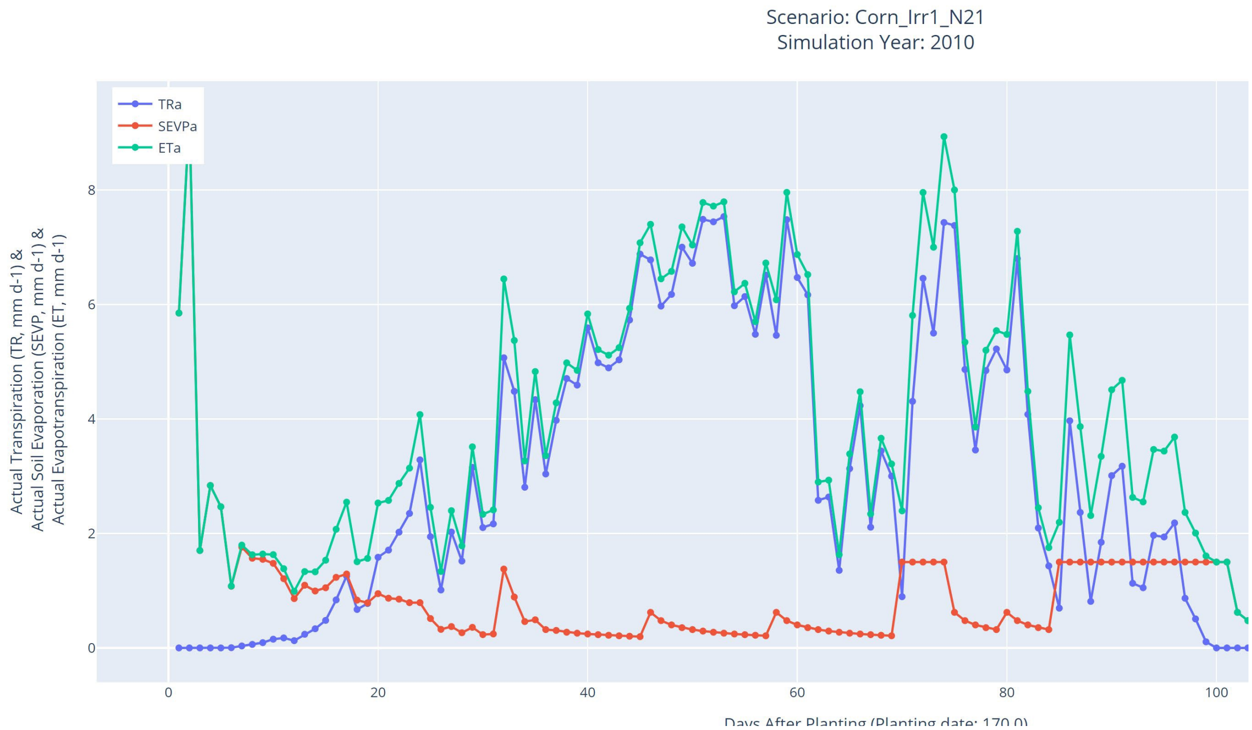

Figure 22. Corn - Daily Transpiration, Soil Evaporations and Total Evapotranspiration.

The reduction in crop transpiration occurring in the period from 60 to 70 days after planting was associated with a reduction in solar radiation, temperature and vapor pressure deficit during this portion of the growing season.

The cumulative water balance components during the growing season are illustrated on Figure ??. As shown on the Figure 23, the crop was irrigated five times during the growing season including on days 3, 32, 47, 58 and 80 days after planting. The total amount of applied irrigation water was 326 mm.

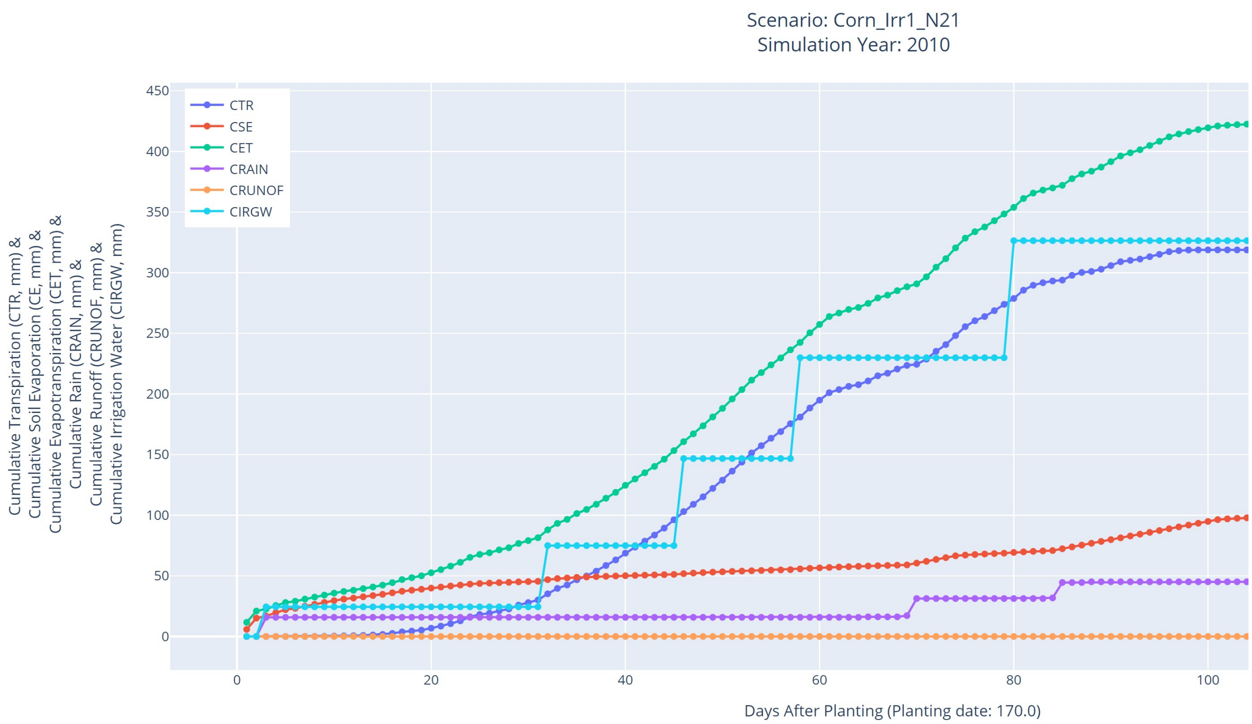

Figure 23. Corn - Cumulative Water Balance Components.

BPCLAWS also generates a variety of graphs providing information about the daily nitrogen budget components of the crop and HYDDEP layer. Figure 24 illustrates the daily amounts of nitrogen

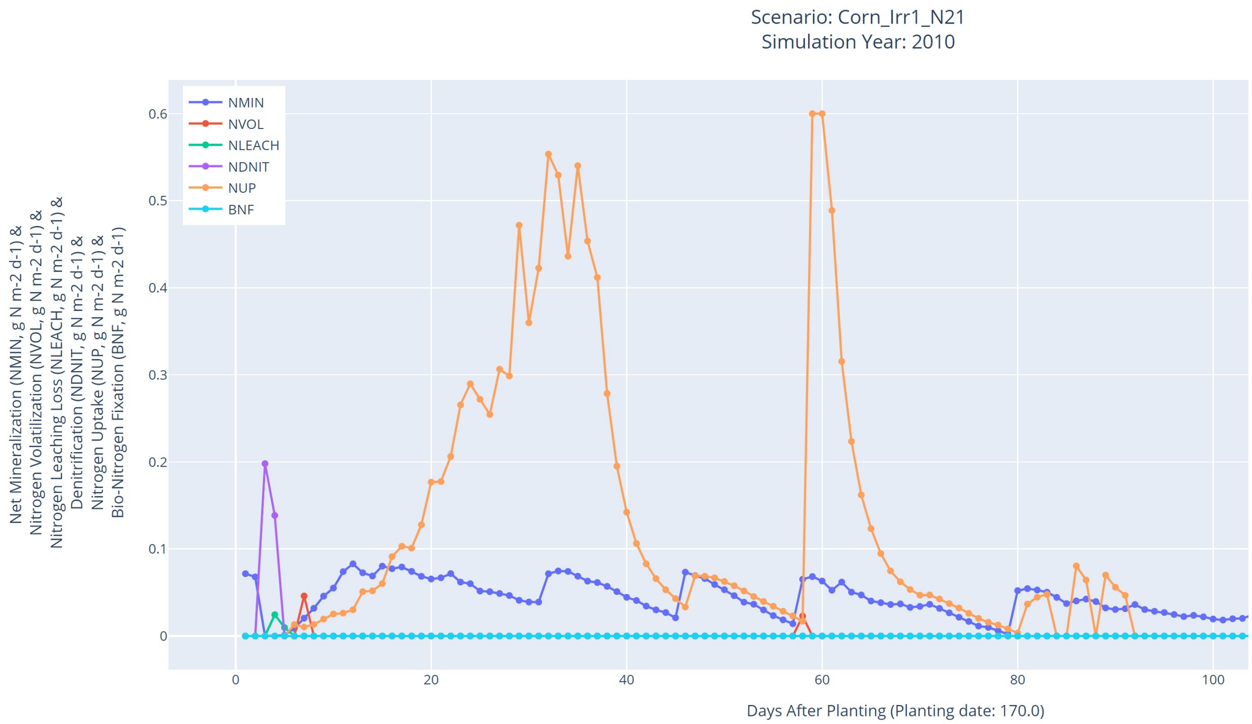

Figure 24. Corn - Daily Nitrogen Budget Components in the HYDDEP Layer.

mineralization (NMIN), volatilization (NVOL), leaching (NLEACH), denitrification (NDNIT), crop uptake (NUP) and bio-fixation (BNF). As shown, an increased amount of NUP is associated with the fertilizer application event occurring on day 58 after planting. In BPCLAWS as illustrated by Figure 25, details of the daily transfer of nitrogen between plant organs can be examined during the growing season.

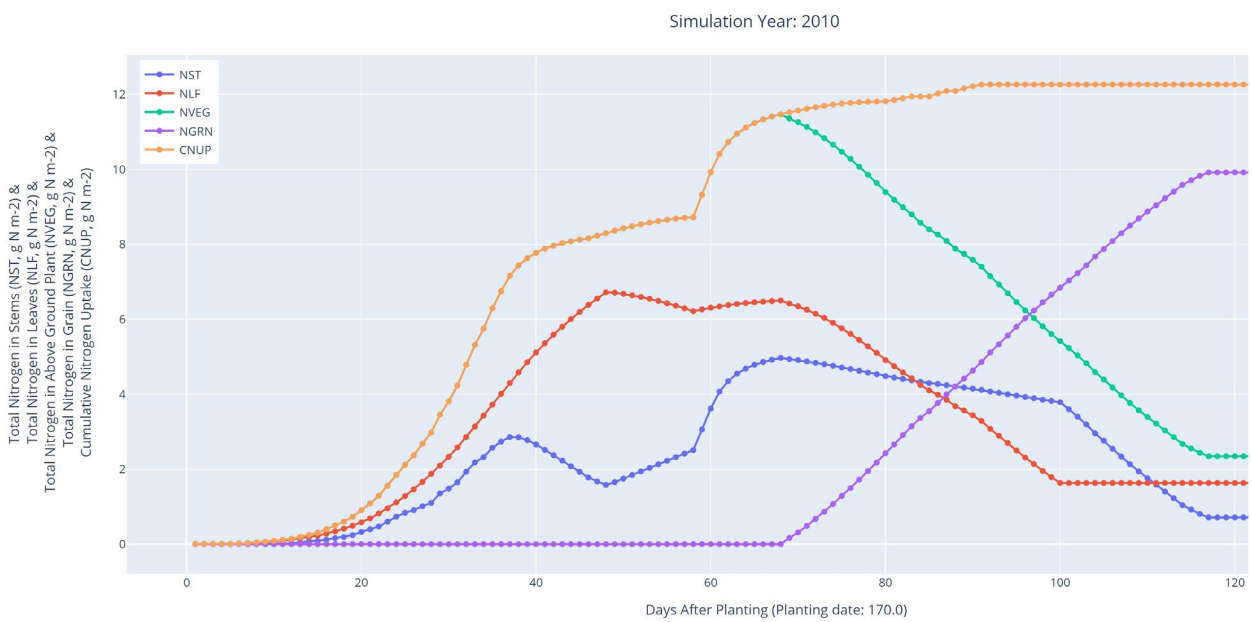

Figure 25. Corn - Daily Nitrogen Content of Plant Organs.

As shown on Figure 25, after the onset of seed formation beginning on day 68 after planting, the nitrogen content of the stems (NST), leaves (NLF) are decline as nitrogen is transferred to the grains.

BPCLAWS also provides several additional annual summaries. Figure 26 illustrates the total annual crop evaporation (CETa), transpiration (CTRa), soil evaporation (CSEVPa) and vapor pressure deficit (CVPD) for over the 5-year period covered by the corn crop simulation. Figure 26 shows a summary of total annual above ground crop weight (WTOP), vegetative stems and leaves (WVEG), grain yield (WGRN) and harvest index (HI). In this simulation, grain yield ranged from 739 to 909 g/m^2 approximately equivalent to 74 to 91 metric tons per hectare.

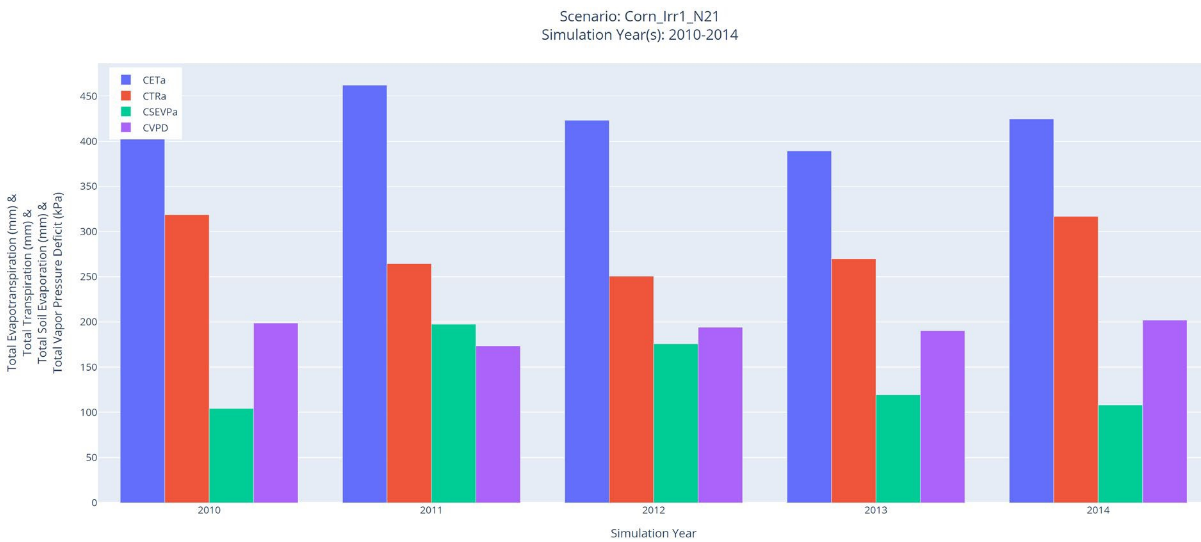

Figure 26. Corn - Annual Summary of Crop Evapotranspiration, Transpiration, Soil Evaporation and Vapor Pressure Deficit.

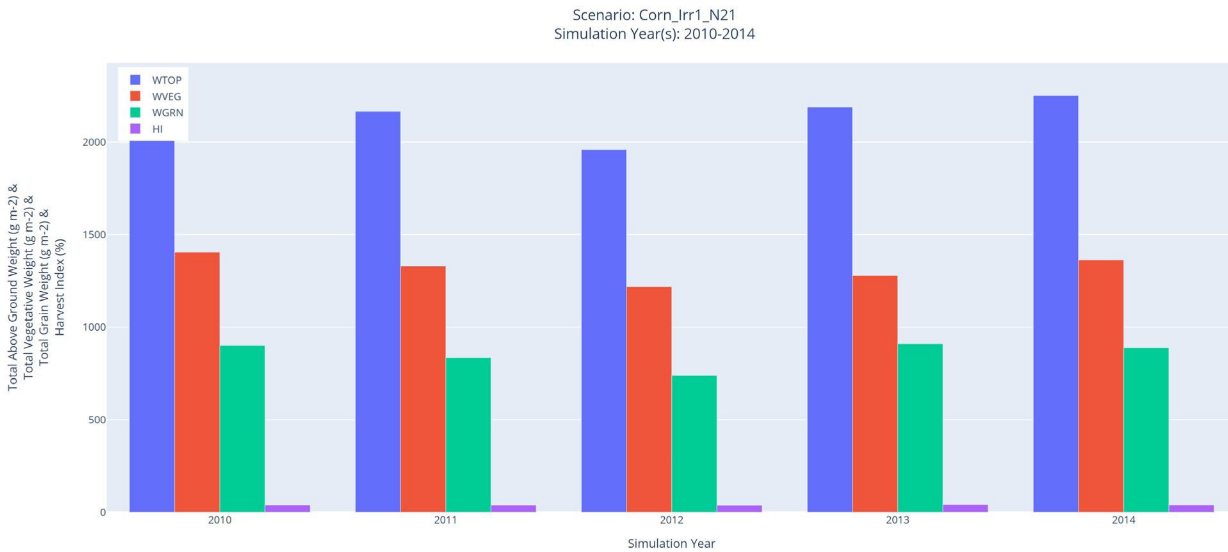

Figure 27. Corn - Total Annual Weight of Above Ground Crop Matter, Vegetative Stems and Leaves, Grain and Harvest Index.

Small Grains - Legume

Soybeans are a major crop grown in the Great Plains region of the western United States. Although it is grown in some as a rainfed crop it is also irrigated in parts of the Central and Northern Great Plains. It is annual warm season, legume field crop that uses the C3 photosynthetic pathway. In the BPCLAWS scenario, a 5-year period from 2010 to 2014 is simulated with the same weather conditions as the wheat crop. Planting of the crop occurred on June 22 (Julian day 173). The crop was managed by irrigating it three times during the growing season based on NDSs of 0.1, 0.3 and 0.5 which occurred on days 11, 35 and 60 after planting. It was also fertilized once on the day of planting in the amount of 2.3 g N m^{-2} of which 2% volatilized on the same day.

As some of the daily time series graphs have already been described, the discussion of soybeans will focus on a few cumulative daily and annual graphs. Figure 28 illustrates the daily cumulative water

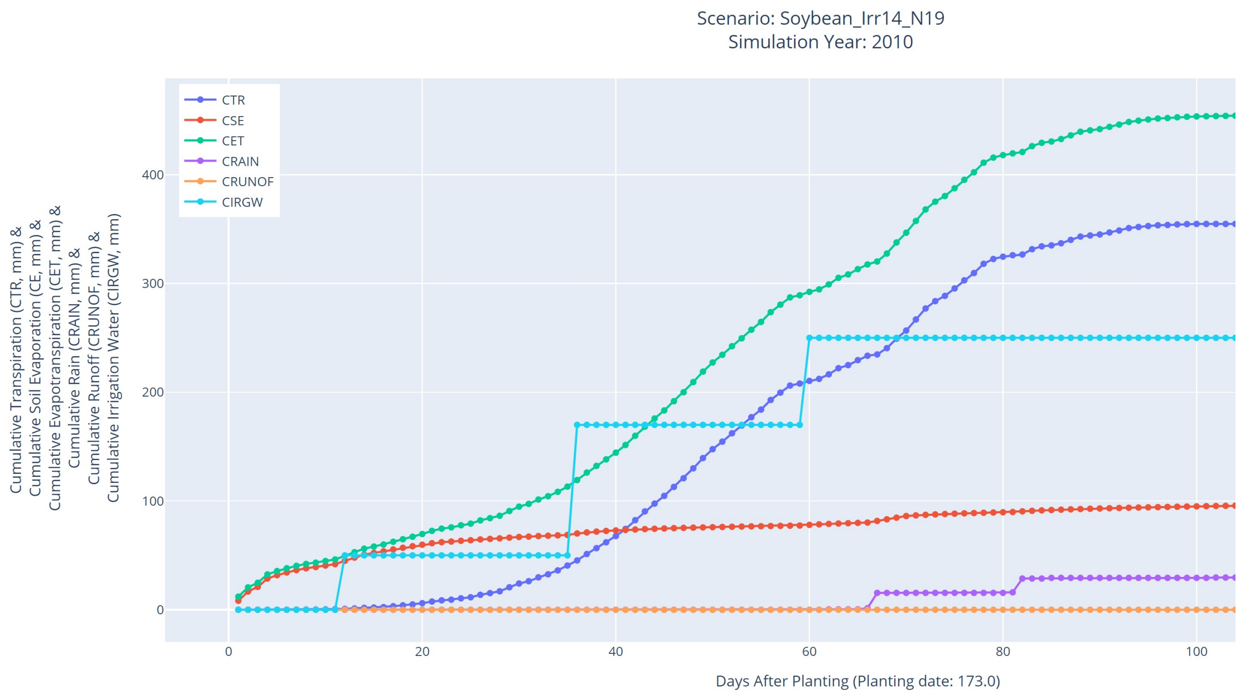

Figure 28. Soybean - Cumulative Water Balance Components.

balance components. In addition to the three irrigation events totaling 250 mm of applied water, there were 3 rainfall events totaling 65 mm occurring in the later part of the growing season. The crop evapotranspiration totaled 457 mm of which crop transpiration was approximately 78 %.

Figure 29 presents the nitrogen budget components. Of note is the contribution of biological nitrogen fixation (CUMBNF) starting on day 52 and end on day 78 after planting. For this soybean crop, bio-fixation contributed 7.3 g N m^{-2} to crop growth. It also provides information indicating that 2 denitrification events totaling 1.9 g N m^{-2} and one leaching of 1.1 g N m^{-2} event occurred during the growing season.

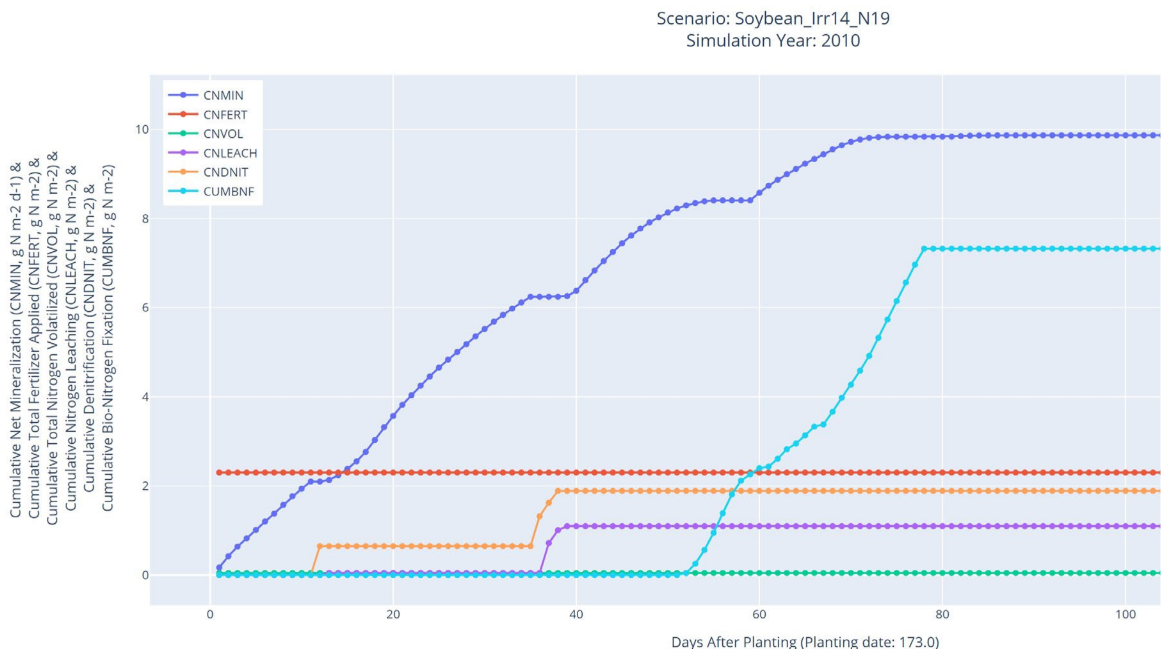

Figure 29. Soybean - Cumulative Nitrogen Budget Components.

Figure 30 illustrates the accumulation and translocation of dry matter between plant organs during the growing season. The translocation from the vegetative organs to the grains begins on day 72

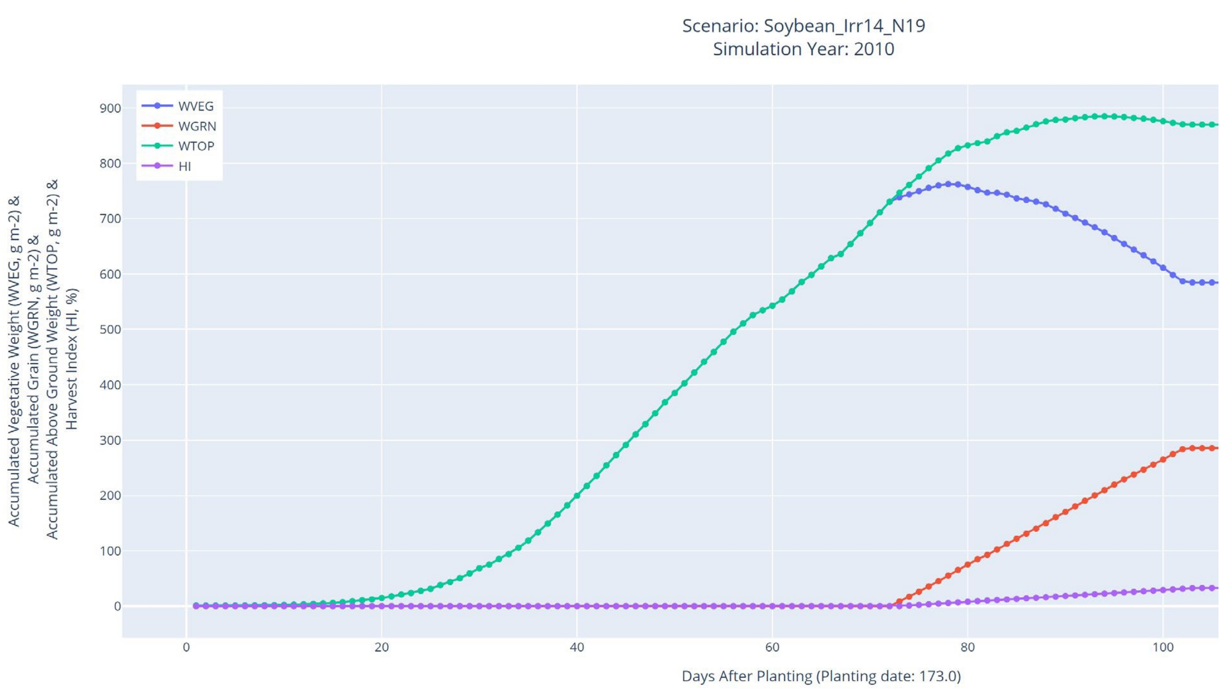

Figure 30. Soybean - Cumulative Weights of Crop Organs during Growing Season.

and is completed by day 103 after planting. The Harvest Index increases during this period of a maximum of 33 %.

Figure 31 presents the annual summary of the total annual crop evaporation transpiration, soil evaporation and vapor pressure deficit for over the 5-year period of the corn crop simulation.

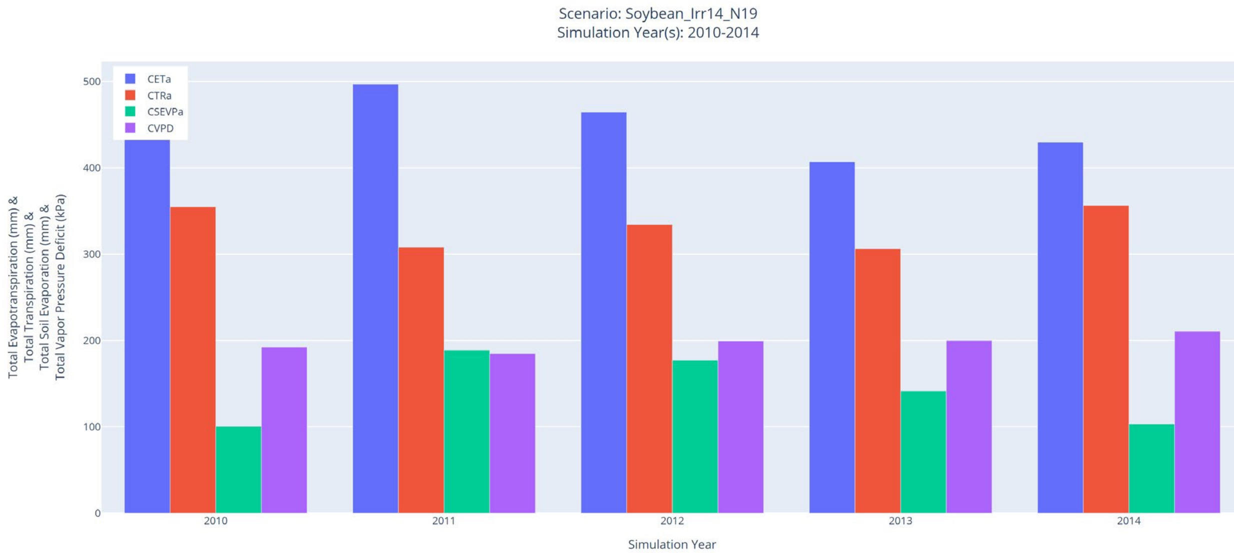

Figure 31. Soybean - Annual Summary of Crop Evapotranspiration, Transpiration, Soil Evaporation and Vapor Pressure Deficit.

Total evapotranspiration ranged from a high of 496 mm in 2011 to low of 407 mm in 2013. However, crop transpiration was higher in 2010 and 2014 than in either of these years.

Figure 32 provides a summary of total annual above ground crop weight, vegetative stems and leaves, grain yield and harvest index.

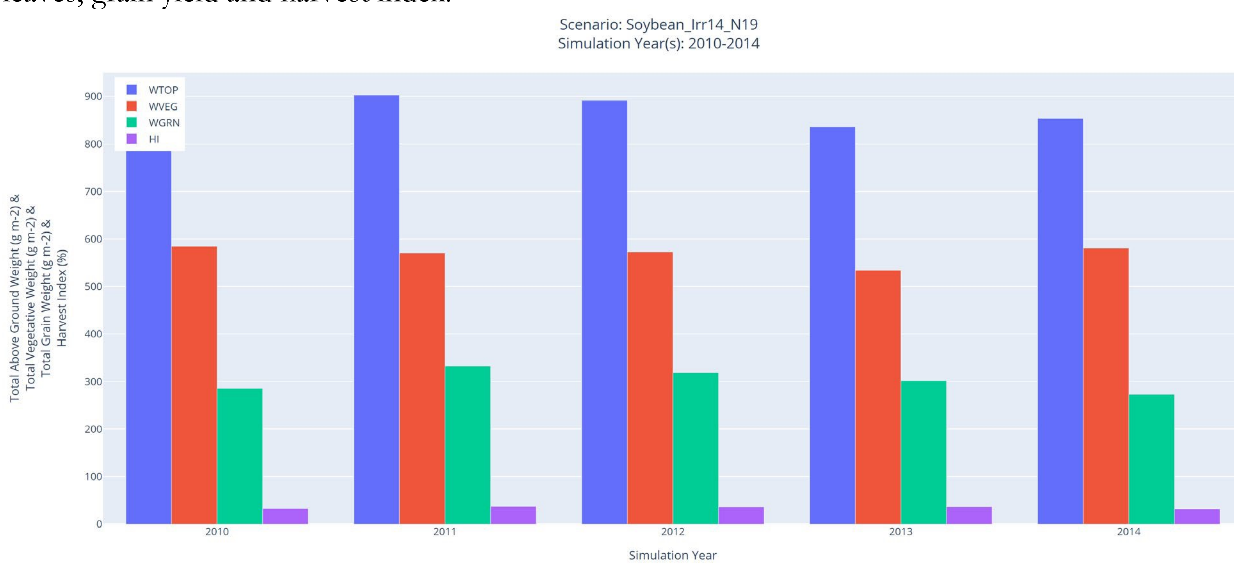

Figure 32. Soybean - Total Annual Weight of Above Ground Crop, Vegetative Stems and Leaves, Grain and Harvest Index.

In this simulation, grain yield ranged from 273 to 332 g m^{-2} approximately equivalent to 27 to 33 metric tons per hectare with the harvest index ranging from 32 to 37%.

Alfalfa and Pasture

Alfalfa is a major crop grown in Reclamation regions of the western United States. It is perennial, legume field crop that uses the C3 photosynthetic pathway. In the BPCLAWS scenario, a 5-year period from 2010 to 2014 is simulated with the same weather conditions as the wheat crop.

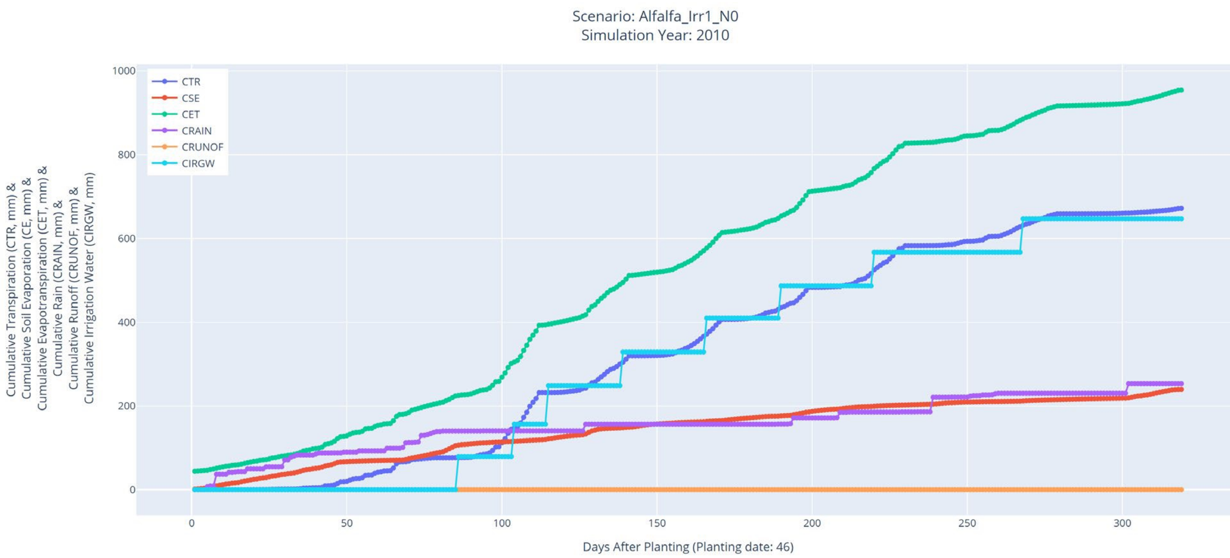

Figure 33. Alfalfa - Cumulative Water Balance Components.

Figure 33 illustrates an alfalfa crop irrigated to maintain soil moisture between field capacity and a fraction of plant available water above 0.5 in the rootzone. There were eight irrigation events applying a total of 647 mm of water. Total crop evapotranspiration was 953 mm of which 70 % was transpiration. Figure 34 shows the weight of plant vegetative matter produced. During the growing season, there

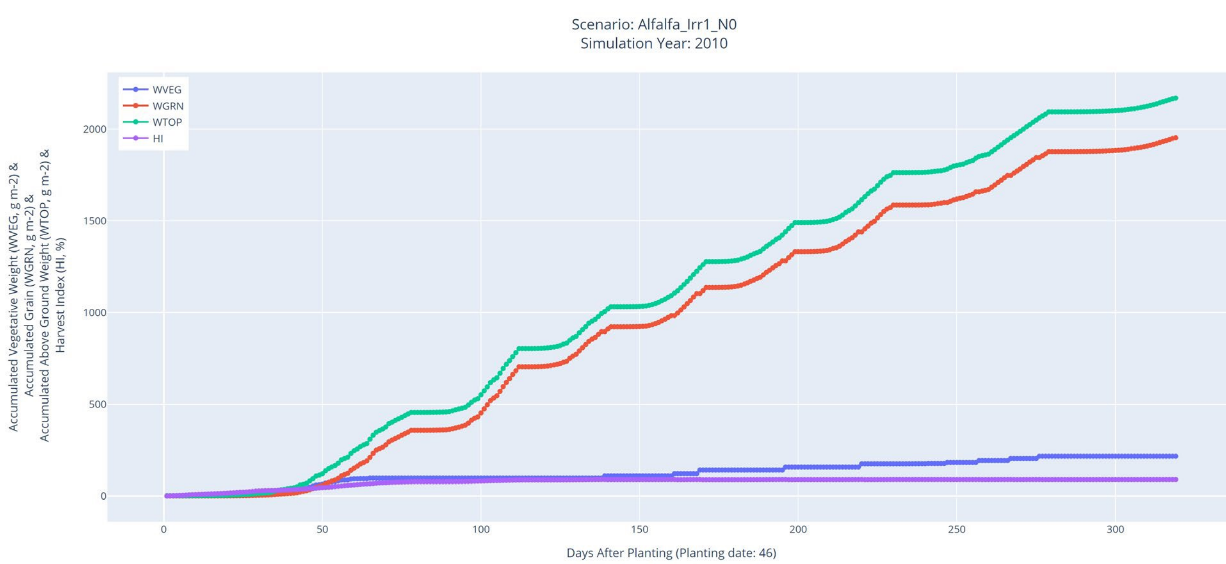

Figure 34. Alfalfa - Cumulative Weights of Crop Organs during Growing Season.

were a total of eight cuttings producing an accumulated total weight of 1952 g m^{-2} (19.5 metric tons per hectare) of hay with a harvest index of 90 %. Between cuttings relatively small amounts of vegetative matter was produced. Nitrogen fertilization and mobilization was not simulated with this crop.

Figure 35 presents the annual summary of the total annual crop evaporation transpiration, soil evaporation and vapor pressure deficit for over the 5-year period of the alfalfa crop simulation.

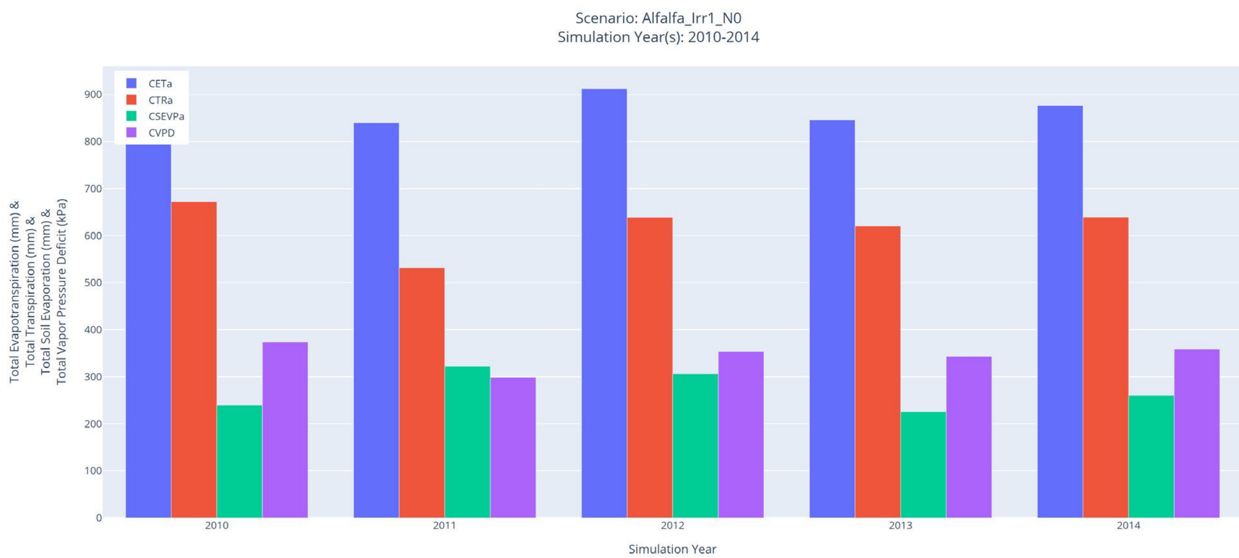

Figure 35. Alfalfa - Annual Summary of Crop Evapotranspiration, Transpiration, Soil Evaporation and Vapor Pressure Deficit.

Total evapotranspiration ranged from a high of 912 mm in 2012 to low of 840 mm in 2011. Crop transpiration was highest in 2010 (953 mm) and lowest in 2011 (531 mm).

Figure 36 provides a summary of total annual above ground crop weight, vegetative stems and leaves, grain yield and harvest index. In this simulation, hay yield ranged from 1952 to 1680 g m^{-2} approximately equivalent to 17 to 20 metric tons per hectare with the harvest index ranging from 90 to 91%.

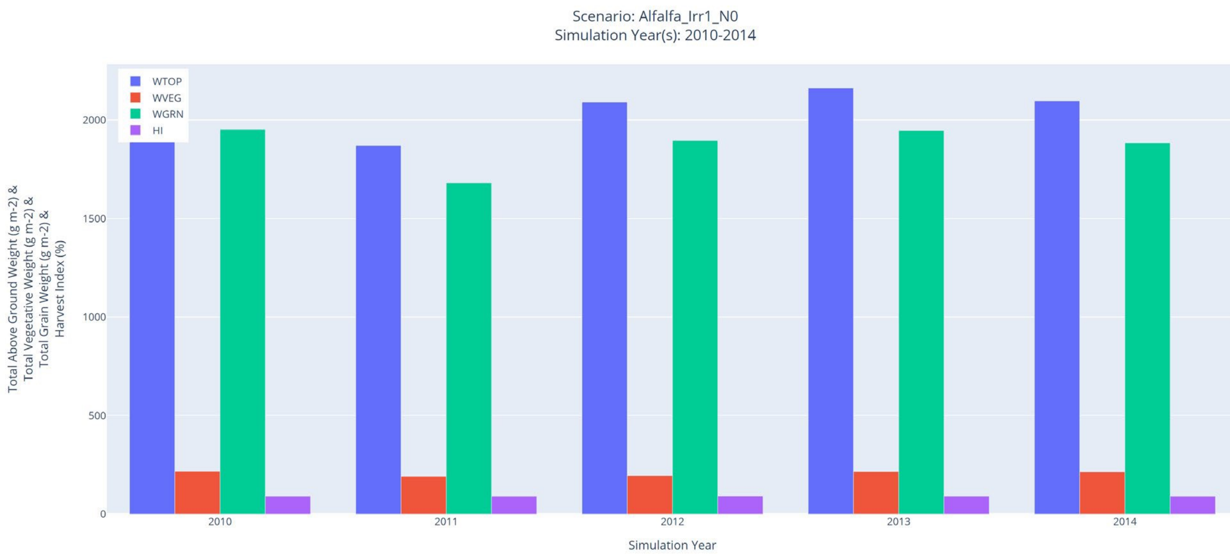

Figure 36. Alfalfa - Total Annual Weight of Above Ground Crop, Vegetative Stems and Leaves, Grain and Harvest Index.

Tree Crops

Almond is a major crop grown in Central Valley of Reclamation's California Great Basin Region. It is a perennial, deciduous orchard crop that uses the C3 photosynthetic pathway. In this scenario, almond trees were simulated during a 5-year period from 2010 to 2014. As shown on Figure 37, a precipitation pattern typical of a Mediterranean climate similar to California' climate occurred with rainfall mostly in the winter and early spring months.

Figure 37. Almond - Cumulative Water Balance Components.

In 2010, the total amount rainfall was 200 mm. The almond trees were also irrigated twice during the growing season with a total amount of 219 mm applied to maintain soil moisture between field capacity and a fraction of plant available water above 0.5 in the rootzone. Total crop evapotranspiration during the growing season was 418 mm with crop transpiration being 62% of this total. Figure 38 shows the weight of plant vegetative matter produced. In 2010, bud burst occurred on the 38th day of the year (February 7) and seed formation began on the 70th day of the year (March 11).

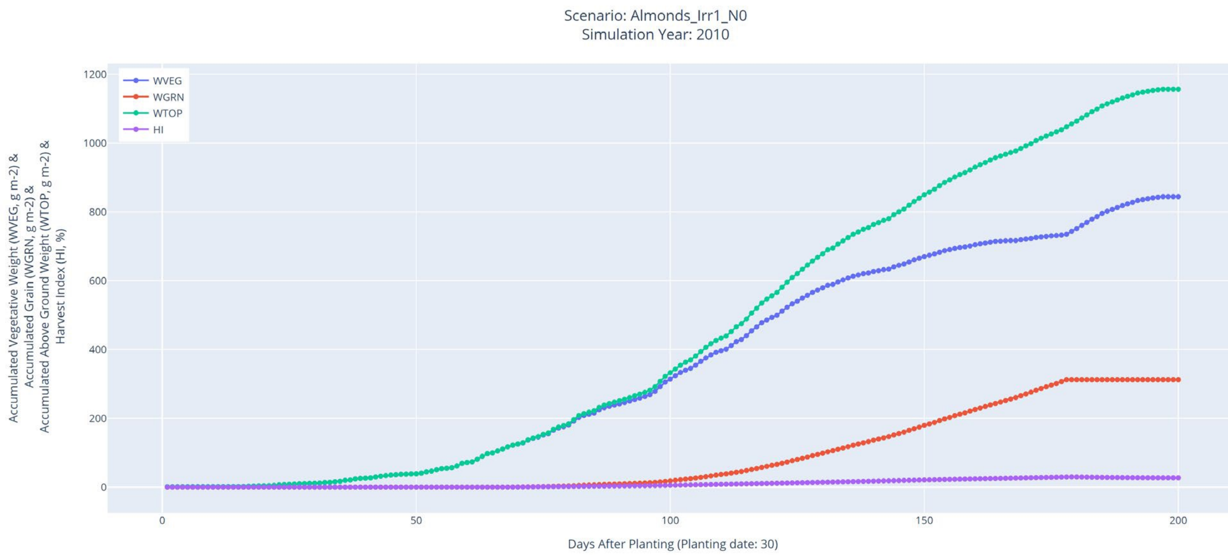

Figure 38. Almond - Cumulative Weights of Crop Organs during Growing Season.

Formation of the nuts was completed by the 178 day of the year (June 27). The total weight of the nuts produced was 312 g m^{-2} (approximately 31 metric tons per hectare). Figure 39 presents the annual summary of the total annual crop evaporation transpiration, soil evaporation and vapor pressure deficit for over the 5-year period of the alfalfa crop simulation.

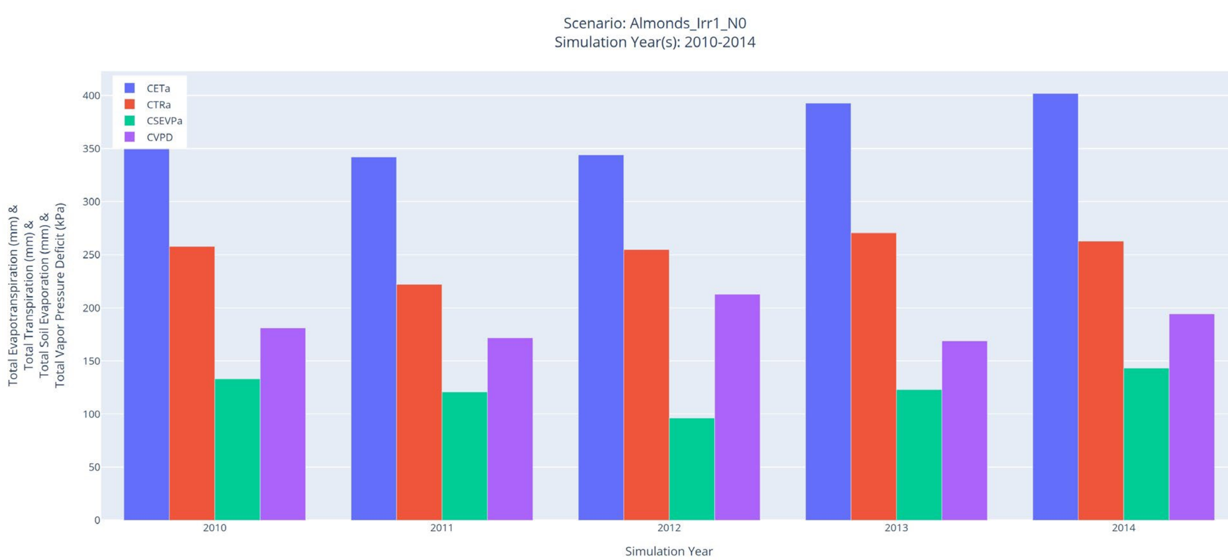

Figure 39. Almond - Annual Summary of Crop Evapotranspiration, Transpiration, Soil Evaporation and Vapor Pressure Deficit.

Total evapotranspiration ranged from a high of 401 mm in 2014 to low of 342 mm in 2011. Crop transpiration was highest in 2013 (271 mm) and lowest in 2011 (222 mm).

Figure 40 provides a summary of total annual above ground crop weight, vegetative stems and leaves, grain yield and harvest index.

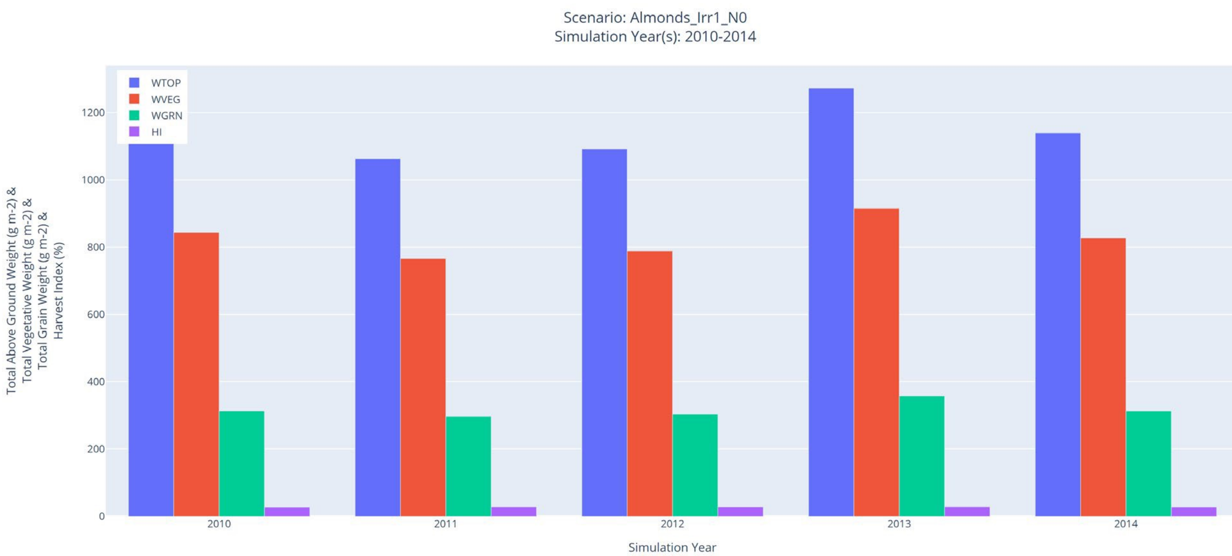

Figure 40. Almonds - Total Annual Weight of Above Ground Crop, Vegetative Stems and Leaves, Grain and Harvest Index.

In this simulation, nut production ranged from 296 to 357 g m^{-2} approximately equivalent to 30 to 36 metric tons per hectare with the harvest index ranging from 27 to 28%.

Rice

Rice is major food crop which is grown world-wide as well as in the Sacramento Valley of Reclamation's California Great Basin Region. However, the current rice management options in BPCLAWS do not reasonably reflect how rice is managed there. Consequently, simulations of this crop must await future improvements in the BPCLAWS code.

Conclusions

The Bio-Physical Crop Land Atmosphere Water Simulator was developed to address research needs identified by Reclamation, U.S. Army Corp of Engineers and other Federal and Non-Federal Partners (Reclamation 2011). Specifically, the need to better understand how climate and CO_2 changes impact plant physiology and how impacts vary by crop type and affect irrigation demand was identified as a high priority research need. To address these research needs, the BPCLAWS project developed a bio-physical model with the capability to simulate crop water demands, biomass and yield based on plant physiological responses to climate using freely distributable, open source code in Python. The BPCLAWS model was developed from the well-known, peer reviewed Simple

Spreadsheet Model (Soltani and Sinclair, 2012). The SSM-iCrop2N model code (Soltani et al 2020) was converted from VBA to Python. The BPCLAWS was verified by simulating a variety of crop types and comparing the crop water use, bio-mass production and yield with the SSM-iCrop2N model. In addition, new daily and annual summary graphical capabilities were developed using the Plotly python library to provide users with high quality graphics to efficiently analyze simulation results and effectively compare simulations of multiple crop management options.

Recommendations and Next Steps

The BPCLAWS model is a necessary step in the development of a agricultural water management system. In its present development stage, it can be used for seasonal and multiyear planning studies focused on agricultural water demands and economic crop yields. However, the longer-term goal of developing a robust forecasting system for irrigation scheduling and crop management will require additional effort. A few recommendations and next steps towards accomplishing these goals are listed below.

- BPCLAWS simulations of major crop types grown in the Reclamation regions of the western USA should be performed to develop local and regional scale crop models suitable for crop and water management analyses.

- The BPCLAWS code and API should be modified to provide the capabilities for forecasting short term irrigation scheduling based on downscaled weather forecasts. This goal can be accomplished by integrating the BPCLAWS model with the West-wide Evapotranspiration Forecast Network (S&T Project 1763). This will require making incoming solar radiation forecasts from the Global Forecast System and Climate Forecast System model available in the API.

- A user interface and error handling capabilities should be developed to make the setup of simulations and detection of erroneous inputs more robust. As part of this effort, the organization of input files and the naming of variables should be modified to make the code compatible with the Python standards. The BPCLAWS code should be modified to improve its modularity by turning repetitive code into class methods and functions.

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A1. BPCLAWS Methods, Parameters and Variables

In this appendix, a brief description of the BPCLAWS code, its methods and their associated parameters and variables. Figure ?? provides a flowchart indicating the order executions of the methods and the main decision control variables. This information along with extensive comments are also included in the BPCLAWS python code.

Class Crop

```
Initializes the dataframes and primary input parameters that contain
information that specifies the crop scenarios and how the simulation
will be performed from user input.
Parameters
--------------
manage_df : pandas DataFrame
    contains scenario information describing the scenario name,
    length of simulation, planting date criteria, water and
    nitrogen management as well as rice ponding and forage
    cuttings.
crop_df : pandas DataFrame
    contains crop information describing characteristics used
    to compute phenology, canopy developemnt and senescence,
    dry matter production and translocation, growth stage
    thresholds, transpiration, water stress factors, nitrogen
    content of plant organs and fixation, and salt effects on
    crop yield.
soil_df : pandas DataFrame
    contains soil information describing soil depth and layers,
    albedo, runoff and drainage properies, soilwater holding
    capacity, soil nitrogen and salinity
location_df : pandas DataFrame
    contains location information describing latitude, VPD
    correction factor, weather file name, user specified
    changes to temperature and precipitation data and
    reading weather file data.
weather_df : pandas DataFrame
    contains daily weather data including year, day of the
    year, solar radiation, maximum and minimum temperature,
    and precipitation
irrigation_df : pandas DataFrame
    contains irrigation management information describing
```

the number of irrigation applications, irrigation
application criteria, allowable soil water depletion
and amount of water applied
nferti_df : pandas DataFrame
contains fertilizer application information describing
number of fertiizer applications, fertilizer application,
criteria, when applied, amount applied and fraction
volatilized
scenario_name : str, optional
user input string specified in the Scenario column of the
scenario_inputs.csv file as an unique identifier.
The default is None for error checking.
scnNo : int, optional
the scenario number currently being simulated. The
number of scenarios is the variable "num_scenarios".
It is determined by the number of rows (excluding header)
in the sceanrio_inputs.csv file.
The default is None for error checking.
LocRowNo : int, optional
numeric value in the LocRowNo column of the
scenario_inputs.csv file corresponding to a value in the
#Loc column of the location_inputs.csv file where location
inputs are specified. The default is None for error checking.
MangRowNo : int, optional
numeric value in the MangRowNo column of the
scenario_inputs.csv file corresponding to a value in the
#Manag column of the manage_inputs.csv file where management
inputs are specified.The default is None for error checking.
SoilRowNo : int, optional
numeric value in the SoilRowNo column of the
scenario_inputs.csv file corresponding to a value in the
#Soil column of the soil_inputs.csv file where soil
inputs are specified.The default is None for error checking.
CropRowNo : int, optional
numeric value in the SoilRowNo column of the
scenario_inputs.csv file corresponding to a value in the
#Crop column of the crop_inputs.csv file where crop
inputs are specified. The default is None for error checking.
location_name : str, optional
the sceanrio location found in the Location column
of the location_inputs.csv file.
The default is None for error checking.
manage_name : str, optional
the name of the management scenario located in the
Manag column of the manage_inputs.csv file.
The default is None for error checking.
soil_name : str, optional
the name of the scenario's soil type located in the

    Soil column of the soil_inputs.csv file.
    The default is None for error checking.
crop_name : str, optional
    the name of the scenario's crop type located in the
    Crop column of the crop_inputs.csv file.
    The default is None for error checking.
weather_file : str, optional
    the name of the weather csv file located in the
    Weather folder. It is found in the Weather column of
    the location_inputs.csv file.
    The default is None for error checking
weather_first_row : int, optional
    the value in the WthFirstRow column of the
    location_inputs.csv for the current sceanrio.
    It indicates the first row of the scenario's weather
    file to start reading the weather data.
    The default is None for error checking.
Pyear : int, optional
    the scenario's starting year number located in the Fyear
    column of the manage_inputs.csv file.
    The default is None for error checking.
yrno : int, optional
    the scenario's number of years to simulate located in the
    yrno column of the manage_inputs.csv file.
    The default is None for error checking.
water : int, optional
    the scenario's water management option (0,1,2,3) number
    located in the water column of the manage_inputs.csv file.
    The default is None for error checking.
nitrogen : int, optional
    the scenario's nitrogen management option (0,1,2) number
    located in the nitrogen column of the manage_inputs.csv
    file. The default is None for error checking.

Notes

The "optional" keyword arguments for this class are not
optional in order to run a simulation. The keyword
arguments are required and are set as keyword
arguments in order to have default values for
debugging purposes. This maybe altered in
future versions.

LocManageInputs Method

This method obtains many of the variables used in other class methods and functions. It is invoked once by the SimMain() function for each year included in the scenario's simulation. The manage_df and location_df dataframe inputs are read from manage_inputs.csv and location_inputs.csv files.

Input parameters and variables.

NAME: data type, initial value (if any)
Brief description and units

LAT: float
Latitude of location (negative for south latitudes)
VPDF: float
A weighting coefficient skewed for the times of the day when the transpiration rate is high to reflect the daily pattern of transpiration rate;
0.65 for humid and subhumid climates
0.75 for arid and semi-arid climates
tchng: float
Changes temperature by tchng (oC)
pchng: float
Changes RAIN * pchng multiplier
CO2: float
CO2 concentration (PPM)
FixFind: int
Specifies option to find planting date
SimDoy: float
Starting simulation day of the year
Pdoy: float
Planting day of the year (Julian)
SearchDur: int
Number of days to search from SimDay
RfreeP: float
Number of rain free days before sowing. Note RfreeP = 5 is coded
SowTmp: float
5 day moving average temperature required for sowing. Sowing is done when 5-day average temperature just goes above or below SowTmp depending to the selected sowing rule.
SowWat: float
Fractional soil water content of layer 1 (FTSW1, ND) that is required for sowing when FixFind = 4 or 5; it is

cumulative rain fall amount (mm) when FixFind = 6 or 7

water: int

Soil water management control variable - no soil water effects = 0, irrigate to soil water fraction < management allowable depletion (MAD = IRGLVL) in root zone = 1, only rain water for crop supply = 2, user selected number of irrigation events = 3

IRNUM: int

Number of irrigation events associated with WATiT

IRGWI: float

Amount of irrigation water appled (mm)

WATiT: int

WATiT = 1 - irrigation based on days after planting (DAP) with IRNUM number of irrigations applied in amount of IRGWI (mm)
WATiT = 2 - irrigation based on normalized developement stage (NDS) with IRNUM number of irrigations applied in amount of IRGWI (mm)
WATiT = 3 - irrigation based on day of the year (DOY) with IRNUM number of irrigations applied in amount of IRGWI (mm)

IrrigRowNo: int

Scenario identifier for irrigation management

IRGLVL: float

Fraction transpirable soil water (FTSW) threshold when the crop needs to be irrigated

StopDoy: int

Day of year (DOY) when crop must be harvested even if not mature

ClipNo: int

Number of forage cuttings

minWH: float

Minimum depth of water in flooded rice fields
minWH = 0 for non-rice crops

maxWH: float

Maximum depth of water in flooded rice fields

WatDep: float, 0

Depth of water ponding for rice (mm)

nitrogen: int

Nitrogen simulation control variable - no nitrogen simulation = 0, effects of nitrogen on canopy development only = 1 & additionally include soil N effects = 2

NfertRowNo: int

Scenario identifier for nitrogen management

NFERT = float, 0

Amount of applied N fertilizer (g N m-2)

CNFERT: float, 0

Cumulative amount of N fertilizer applied (g N m-2)

NCON: float, 0

Soil water N concentration (g N g-1 H20)

NVOL: float, 0

Amount of N fertilizer volatilized (g N m-2)

CNVOL: float, 0

Cumulative amount of N fertilizer volatilized (g N m-2)
NLEACH: float, 0
Amount of soluble N leached (g N m-2)
CNLEACH: float, 0
Cumulative amount of soluble N leached (g N m-2)
NMIN: float, 0
Daily rate organic N mineraliztion (g N m-2 day-1)
CNMIN: float, 0
Cumulative amount of organic N mineralization (g N m-2)
NDNIT: float, 0
Amount of N denitrified (g N m-2)
CNDNIT: float, 0
Cumulative amount of N denitrified (g N m-2)
SNAVL: float, 0
Amount of plant available soil N (g N m-2)
NSOL: float, 0
Total inorganic N [NO3 + NH4] in the HYDDEP layer (g N m-2)
NUP: float, 0
Daily rate of nitrogen accumulation in crop above-ground organs (g N m-2 d-1)
NLF: float, 0
Amount of leaf N weight (g N m-2)
NST: float, 0
Amount of stem N weight (g N m-2)
NVEG: float, 0
Amount of N in vegetative organs [leaves + stems] (g N m-2)
NGRN: float, 0
Amount of seed N weight (g N m-2)
CNUP: float, 0
Cumulative amount of N in crop above-ground organs (g N m-2)
CUMBNF: float, 0
Cumulative bio-fixation of nitrogen by legumes (g N m-2)
INSOL: float, 0
Initial inorganic N in HYDDEP layer (g N m-2)
dtBSG: float, 0
Number of days after planting to beginning of seed growth
MTMIN2: float, 0
Average daily TMIN before beginning of seed growth (oC)
MTMAX2: float, 0
Average daily TMAX before beginning of seed growth (oC)
BNF: float, 0
Daily rate of biological nitrogen fixation (g N m-2 d-1)
DLAI: float, 0
Daily decrease (senescence) in leaf area index (m2 m-2 d-1)
XNLF: float, 0
Daily rate of nitrogen mobilized from leaves (g N m-2 d-1)
NFC: float, 0
Coefficient of biological nitrogen fixation per unit

vegetative mass (g N g-1)
NDS: float, 0
Fraction of temperature units to harvest
(Normalized Development Stage)
DAS: float, 0
Days after start of simulation - This variable is not currently
used anywhere in code
DAP: float, 0
Days after planting (days)
SNOW: float, 0
Snow depth (cm)
MAT: int, 0
Crop maturity indicator variable (Crop mature, MAT = 1)
WSFL: float, 1
Water stress factor for leaf area development
(no stress = 1)
WSFG: float, 1
Water stress factor for growth (dry matter production)
(no stress = 1)
WSFN: float, 1
Water stress factor for nitrogen fixation
(no stress = 1)
WSFDS: float, 1
Water stress factor for phenological development
(no stress = 1)
WSXF: float, 1
Water stress factor for flooded conditions
(no flooding = 1)

FindSimSowDate Method

This method obtains the scenario's planting day of the year (Pdoy) based on user sepecified criteria (FixFind) indicating suitable weather conditions for sowing (planting) the crop. The scenario's parameters are obtained by LocManagInputs() before FindSimSowDate() is called once by the SimMain() function for each year included in the scenario's simulation. The FixFind, SimDoy parameters are read from the manage_inputs.csv and YR, DOY, SRAD, TMAX, TMIN & RAIN varaibles are read from weather_inputs.csv files. The method searches until the Pdoy is found or the until the search duration parameter SearchDur is exceeded.

\---

Input parameters and variables.

NAME: data type, initial value (if any)
Brief description and units

FixFind: int
    specifies the type of user specified weather conditions
    desired for planting the crop
SimDoy: float
    Julian day of the year (DOY) for starting the simulation
Pyear: float
    starting year of the simulation
Pdoy: float
    planting day of the year
SearchDur: int
    number of days to search to find Pdoy meeting user defined
    criteria
RfreeP: float
    number of days in rainfree period = 5 days
SowTmp: float
    5-day moving average temperature (oC) to find Pdoy meeting
    user defined criteria
SowWat: float
    has multiple uses. See Notes below
ForcTB: float
    basal temperature (oC) for bud burst of tree crops
ForcReq: float
    temperature units (oC) thresold required for bud burst in
    tree crops
SowWat parameter has multiple uses depending on FixFind parameter:

    FixFind = 4 or 5 => SowWat is fractional soil water content
                (FTSW, ND) of the DEP1 upper layer

    FixFind = 6 or 7 => SowWat is the cumulative precipitation (mm)
                in a 5-day period

Weather Method

This method obtains daily weather information for the current scenario's simulation from the weather_df dataframe. The weather_df data is read from the weather file named in the Weather column of the location_inputs.csv file. The inital value of wthRow is read from the WthFirstRow column of location_df. This method is invoked first by LocManagInputs() and then by FindSimSowDate() at the beginning of each scenario's simulation until the planting day of the year (Pdoy) is found. After the Pdoy is found, it is invoked by SimMain() function on a daily basis in the loop over the years included in the scenario's simulation to get each day's weather inputs.

Input parameters and variables.

NAME: data type, initial value (if any)
Brief description and units

Yr: float
year of the weather data
DOY: float
Julian day of the year
SRAD: float
solar radiation (MJ m-2 d-1)
TMAX: float
maximum daily temperature (oC)
TMIN: float
maximum daily temperature (oC)
RAIN: float
daily precipitation (mm)
tchng: float
amount of temperation change to be applied to Tmax & Tmin is input in the LocManageInputs() method
pchng: float
multiplicative factor to apply to RAIN data is input in the LocManageInputs() method
TMP: float
average daily temperature (oC)
SNOWMLT: float
amount of daily snowmelt (cm)
SNOW: float
depth of snow (cm)
wthRow: float
starting row number in the WthFirstRow column of location_df

PhenologyBD Method

This method computes the daily temperature units (DTU) from the average daily temperature (TMP) using the temperature function (tempfun). It also computes the normalized development stage (NDS) and days after planting (DAP) to beginning of seed groeth (BSG), termination of seed growth (TSG) and crop maturity (MAT, NDS=1). The parameters are read from crop_df which obtains values from the crop_inputs.csv file. It is invoked on a daily basis by the SimMain() method in the loop over the years included in the scenario's simulation until crop maturity

(MAT = 1) or DOY = StopDoy is reached.

Input parameters and variables.

NAME: data type, initial value (if any)
Brief description and units

TBD: float
base temperature for development (oC)
TP1D: float
lower optimum temperature for development (oC)
TP2D: float
upper optimum temperature for development (oC)
TCD: float
ceiling (maximum) temperature for development (oC)
tuHAR: float
in field crops, temperature units (tu, oC) from sowing to harvest; in forages, tu from beginning of regrowth to harvest; in rice, tu from transplanting to harvest, in trees, tu from bud burst to harvest or leaf fall
frEMR: float
fraction of harvest temperature units (tuHAR) to emergence. In tree crops, it's value is temperature units (tu, oC) from bud burst to the beginning leaf growth (leaf emergence)
frBSG: float
fraction of harvest temperature units (tuHAR) to beginning of seed or fruit growth
frTSG: float
fraction of harvest temperature units (tuHAR) to the termination of seed or fruit growth
frPM: float
fraction of harvest temperature units (tuHAR) to plant maturity
frBLS: float
fraction of harvest temperature units (tuHAR) to beginning of leaf senescence
frBNF: float
fraction of harvest temperature units (tuHAR) to beginning of nitrogen fixation
DAP: int, 0
days after planting
NDS: float, 0
fraction of cumulative temperature units (tu, oC) to harvest (CTU/tuHAR). Also referred to as normalized development stage.
CTU: float, 0
cumulative temperature units (oC)
WSFDS: float, 1

Water stress factor for phenological development (no stress = 1)
Note WSFDS = (1 - WSFG) * WSSD + 1 ; WSFG = water stress factor for RUE ; WSSD is a coeff that specifies how much the phenological development rate increases (>0) or decreases (<0) with decreasing soil moisture. A value of 0.25 means that it increases up to a maximum) of 25% by the highest water deficit (WSFG = 0) and a value of -0.25 means it decreases by a maximum of 25% by the highest water deficit

DAYT: float, 0
number of days from sowing until maturity (MAT)

dtBSG: float, 0
number of days to beginning of seed growth (BSG)

dtTSG: float, 0
number of days to termination of seed growth (TSG)

dtHAR: float, 0
number of days to harvest

SRAINT: float, 0
sum of RAIN from sowing to MAT (mm)

STMINT: float, 0
sum of TMIN from sowing to MAT (oC)

STMAXT: float, 0
sum of TMAX from sowing to MAT (0C)

SSRADT: float, 0
sum of solar radiation (SRAD) from sowing to MAT (MJ m-2)

SUMETT: float, 0
Sum of soil evaporation (SEVP) + plant transpiration (TE) from sowing to MAT (mm)

DAY2: float, 0
number of days from sowing to beginning of seed growth (BSG)

SRAIN2: float, 0
sum of RAIN from sowing to BSG (mm)

STMIN2: float, 0
sum of TMIN from sowing to BSG (oC)

STMAX2: float, 0
sum of TMAX from sowing to BSG (oC)

SSRAD2: float, 0
sum of SRAD from sowing to BSG (MJ m-2)

SUMET2: float, 0
sum of soil evaporation (SEVP) + plant transpiration (TE) from sowing to BSG (mm)

DAY3: float, 0
number of days of from BSG to MAT

SRAIN3: float, 0
sum of RAIN from BSG to MAT (mm)

STMIN3: float, 0
sum of TMIN from BSG to MAT (oC)

STMAX3: float, 0
sum of TMAX from BSG to MAT (oC)

SSRAD3: float, 0
sum of SRAD from BSG to MAT (Mj m-2)
SUMET3: float, 0
sum of soil evaporation (SEVP) + plant transpiration (TE) from BSG to MAT (mm)
iniPheno: int, 1
resets initiation variable to not read parameters again

CropLAI Method

This method computes daily canopy development and leaf senescence without the effects of nitrogen limitations. The effects of temperature on the crop canopy above or below user defined thesholds are also simulated. The parameters are read from crop_df which obtains values from the crop_inputs.csv file. It is invoked on a daily basis by the SimMain() function in the loop over the years included in the scenario's simulation when the management variable, nitrogen = 0.

Input parameters and variables.

NAME: data type, initial value (if any)
Brief description and units

----

x1NDS: float
value used to compute coefficients in daily LAI equation
y1LAI: float
value used to compute coefficients in daily LAI equation
x2NDS: float
value used to compute coefficients in daily LAI equation
y2LAI: float
value used to compute coefficients in daily LAI equation
LAIMX: float
maximum leaf area index (LAI, m2 m-2)
SRATE: float
exponent in daily LAI eqn after beginning of leaf senescence
FrzTh float
temperature threshold for freezing effect on leaf senescence (oC)
FrzLDR: float
coefficient used to compute frost stressfunction due to TMIN < FrzTh (ND)
HeatTh: float
temperature threshold for heat stress on leaf senescence during growth stages (oC)

HtLDR: float
  coefficient used to compute heat stress function in LAI due
  to TMAX > HeatTh (ND)
LAI1: float, 0
  yesterdays leaf area (m2/m2/day)
LAI2: float, 0
  todays leaf area (m2/m2)
LAI: float, 0
  leaf area at end of current day (m2/m2/day)
BLSLAI: float, 0
  LAI at beginning of leaf senescence (m2/m2)
MXXLAI: float, 0
  maximum LAI occuring during simulation (m2/m2)
iniLAI: int, 1
  resets initiation variable to not read parameters again

CropLAIN Method

This method computes daily canopy development and leaf senescence including the effects of nitrogen limitations. The effects of temperature on the crop canopy above or below user defined thesholds are also simulated. The parameters are read from crop_df which obtains values from the crop_inputs.csv file. When the management variable, nitrogen = 1 or 2, it is invoked on a daily basis by the SimMain() function in loop over years included in scenario's simulation.

Input parameters and variables.

  NAME: data type, initial value (if any)
    Brief description and units
----

x1NDS: float
  value used to compute coefficients in daily LAI equation
y1LAI: float
  value used to compute coefficients in daily LAI equation
x2NDS: float
  value used to compute coefficients in daily LAI equation
y2LAI: float
  value used to compute coefficients in daily LAI equation
LAIMX: float
  maximum leaf area index (LAI, m2 m-2)
SRATE: float
  exponent in daily LAI eqn after beginning of leaf senescence
FrzTh: float

temperature threshold for freezing effect on leaf senescence (oC)

FrzLDR: float

coefficient used to compute frost stress function due to TMIN < FrzTh (per oC)

HeatTh: float

temperature threshold for heat stress on leaf senescence during growth stages (oC)

HtLDR: float

coefficient used to compute heat stress function in LAI due to TMAX > HeatTh (per oC)

SLNG: float

Specific leaf nitrogen content in green leaves (target, g N m-2)

SLNS: float

Specific leaf nitrogen content in senesced leaves (minimum, g N m-2)

LAI1: float, 0

yesterday's leaf area (m2/m2/day)

LAI2: float, 0

today's leaf area (m2/m2)

LAI: float, 0

leaf area at end of current day (m2/m2/day)

BLSLAI: float, 0

LAI at beginning of leaf senescence (m2/m2)

MXXLAI: float, 0

maximum LAI occuring during simulation (m2/m2)

iniLAI: int, 1

resets initiation variable to not read parameters again

DMProduction Method

This method computes the crop's dry matter production (DDMP) based on the daily solar radiation (SRAD), temperature (TMP) & carbon dioxide corrected radiation use efficiency (RUE) and fraction of canopy intercepted radiation (FINT). The amount of dry matter translocated from the vegetative organs to the grains after the beginning of seed growth is also determined. Forage crop cuttings are also managed to allow regrowth during the growing season. The parameters are read from crop_df which obtains values from the crop_inputs.csv file. This method is invoked on a daily basis by the SimMain() function in the loop over the years included in the scenario's simulation until crop maturity (MAT = 1) or DOY = StopDoy.

\---

Input parameters and variables.

NAME: data type, initial value (if any)
Brief description and units

TBRUE: float
lower temperature limit for the RUE temperature correction
function tcfrue (oC)
TP1RUE: float
lower optimum temperature for the RUE temperature correction
function tcfrue (oC)
TP2RUE: float
upper optimum temperature for the RUE temperature correction
function tcfrue (oC)
TCRUE: float
upper temperature limit for the RUE temperature correction
function tcfrue (oC)
KPAR: float
extinction coefficient (ND) for photosynthetically active
radiation (PAR) in the canopy interception function (FINT)
IRUE: float
RUE under optimal conditions (g MJ-1)
HIMAX: float
maximum Harvest Index (HI = WGN/WTOP, WGN = g of grain
WTOP = g of above ground dry matter = leaves + stems)
HIMIN: float
Maximum translocatable DM (DDMP, g) from vegetative tissues to the
grains. It is important for grain crops but not important for
forages and trees.
GCC: float
grain conversion coefficient (g of grain per gm of DDMP)
c3c4: float
crop photosynthetic pathway value for CO2 effect on RUE
(eg. c3 = 0.8 & c4 = 0.35)
SUMFINT: float, 0
sum of fraction of intercepted radiation (FINT)
SUMIPAR: float, 0
sum of the photosynthetically active radiation
(PAR = SRAD * 0.48, MJ m-2)
WVEG: float, 1
accumulated vegetative (leaf + stem) dry matter (g m-2)
WGRN: float, 0
accumulated grain dry matter (g m-2)
WSFG: float, 1
water stress factor for growth (dry matter production)
(no stress = 1)
ClipCount: int, 0
number of forage clippings
TRLDM: float, 0

total amount of translocatable dry matter at BSG (g m-2)
iniDMP: int, 1

SoilWater Method

This method computes the hydrologic water balance of the crop rootzone (DEPORT) and the soil profile (SOLDEP). The soil profile is subdivided into upper and lower layers. The upper layer is represented by 2 user specified depths (DEP1 & HYDDEP). The water management parameter (water) determines whether the crop is irrigated (water = 1 or 3) or rainfed only (water = 2). Surface runoff is computed for rainfed crops using the curve number (CN) method and for irrigated crops when the soil is saturated. Soil moisture content and drainage from the upper layers and rootzone (DRAIN) as well as water storage (WSTORG) in deeper soil profile are computed on a daily basis. Water extraction by root growth (EWAT) is included in the water balance. Daily potential evaporation (PET), soil evaporation (EOS) and crop transpiration (TE). Rice water ponding depth is also simulated. Water stress factors affecting crop growth are updated based on rootzone water content. The method's parameters are read from the crop_df, soil_df and manage_df dataframes found in the crop_inputs.csv, soil_inputs.csv and the manage_inputs.csv files. This method is first invoked by the FindSimSowDate method to establish the soil water content at the time of planting and subsequently on a daily basis in the SimMain() function in the loop over the years included in the scenario's simulation.

Input parameters and variables.

NAME: data type, initial value (if any)
Brief description and units

DEPORT: float
initial depth of crop rootzone (mm) which changes during the simulation as roots grow.
frBRG: float
fractional growth stage at beginning of root growth (ND)
frTRG: float
fractional growth stage at termination of root growth (ND)
MEED: float
maximum effective depth of water extraction by roots (mm)
TECREF: float
reference transpiration efficiency coefficient (TEC, Pa)
WSSG: float
FTSW threshold when dry matter production starts to decline (ND)

WSSL: float
FTSW threshold when leaf area development starts to decline (ND)
WSSD: float
Coefficient specifying acceleration (>0) or retardation (<0)
in phenological development in response to water deficit (ND)
tuHAR: float
temperature units (tu, oC) in field crops from sowing
to harvest; in forages, tu from beginning of regrowth to
next cutting; in rice, tu from transplanting to harvest; in trees,
tu from bud burst to harvest or leaf fall.
GRTDP: float
potential daily increase in root depth (mm per oC) it is computed
by (MEED - DEPORT) / ((frTRG - frBRG) * tuHAR)
c3c4: float
crop photosynthetic pathway value for CO2 effect on RUE
(eg. c3 = 0.8 & c4 = 0.35)
RUE385: float
CO2 effect on RUE at 385 ppm (ND) it is computed by
1 * (1 + c3c4 * (log10(385 / 330)))
RUECO2: float
CO2 effect on RUE at user specified atmospheric CO2 concentration
in ppm (ND) relative to 385 ppm (ND). It is computed by
1 * (1 + c3c4 * (log10(CO2 / 330))).
CO2RUE: float
ratio of current RUE effects to 385 effects is defined by
RUECO2 / RUE385 (ND)
CO2TEC: float
CO2 effect on transpiration is defined by CO2TEC = CO2RUE (ND)
TEC: float
corrected transpiration efficiency coefficient (Pa)
TEC = TECREF * CO2TEC
SOLDEP: float
soil profile depth (mm)
DEP1: float
depth of top layer 1 used in calculation of soil water, evaporation
and nitrogen dynamics (mm)
SALB: float
soil albedo (ND)
CN2: float
soil curve number used in runoff calculation
DRAINF: float
drainage rate fraction per day
SAT: float
soil water content at saturation (mm H20 per mm soil depth)
DUL: float
soil water content at drained upper limit (mm mm-1)
EXTR: float
soil water content available for extraction by crop roots (mm mm-1)

CLL: float
soil water content at lower limit of extraction by crop roots (mm mm-1) = DUL – EXTR

SDRAINF: float
drainage rate fraction per day for runoff calculation under saturated conditions (ND)

Slope: float
slope of ground surface for runoff calculation (%)

HYDDEP: float
Additional upper layer soil depth (mm) is coded to be 600 mm (60 cm) or equal to SOLDEP if SOLDEP < 600 mm

MAI1: float
soil moisture availability index for top-layer (0=LL to 1=DUL) (ND). It's primary purpose is to establish an initial amount of plant available soil water in layer 1.

MAI: float
soil moisture availability index for soil profile (0=LL to 1=DUL) (ND). It's primary purpose is to establish an initial amount of plant available soil water in soil profile and initial rootzone.

IPATSW: float
initial plant available soil water content in physical soil profile (mm H20 per mm soil). It is calculated as SOLDEP * EXTR * MAI

ATSW: float
initial plant available soil water in root zone (mm). It is calculated as DEPORT * EXTR * MAI

TTSW: float
initial total potential available soil water in root zone (mm). It is calculated as DEPORT * EXTR

FTSW: float
initial fraction of plant available soil water in root zone (ND). It is calculated as ATSW / TTSW

WSTORG: float
initial plant available soil water stored below the root zone (mm). It is calculated as IPATSW – ATSW

ATSW1: float
initial plant available soil water in upper DEP1 layer (mm). It is calculated as DEP1 * EXTR * MAI1

TTSW1: float
initial total plant available soil water in upper DEP layer (mm). It is computed as DEP1 * EXTR

FTSW1: float
initial fraction of plant available soil water in upper DEP1 layer (ND). It is computed as ATSW1 / TTSW1

WLL1: float
initial soil water content in upper DEP1 layer below lower limit of plant extraction (mm). It is computed as DEP1 * CLL

WAT1: float
initial total amount of soil water in upper DEP1 layer (mm). It is

computed as WLL1 + ATSW1
WSAT1: float
soil water content at saturation in upper DEP1 layer (mm). It is computed as DEP1 * SAT
ATSW60: float
initial plant available soil water content in HYDDEP layer (mm). It is calculated as HYDDEP * EXTR * MAI
TTSW60: float
total plant availble soil water content in the HYDDEP layer (mm). It is calculated as HYDDEP * EXTR
WLL60: float
soil water content in the HYDDEP layer below the lower limit of plant extraction (mm). It is calculated as HYDDEP * CLL
WDUL60: float
soil water content at the upper drainable limit in the HYDDEP layer (mm). It is calculated by HYDDEP * DUL. NOTE - WDUL60 variable is NOT used in this code.
WSAT60: float
soil water content at saturation in the HYDDEP layer (mm). It is calculated as HYDDEP * SAT
WAT60: float
initial total amount of soil water in the HYDDEP layer (mm). It is calculated as WLL60 + ATSW60
EOSMIN: float, 1.5
minimum soil water evaporation (mm d-1)
WETWAT: float, 10
amount of rain and/or irrigation water (mm) required to wet top layer (DEP1) and return soil evaporation back from stage II to stage I
KET: float, 0.5
extinction coefficient for global solar radiation (ND)
CALB: float, 0.23
crop albedo (ND)
LAI: float, 0
initial leaf area index (m2 leaves per m2 ground surface)
BLSLAI: float, 0
LAI at beginning of leaf senescence (m2 m-2)
DTU: float, 0
daily thermal units (oC)
NDS: float, 0
normalized development stage (ND)
DDMP: float, 0
daily dry matter production (g per m2 d-1)
ETLAIMN: float, 0 or 1
minimum ET for trees dormant in winter (mm d-1) - if DEPORT > 800 mm then ETLAIMN = 1 (mm) else ETLAIMN = 0
IRGW: float, 0
amount of irrigation applied (mm)

DYSE: float, 1
    days since last rain and / or irrigation event
CTR: float, 0
    cumulative crop transpiration (mm)
CE: float, 0
    cumulative soil evaporation (mm)
MKT added cumulative ET
CET: float, 0
    cumulative evapotranspiration (mm)
CRAIN: float, 0
    cumulative precipitation (mm)
CRUNOF: float, 0
    cumulative runoff (mm)
CIRGW: float, 0
    cumulative amount of irrigation water applied (mm)
EWAT: float, 0
    soil water (mm) extracted as root zone increases in depth. It is
    calculated as GRTD * EXTR
IRGNO: float, 0
    cumulative number of irrigations events
iniSW: int, 1

PlantN Method

This method simulates the effects of nitrogen on crop growth and yield. It is used in conjunction with CropLAIN() and SoilN() class methods. It is invoked when the parameter nitrogen = 2. The SoilWater() class method should also be used (water = 1,2 or 3) to account for nitrogen fixation associated with legume crops as well as soil processes affecting soil N availablity for crop growth. The parameters are read from crop_df which obtains values from the crop_inputs.csv file. It is invoked by the SimMain() function on a daily basis in loop over years included in scenario's simulation.

Input parameters and variables.

    NAME: data type, initial value (if any)
            Brief description and units

SLA: float
    specific leaf area (m2 g-1)
SLNG: float
    specific leaf nitrogen in green leaves (target, g N m-2)
SLNS: float
    specific leaf nitrogen in senesced leaves (minimum, g N m-2)

SNCG: float
    stem nitrogen concentration in green stems (target, g N g-1)
SNCS: float
    stem nitrogen concentration in senesced stems (minimum, g N g-1)
GNC: float
    grain nitrogen concentration (g N in seed per g dry matter)
MXNUP: float
    maximum rate of nitrogen accumulation in crop above-ground
    organs, stems & leaves, (g N m-2 d-1)
WLF: float, 0.5
    initial leaf dry matter (g m-2)
WST: float, 0.5
    initial stem dry matter (g m-2)
NGRN: float, 0
    initial nitrogen content in seeds (g N)
BNF: float, 0
    daily rate of biological nitrogen fixation (g N m-2 d-1)
CUMBNF: float, 0
    cumulative biological nitrogen fixation (g N m-2)
NST: float
    initial stem nitrogen ccontent (g N m-2). It is calculated by
    WST * SNCG
NLF: float
    initial leaf nitrogen content (g N m-2). It is calculated by
    LAI * SLNG
CNUP: float
    initial nitrogen content in above above-ground organs, stems &
    leaves (g N m-2). It is calculated by NST + NLF
iniPNB: int, 1
    resets initiation variable to not read parameters again

SoilN Method

This method computes the soil nitrogen content and crop available N based environmental conditions, soil properties, mineralization of organic matter, N fertilizer applications and volatilization, leaching of soluble N and denitrification of soluble N under water logged conditions. The parameters are read from the crop_inputs.csv file. When the parameter nitrogen = 2, it is invoked first by FindSimSowDate() method once for each year in the scenario's simulation. It is subsequently invoked by the SimMain() function on a daily basis in the loop over the number of years in the scenario's simulation.

Input parameters and variables.

NAME: data type, initial value (if any)
Brief description and units

FG: float
Fraction of soil particles > 2 mm (ND)

BD1: float
Soil bulk density (g cm-3)

NORGP: float
Soil organic N (%)

FMIN: float
Fraction of soil organic N available for mineralization (ND)

NO3: float
Nitrate nitrogen (g N m-2)

NH4: float
Ammonium nitrogen (g N m-2)

CNFERT: float, 0
number of fertilizer applications

CNVOL: float, 0
amount of volatilized N (g N m-2) Note - volatilization of N fertilizer occurs on the day of application

CNLEACH: float, 0
amount of N leached (g N m-2)

CNMIN: float, 0
amount of organic N mineralized (g N m-2)

CNDNIT: float, 0
amount of denitrified N (g N m-2)

SOILM: float
soil weight of the HYDDEP layer (g soil m-2). It is calculated as HYDDEP * BD1 * (1 - FG) * 1000

NORG: float
total organic soil N in HYDDEP layer (g N m-2) It is calculated as NORGP * 0.01 * SOILM

MNORG: float
amount of mineralizable soil organic nitrogen in HYDDEP layer (g N m-2). It is calculated as NORG * FMIN

NSOL: float
total inorganic N in the HYDDEP layer (g N m-2). It is calculated as NO3 + NH4

NCON: float
initial soil N concentration in the HYDDEP layer (g N g-1 H20). It is calculated as NSOL / (WAT60 * 1000)

INSOL: float
initial soil N concentration in the HYDDEP layer (g N m-2). It is = NSOL

iniSNB: int, 1
resets initiation variable to not read parameters again

Note -NO3 & NH4 (g N m-2) may be calculated from NO3 & NH4 (ppm) from SOILM using the following formulas:

NO3 = NO3 (ppm) * (14 / 62) * 0.000001 * SOILM
NH4 = NH4(ppm) * (14 / 18) * 0.000001 * SOILM

where (14 / 62) is MW N / MW NO3 & (14 / 18) is MW N / MW NH4

Note - conversion factor 1 ppm N = 1 mg N/L = 0.000001 g N/gH20

Note - there are 1000 g H20 / mm H20 depth per m2 of soil surface assuming the density of water is 1 g per cm3

A2. Weather Forecast API – User's Guide

API Queries and Data Return

As mentioned, a primary goal of this project is to add value to the station observations by providing forecasts based on those provided by the NOAA GFS and CFS forecast models. While direct access to these forecasts via the web-based user interface is useful, more advanced users might want rapid access to the actual forecast data in a convenient and automatable manner. This type of functionality is often achieved by coding an application programming interface (API) that allows the extraction of values by formatting the URL string in a manner that allows access to the forecasts, allowing for the user to bypass the web-based interface. This allows the use of tools such as curl, which is a command-line utility for transferring data from or to a server designed to work without user interaction. With curl, you can download or upload data using one of the supported protocols including HTTP, HTTPS, SCP, SFTP, and FTP. Another popular utility for retrieving content from web servers is "wget," whose name derives from the World Wide Web and also supports downloading via HTTP, HTTPS, and FTP.

Below are three example URLs for retrieving station and gridded point data from the WwET4Cast server. Note that absolute forecasts of the station ETo are only being made for the 16-day, GFS forecasts. Because the longer range forecasts from the CFS that go out 60 days and 9 months are generally presented as anomalies relative to the historic forecasts, it is not considered that absolute forecasts for these seasonal forecasts are that useful.

Parameters needed for retrieving observational data, GFS forecasts, and CFS forecasts for individual stations for the GFS forecasts. Note that the *%20* in the string that formats the date is used to encode a space character in the URL expression:

Note that the station data download are only for the ETo estimated values and in fact, since these data are available from the Agrimet and CIMIS sites, we recommend retrieving the data from there. For the ETo extraction, a Station's data can be downloaded as:

https://hydro.rap.ucar.edu/HydroInspector/WW_ETfcst/servlet/servlet.php?requestType=getTimeSeriesData&productId=agrimet&id=golw&start=2020-12-03%2019:12:00&end=2020-12-24%2014:24:00&model=gfs

ProductId= agrimet or cimis (station network)
Start= YYYY-MM-DD (start day for which data are to be returned)
End = YYYY-MM-DD (end ay for which data are to be returned)
id = station id (agrimet or cimis)
forecastCycle= YYYMMDDHH (year, month, day, and hour of the particular forecast cycle. The available forecast cycle times are 00, 06, 12, and 18 Z.
Model=gfs or cfs (the Global Forecast System Model and the Climate Forecast System Model. This request requires this field since it is returning the model forecast)
latitude = latitude of grid point
longitude = longitude of grid point

For the climate model forecasts, there are data for several meteorological variables available via the web-based API for both the GFS and CFS Forecasts. The variable name and the abbreviation that should be used for extraction from the API include:

ProductId Options
refevt: Reference Evapotranspiration (mm)
tasmax: Maximum daily temperature (oC)
tasmin: Minimum daily temperature (oC)
windspeed: Daily average windspeed (m/s)
rhum: Relative Humidity (%)
pr: precipitation (mm)
ps: Surface pressure (mbar)
netrad: Net radaiation (w/m2)

This one returns 60-day CFS data at a lat/lon point.

https://hydro.rap.ucar.edu/HydroInspector/WW_ETfcst/servlet/servlet.php?requestType=getTimeSeriesData&productId=etfcst&variable=refevt&start=2020-12-03%2019:00:00&end=2020-12-24%2014:24:00&model=cfs60&forecastCycle=2020120700&latitude=43.85&longitude=-118.0

This one returns forecast data for the 9-month forecast, at a lat-lon point: (Note the 'forecastCycle' parameter)
https://hydro.rap.ucar.edu/HydroInspector/WW_ETfcst/servlet/servlet.php?requestType=getTimeSeriesData&productId=etfcst&variable=refevt&start=2021-01-02%2004:00:00&end=2021-12-30%2021:36:00&model=cfs&forecastCycle=2021022700&latitude=45.3&longitude=-122.8

Note that this call returns an agrimet station forecast for a particular forecast cycle (available field for returning station estimates is only ETo) https://hydro.rap.ucar.edu/HydroInspector/WW_ETfcst/servlet/servlet.php?requestType=getTimeSeriesData&productId=agrimet&id=fogo&start=2021-02-27%2000:00:00&end=2021-03-16%2014:24:00&forecastCycle=2021022700&model=gfs

Data Sets that Support the Final Report

There are two primarily observational datasets used in this project including 1) the AgriMet data and 2) the CIMIS data; and there are two Global Climate Model (GCM) forecast models being used including the Global Forecast System (GFS) and the Climate Forecast System (CFS) models.

Data Description: Since this is a data intensive project, the attributes of the data are presented primarily in the body of the report. The GFS data reference is NCEI DSI 6182, NCDC-GFS_FORECAST, gov.noaa.ncdc:C00634; while the CFS data reference is NCEI DSI 2001_01, gov.noaa.class:NCDC-CFSV2_FORECAST, gov.noaa.ncdc:C00877

Approximate total size of all files: The data archive as of 1 March 2021 is approximately 8 GB and includes a copy of the AgriMet and CIMIS station data (400 MB); and the forecast data (7.6 GB).

A3. Description of Selected Crop Models

Ecophysiological models have been applied to study the effects of climate conditions on agroecosystems for several decades. Using explicit search and selection criteria to identify climate change crop studies, White et al. (2011) identified 221 journal publications that addressed simulation methods, impacts and adaptations relative to climate change. Of these reviewed studies, their primary focus was impacts (66%), methods (19%) and adaptation (15%). Of the 35 crops explicitly identified, the most studied crops included wheat (35%), maize (25%), rice (11%), soybean (7%) and potato (3%). Taken together, these crops represented 80% of the studies reviewed. Tubiello and Ewert (2002) reported similar results. About 25% of the studies (55) were focused on the United States.

White et al. (2011) indicated that more than 70 models had been applied to study climate change effects on agroecosystems in the 221 studies reviewed. In these studies, the 5 most frequently used models were referenced in more than 50% of the studies. In the order of their prevalence, the top 5 models included CERES (29%), EPIC (11%), APSIM (6%), CropSyst (4%) and DSSAT - CSM+CropGro (4%). In a survey of the crop modeling community, Rivington and Koo (2010) obtained similar results relative to the most commonly used models. Brief descriptions of the most commonly used models are provided below:

1. CERES (Crop Environment Resource Synthesis) models have been developed for a variety of crops including wheat, maize, rice, sorghum, millet, and barley. CERES models were among the earliest crop models developed which probably influenced the prevalence of CERES references in the White's literature review. These ecophysiological models are deterministic but not overly mechanistic. Their primarily focus is on how cultivar properties, planting density, climate (including

CO_2), soil water, and nitrogen affect crop growth, development, and yield. Their primary purpose is to examine how alternative management practices (fertilization and irrigation) affect yield at the farm and regional scales. They have also been used to study nitrogen leaching and the effects of climate change.

CERES models account for a variety of crop development, growth and yield processes in the following:

- Phenological development stages
- Growth of leaves, stems, and roots
- Biomass accumulation and partitioning in plant organs
- Soil water balance and crop water use
- Transformations of nitrogen in the soil, uptake by roots, and partitioning between plant organs

Crop biomass accumulation is calculated independently of the plant development. Biomass production is simulated as a function of radiation use efficiency, leaf area index with reductions due to temperature and moisture stresses. Cultivar phenological development stages are computed based primarily on accumulated degree-days. Photosynthesis determines the growth rate of leaves, stems and roots. The root zone soil water content is computed based on soil characteristics affecting runoff, infiltration and drainage. Mineral nitrogen dynamics in the soil profile are also simulated.

Data inputs include:

- Climate variables such as latitude, daily solar radiation, temperature and precipitation and atmospheric CO_2 concentration and
- Management variables such as sowing date, plant density, row spacing, sowing depth, irrigation and fertilizer schedules and
- Crop genetic constants, phenology and growth parameters and
- Soil parameters such as albedo, soil texture and water holding properties and profile characteristics

Many of the original CERES crop models (e.g. CERES-Wheat) have been updated for use in the DSSAT-CSM model described below.

Key references relevant to the CERES models include Jones and Kinery (1986) and Mearns et al. (1999). Additional online information for the CERES models is available at http://epicapex.brc.tamus.edu/

2. EPIC (Environmental Policy Integrated Climate) was originally developed during the 1980's to simulate effects of soil erosion on agricultural productivity in the United States. It is a deterministic, field scale, daily time step model designed to simulate drainage areas that are characterized by homogeneous weather, soil characteristics, crops, and management practices including tillage effect on surface residue, soil bulk density and nutrients as well as fertilizer and irrigation effects on crop yield.

EPIC's crop growth model uses approaches that are similar to the CERES models. One significant difference is a simpler representation of phenological stages in crop development. The biophysical processes represented in the model include:

- Solar radiation, saturation vapor pressure, canopy and soil albedo effects on potential evaporation in default method; other PET methods (5) available
- Plant evaporation computed as linear function of potential evaporation and Leaf Area Index (LAI) ; two stage soil evaporation based on soil characteristics
- Biomass production function of photosynthetically active radiation (PAR) and crop specific radiation use efficiency (RUE) with adjustment for water, temperature, nitrogen, phosphorous stresses.
- Daily adjustment of potential biomass into above ground and root growth that reflect water, temperature and nutrient stresses (nitrogen and phosphorous)
- Canopy development and senescence computed as function of biomass and crop specific maximum LAI
- Influence of atmospheric CO_2 on biomass production and canopy resistance in the Penman Monteith ET equation can be simulated
- Crop yields are computed by accumulating growing season weighted daily increments of stress adjusted biomass up to a maximum crop specific yield

EPIC requires more than 400 input data items including about three hundred climatic characteristics and 50 crop parameters (Adejuwon, 2005). However, many of these inputs can be obtained or estimated from existing EPIC databases.

Data inputs include:

- Climate variables including precipitation, solar radiation, relative humidity, minimum and maximum temperature, wind speed and atmospheric CO_2 concentration.
- Management variables such as details of farm operations including scheduling of tillage, type and amounts of fertilizer and pesticides applied, irrigation, density of planting, among others.
- Crop parameters such as radiation use efficiency, crop height, canopy development and senescence, basal and optimal growth temperatures, optimum crop yield, root - shoot biomass production ratio, maximum root depth, maximum LAI.
- Soil parameters such as bulk density, water-holding capacity, wilting point, hydraulic properties and profile characteristics.

The APEX (Agricultural Policy / Environmental eXtender) model enhances the EPIC model capabilities to simulate entire farms and small watersheds. APEX has additional algorithms that route water, sediment, nutrients, and pesticides from farms through watersheds and channels. It also has groundwater and reservoir simulation capabilities. New versions of these models (WinEPIC and WinAPEX) have also been developed recently.

Key references relevant to the EPIC model include Williams et al. (1989) and Williams et al. (2008) and Stockle (1992). Additional online information for EPIC and APEX models is available at http://epicapex.brc.tamus.edu/

3. APSIM (Agricultural Production Systems Simulator) is an ecophysiological model designed to simulate growth, development and yield of crops, pastures and forests in relation to climate, plant genotype, soil characteristics and management practices affecting long-term productivity such as loss of soil organic matter, structural degradation, acidification and erosion. APSIM is a deterministic, multi-crop area based, daily time step model with existing capabilities to simulate more than 20 crops including wheat, maize, rice, soybean, potato, sorghum, millet, various grain legumes, safflower, sunflower, cotton, sugarcane, lucrene (alfalfa) and others.

The APSIM uses a generic crop model template (GCROP) that consists of component sub-modules for crop parameters (CPF); basic plant physiological process (CPL), crop components such as phenology and biomass (GMS) and a standard interface (SCI) to manage interactions with other APSIM modules (e.g. soils, meteorology). The biophysical processes simulated in GCROP include:

- Transpiration – calculated as minimum of water supply (based on soil water content and root distribution) and water demand (based on radiation energy for biomass production)
- Phenology – crop growth stages computed based on accumulated thermal time (degree days) and photoperiod. Development may be reduced by water or nitrogen stress
- Biomass – calculated as minimum of either energy supply (based on intercepted radiation and RUE) or crop growth stage dependent water supply (based on transpiration efficiency and VPD) effects on daily biomass production; computes Harvest Index for yield; and re-translocates carbon between plant parts
- Leaf Area Development – calculated from thermal time effects on daily increase in number of leaves and leaf size; maybe limited by carbon and water supply and senescence
- Senescence – computed as function of age, light competition, water and temperature stresses
- Nitrogen – simulates demand, uptake, fixation and re-translocation in plant

The MICROMET module (Snow and Huth, 2004) was developed to improve capabilities to compute ET using the Penman Montheith equation in multilayer and intermingled canopies such as occur in forested, chaparral and inter-cropped field areas.

APSIM data inputs are dependent on the particular user selected modules included in the simulation. A brief description of data inputs employed by some of the modules relevant to this study is provided below:

- Plant module inputs include basic information about crop canopy and root characteristics such as RUE, canopy light extinction, leaf senescence, max crop height and rooting depth, development stages and associated degree days, plant organ fractionation coefficients, soil water extraction limits, specific root length and others
- Soil module includes inputs for simulating soil water, nitrogen, carbon, phosphorus and temperature; soil management practices such as fertilization, irrigation and erosion.
    - Soil water processes can be simulated by either a cascading bucket approach (SoilWat) similar to the EPIC and CERES models or by a numerical solution of unsaturated flow (SWIM2). Hydrologic processes simulated include runoff, drainage, soil and potential evaporation, unsaturated flow, solute flux and flow
- Meteorology module includes station name, latitude and temperature, precipitation and radiation data at daily, monthly or annual time scales
- Manager module allows user to control APSIM simulations.

Key references relevant to the APSIM model include Wang et al. (2002) and Keating et al. (2003); Additional online information is available from the link http://www.apsim.info/Wiki/

4. CropSyst (Cropping Systems Simulation Model) is an ecophysical model developed for the purpose of simulating the effects of the climate, soils, and management practices including crop rotations, cultivar selection, irrigation, nitrogen fertilization, soil and irrigation water salinity, tillage operations, and crop residue on agroecosystems. It is a multi-year, multi-crop, daily time step that simulates a single biophysically homogeneous area managed in a uniform manner. Functionality for simulating multiple land areas is available through ArcGIS.

The CropSyst modules provide algorithms that compute water and nitrogen budgets, phenology, biomass production including the effects of CO_2, canopy development, root growth, crop yield and residue. The methods used to simulate these biophysical processes are briefly described below:

- Water budget – components include precipitation, irrigation, runoff, infiltration, soil evaporation, plant transpiration, redistribution, and deep percolation
  - Redistribution can be simulated by a simple cascading approach similar to APSIM, EPIC and CERES models or a numerical solution of the Richard's equation similar to APSIM
  - Potential crop ET is computed using either a Penman-Monteith or Priestly Taylor based reference crop and crop specific coefficients; actual crop ET is computed based on PET and plant available soil water
- Nitrogen budget – simulated N processes include fixation, mineralization, nitrification, and denitrification; crop N uptake is determined as the minimum of crop nitrogen demand (growth requirements plus its deficiency demand difference between the crop maximum and actual nitrogen concentration) and potential nitrogen uptake
- Phenology - daily accumulation of thermal time (daily average temperature above a base temperature and below a cutoff temperature) during specific growth stages; vernalization and photoperiod requirements need to be considered
- Biomass – uses minimum value based on biomass-temperature-VPD and biomass-PAR-RUE relationships; nitrogen and water stresses may reduce biomass
- Canopy development – LAI is computed a function of biomass accumulated during crop growth stages including senescence
- Root growth - root depth increases to a maximum depth as canopy develops; root density is assumed zero at the current soil depth and increases linearly to a maximum density at a depth near the soil surface
- Yield – computed from total daily accumulated biomass at physiological maturity and stress adjusted Harvest Index (harvestable yield /aboveground biomass)

CropSyst inputs depend on which modules are included in the simulation. Brief descriptions of module inputs are provided below:

- Soil module - layer thickness and texture must be specified; bulk density, volumetric water content and unsaturated water content and water potential relationship parameters may be specified or computed by pedo-transfer functions based on soil texture
- Plant module - Phenology (basal and optimum temperatures, thermal time requirements to reach specific growth stages); Morphology (Maximum LAI, root depth, specific leaf area, leaf area duration, root characteristics and others); Biomass (growth transpiration biomass

coefficient, radiation-use efficiency, nitrogen demand and root uptake parameters water, N and salinity and CO_2 sensitivity parameters); Yield harvest index; Residue decomposition and shading parameters

- Meteorology module - requires temperature, precipitation and radiation for PT method; plus wind, humidity for PM method; weather generation capabilities are included in CropSyst
- Management module – includes scheduled and automatic management events such irrigation application date, amount, and salinity concentration; nitrogen fertilization application date, amount, source, and application mode, tillage operations, and residue management; management events can be scheduled using actual date, relative date (relative to year of planting or synchronized with phenological events.

Key references relevant to the CropSyst model include Stockle et al. (1992) and Stockle et al. (2003); Additional information is available at http://bioearth.wsu.edu/cropsyst_model.html

5. DSSAT-CSM (Decision Support System for Agrotechnology Transfer) was designed to integrate knowledge about soil, climate, crops and management to support better decisions about transferring agricultural production technologies from one location to others. It is a deterministic ecophysiological model that simulates the effects of soil, water and management on the daily growth, development and yield of multiple crops grown in a uniform area over multiple years. The Cropping System Model (CSM) is used to simulate crops using a single soil and a single weather module. As of Version 4.5, over 28 crops are supported by DSSAT-CSM.

DSSAT-CSM simulates various biophysical processes affecting crop growth, development and yield. Methods used include the following:

- Water budget – methods include runoff using SCS approach, infiltration and redistribution using the cascading bucket approach, soil water content including upward unsaturated flow; two stage soil evaporation with actual plant transpiration computed as minimum of potential evaporation and root water uptake based on soil water content and root density, PET can be computed by PM, PT or Richie's method (see APSIM model)
- Carbon and Nitrogen budget – decomposition of soil organic matter computed as function of computed soil temperature and water content; accounts for plant senescence (above ground and subsurface) and transport by soil water
- Phenology – life cycle growth stages computed as function of temperature, photoperiod and sensitivity to N and P availability
- Plant growth – crop photosynthesis computed as function of RUE adjusted for light interception, plant density, CO_2 concentration and N, temperature and water stresses or hourly hedgerow light interception-leaf-level based on canopy development and orientation, CO_2 and temperature; accounts for growth stage dependent plant organ assimilate needs and respiration effects; root growth based on growth stage dependent carbohydrate requirements
- Yield – computed based on plant growth and stresses during growth period

DSSAT-CSM inputs depend on which methods and sub-modules are included in the simulation. Brief descriptions of some of the general types of module inputs are provided below:

- Land Use Module - includes site latitude and longitude; average annual temperature and amplitude, slope and aspect, and others

- Weather - daily solar radiation, maximum and minimum temperature, precipitation and other simulation specifics characteristics (e.g. humidity and wind for PM ET)
- Soil - layer thicknesses, upper and lower soil water content limits, bulk density, organic carbon, pH, rooting and drainage factors
- Crop - photosynthesis and respiration coefficients associated with growth stages; plant organ composition parameters; carbon and nitrogen mining parameters; plant growth, senescence and dry matter partitioning parameters; phenology, crop height and width parameters

Key references relevant to the DSSAT-CSM model include Jones et al. (1989a) and Jones et al. (2003); Additional information is available at http://dssat.net/about

While not included in the White (2011) study, the WEAP-PGM model is described in this section because it was the model selected for use in this study. Furthermore, it is a model in which Reclamation has employed in several studies of the effects on climate change on California's Central Valley (Reclamation, 2016).

6. WEAP-PGM (Water Evaluation and Planning system – Plant Growth Model)
The Water Evaluation and Planning System (WEAP) is a decision support system for integrated water resources management and policy analysis. WEAP was created in 1988 and continues to be developed and supported by the Stockholm Environment Institute (SEI), a non-profit research institute. The Plant Growth Method (PGM) was added to WEAP in 2015. The result of previous collaborative effort between Reclamation and SEI, PGM simulates daily ET, plant growth, yield as functions of temperature, solar radiation, atmospheric humidity, and wind speed and CO_2, heat unit accumulation, and temperature and water stress. The PGM algorithms are based on the SWAT and EPIC models described above. WEAP-PGM can simulate both the hydrology and management of complex, multi-priority water management systems. Additionally, WEAP-PGM has been calibrated to simulate many types of crops grown in Central Valley of California.

The PGM simulates the infiltration and redistribution of soil moisture differently than SWAT or APEX. Infiltration is simulated using the Phillips equation to account for the effects on unsaturated flow in a multi-layer soil profile. PGM also has the capability to account for the effects of a shallow ground water table on root zone soil moisture.

In order to simulate the effects of climate on crop water use, biomass and yield, PGM algorithms simulate the following processes:

- Effects of temperature on soil evaporation and plant transpiration
- CO_2 effects on radiation use efficiency (RUE).
- CO_2 effects on crop leaf area (LAI).
- CO_2 effects on crop transpiration.
- VPD effects on crop transpiration.
- VPD effects on radiation use efficiency (RUE).
- Plant growth and yield driven by accumulation of daily heat units.
- Effects of temperature and water stress on crop biomass and yield.

WEAP-PGM requires both crop parameters, soil properties and climate variables. Some crop parameters may be estimated from existing WEAP-PGM crop database. However, it is important to recognize that calibration of the crop parameters is typically required.

Data inputs include:

- Climate variables include daily precipitation, maximum and minimum temperature, incoming short wave length solar radiation, relative humidity or dew point temperature, wind speed and atmospheric CO_2 concentration.
- Crop parameters including radiation use efficiency, crop height, canopy development and senescence, basal and optimal growth temperatures, growing season heat units, optimum crop yield, root - shoot biomass production ratio, maximum root depth, maximum LAI as well as parameters describing the effects of VPD and CO_2 on RUE and LAI.
- Soil parameters such as field capacity, wilting point, saturated and unsaturated soil hydraulic properties and profile characteristics.

Key references relevant to the WEAP-PGM model include Reclamation (2016). A detailed description of the WEAP algorithms is presented in Appendix A of this report. Additional information is available at https://www.weap21.org/index.asp?action=200 .