RICCAR

Regional Initiative for the Assessment of Climate Change Impacts on Water Resources and Socio-economic Vulnerability in the Arab Region

A training manual for agricultural extension agents:

The use of RICCAR climate data in a crop model (APSIM) to identify context-based climate adaptation and mitigation options

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Regional Initiative for the Assessment of Climate Change Impacts on Water Resources and Socio-Economic Vulnerability in the Arab Region (RICCAR)

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The United Nations Economic and Social Commission for West Asia

ICARDA

International Center for Agricultural Research in the Dry Areas

Sida

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Authors:

International Center for Agricultural Research in the Dry Areas (ICARDA)
United Nations Economic and Social Commission for Western Asia (ESCWA)

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PREFACE

The Regional Initiative for the Assessment of Climate Change Impacts on Water Resources and Socio-Economic Vulnerability in the Arab Region (RICCAR) is a joint initiative of the United Nations and the League of Arab States.

RICCAR was launched under the auspices of the Arab Ministerial Water Council in 2010 and derives its mandate from resolutions adopted by this council as well as the Council of Arab Ministers Responsible for the Environment, the Arab Permanent Committee for Meteorology and the ESCWA Ministerial Session.

RICCAR is implemented through a collaborative partnership involving 11 regional and specialized organizations. The RICCAR Regional Knowledge Hub (RKH) is managed by the United Nations Economic and Social Commission for Western Asia (ESCWA) and the Arab Center for the Studies of Arid Zones and Dry Lands (ACSAD) with the Food and Agriculture Organization of the United Nations (FAO) hosting the Arab/Middle East and North Africa (MENA) Domain data portal. ESCWA coordinates the regional initiative under the umbrella of its Arab Centre for Climate Change Policies.

The present training manual was prepared through a collaborative partnership between ESCWA, ICARDA, and the APSIM initiative. The Morocco activity is partially supported by the CGIAR ClimBER initiative: Building Systemic Resilience Against Climate Variability and Extremes.

This training material is intended to comprehensively train a non-expert user on how to use RICCAR data to run the APSIM model such that the trainee could use it to further develop their skills in modelling-based analysis to support their climate adaptation projects. Considering the spatial resolution of the datasets and moderate levels of site-specific parameterizations will be required for site-level calibration and validation (CALVAL) and operational use. This is not an academic research document on the use of climate data to run the APSIM model. This should only be considered as training material.

Funding for the guide was provided by the Government of Sweden through the Swedish International Development Cooperation Agency (Sida) under a project focused on water and food security in a changing climate context and is implemented by ESCWA. The project component provides enhanced policy coherence across the water and agricultural sectors through institutional mechanisms and the provision of informed policy guidance and risk analysis, expanding the local knowledge base though science-based assessments and analysis of climate impacts on strategic sectors. It also empowers diverse communities through applied capacity building initiatives.

ABBREVIATIONS AND ACRONYMS

APSIM	Agricultural Production Systems Simulator
ICARDA	International Center for Agricultural Research in the Dry Areas
ESCWA	Economic and Social Commission for West Asia
IPCCN	Intergovernmental Panel on Climate Change
CBCAO	Context-Based Climate Adaptation Option
MENA	Middle East and North Africa
CSA	climate-smart agriculture
RICCAR	Regional Initiative for the Assessment of Climate Change Impacts on Water Resources and Socio-Economic Vulnerability in the Arab Region
GCM	global climate model
CNRM	Centre National de Recherches Météorologiques
GFDL	Geophysical Fluid Dynamics Laboratory
RCP	representative concentration pathway
SSP	shared socioeconomic pathways
DBS	distribution-based scaling
GHG	greenhouse gas
APSRU	Agricultural Production Systems Research Unit
UI	user interface
NETCDF	Network Common Data Form
BE	Big-endian
LE	Little-endian
DOY	day of the year
ECMWF	European Centre for Medium-Range Weather Forecasts
ET	evapotranspiration
LMP	lower Mesopotamian plain
SOC	soil organic carbon

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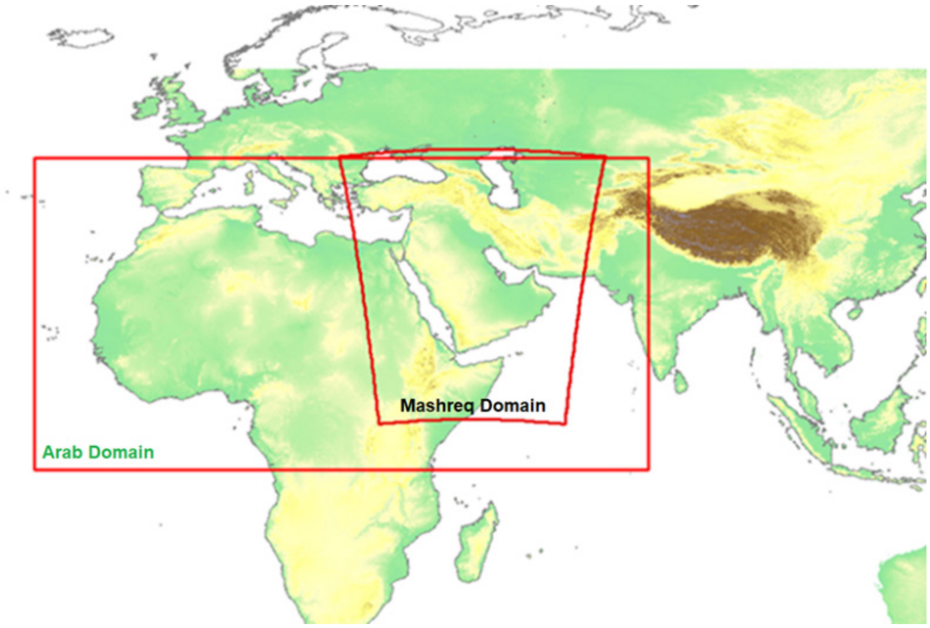
1 GENERAL OVERVIEW OF THE TRAINING MATERIAL

A. Introduction and purpose of this training material

The Arab region in the Middle East and North Africa (MENA) represents a substantial area of the terrestrial landmass encompassing several countries and ecosystems. This area is generally drier and warmer compared to the rest of the world and has extreme resource limitations that are highly vulnerable to a changing climate, geopolitical instability and land degradation (Slimani & Aidoud, 2004). Agriculture (crops and livestock) is a critical source of employment and a potential option for engaging rural youth. However, environmental degradation coupled with declining and variable agricultural productivity may pose a massive challenge already beset by instability and declining oil reserves (Tagliapietra, 2017). The Arab region is also subjected to short and long-duration climate extreme events, and the overall impact of their cascading effects on ecosystems, societies and economies is still an open question. Climate change, along with post-war geopolitical complexities, has greatly affected the Arab region in terms of its economy and social balance. Climate change has penetrating effects on the region's agriculture sector and hence its economy. These are mainly manifested via changes in water resources and extreme weather conditions such as heatwaves and a drastic decline in precipitation.

Although several downscaled and bias-corrected climate datasets are available, their operational use is too challenging for lay and novice users. To make the data meaningful, it must be assimilated into crop models to support context-specific climate-smart agriculture (CSA) solutions that often present technical challenges. To overcome these, and to support increased utilization of the data, a training manual on how to use the Regional Initiative for the Assessment of Climate Change Impacts on Water Resources and Socio-Economic Vulnerability in the Arab Region (RICCAR) data in a popular crop simulation model has been developed. The main objective of this training material is to develop instructional materials for agriculture extension agents and practitioners interested in using crop modelling in their activities on how to integrate and utilize long-term climate data in a typical and commonly used crop model such as APSIM and identify a Context-Based Climate Adaptation Option (CBCAO).

Representation of the RICCAR-Arab Domain and the RICCAR-Mashreq Domain available through ESCWA



B. The RICCAR climate data series

An ensemble climate product developed under the RICCAR project is used for the long-term future climate data inputted into the crop simulation model. RICCAR is an outcome of a collaborative effort between the Economic and Social Commission for Western Asia (ESCWA), the League of Arab States and respective specialized organizations in response to the request of the Arab Ministerial Water Council and the Council of Arab Ministers Responsible for the Environment to deepen the understanding of the impact of climate change. The RICCAR initiative aims to assess the impact of climate change on freshwater resources in the Arab region through a consultative and integrated assessment that seeks to identify the socioeconomic and environmental vulnerability caused by climate change impacts on water resources in the Arab region. There are two series of RICCAR climate products as shown in table 1: (1) the RICCAR-Arab Domain and (2) the RICCAR-Mashreq Domain. In this training manual, the datasets will be used according to the context. The RICCAR-Arab Domain consists of the outputs of three global climate models (GCMs) (CNRM-CM5, GFDL-ESM2M and EC-EARTH[1]) that were downscaled and bias-corrected (1951-2100) for different climate change scenarios (representative concentration pathway (RCP) 4.5 and 8.5). The spatial resolution is 50 km with a daily time step from 1951 to 2100. The RICCAR-Mashreq Domain consists of the outputs of six GCMs (CMCC-CM2-SR5, CNRM-ESM2-1, EC-Earth3-Veg, MPI-ESM1-2-LR, MRI-ESM2-0 and NorESM2-MM[2]) that were downscaled and bias-corrected for the SSP5-8.5 climate change scenario. The geographical area of these two domains is shown in the map. In this manual, these climate products were strategically analysed, and the climate change dynamics of the Arab region were studied.

TABLE 1: Comparison of RICCAR-Arab Domain and RICCAR-Mashreq Domain

	Arab Domain	Mashreq Domain
Spatial extent	27W-76E, 7S-45N	24E-69E, 0N-46N
Spatial resolution	0.44° (~50 km)	0.10° (~10 km)
Temporal extent	1951-2100	1961-2070
Temporal resolution	Daily	Daily
Scenarios	RCP 4.5, RCP 8.5	SSP5-8.5
Driving GCM (the average of these GCMs is used)	CNRM-CM5 GFDL-ESM2M EC-EARTH	CMCC-CM2-SR5 CNRM-ESM2-1 EC-Earth3-Veg MPI-ESM1-2-LR MRI-ESM2-0 NorESM2-MM
Downscaling regional climate model (RCM)	RCA4	HCLIM-ALADIN
Bias correction method	Distribution-based scaling (DBS)	Multi-scale bias adjustment (MidAS v0.1)
Use in this manual	Morocco (chapter 4)	Iraq (chapter 5) and Jordan (chapter 6)

C. Climate-smart agricultural interventions studied

To train the non-expert user on how to use long-term climate data (RICCAR) along with a crop simulation model, three test cases with unique climate adaptation needs were identified. Further to this, comprehensive numerical experiments were designed to explore climate vulnerabilities and climate adaptation options employing a scenario-based approach. The novice user will acquire broad knowledge in using APSIM if the three exercises are carefully worked through. The three studies identified for this manual include:

- Case study of Morocco, an example of a rainfed agroecosystem: The training manual demonstrates yield gap evolution under climate change in a rainfed agroecosystem and shows the relative effects of two Intergovernmental Panel on Climate Change (IPCC) scenarios (RCP 8.5 and RCP 4.5). Additionally, supplementary irrigation is applied as a key climate adaptation measure in a location suffering from increasing droughts in order to augment water supply in extremely dry weather conditions.
- Case study of Iraq, an example of an irrigated agroecosystem: The training manual demonstrates changes in water productivity and yield dynamics in an arid but irrigated agroecosystem. It demonstrates how judicious irrigation techniques as opposed to conventional irrigation as a climate adaptation measure can enhance water productivity while also maintaining and possibly maximizing yield.
- Case study of Jordan, an example of a semi-arid agroecosystem: The training manual demonstrates crop diversification and defines optimum cropping patterns (through the selection of alternate resilient crops) as a key climate adaptation measure and assesses impacts on soil carbon sequestration.

BOX 1: Definition of climate downscaling and bias correction

Downscaling is the procedure of using coarse-scale climate models to make climate predictions at finer temporal and spatial scales for local level analysis and planning. There are two approaches to downscaling: (1) dynamical – where outputs from GCMs are used to drive higher resolution regional climate models with a better representation of local terrain and other conditions, and (2) statistical – where statistical links are established between large-scale climate phenomena and observed local-scale climate.

Bias correction is the process of scaling climate model outputs to account for their systematic errors, in order to improve their fitting to observations.

TABLE 2: Comparison of the various climate-smart interventions that will be studied

	Case study	Context	Hypothesis-based CSA intervention
Climate adaptation	Morocco Region of interest (ROI): Rabat-Salé-Kénitra	Rainfed system	Climate analysis shows that the annual precipitation in this area is significantly reduced and as such rainfed farming is no longer viable. Thus, supplementary irrigation is the most appropriate climate adaptation measure suggested in this context to sustain agriculture. Adaptation: RICCAR-based crop modelling will be used to explore how well supplementary irrigation can help to sustain crop yields under climate change under the business-as-usual scenario (RCP 8.5).
	Iraq ROI: Lower Mesopotamian plain	Irrigated system	Climate analysis shows that the annual temperature in this area significantly increases and as such irrigated farming can be sustained only by increasing irrigation quantities, which is a huge burden on water resources. Adaptation: RICCAR-based crop modelling will be used to explore water productivity under the conventional inefficient flooding method in comparison to the efficient drip irrigation method and under climate change.
Climate mitigation	Jordan ROI: Jordan valley	Irrigated system	Under the currently existing cropping pattern, the ability to sequester carbon as climate mitigation is minimal. It is hypothesized that crop diversification will enhance soil carbon sequestration. Mitigation: RICCAR-based crop modelling will be used to explore how much carbon sequestration gain can be achieved by increasing the diversity of crops in the crop rotation using a scenario-based approach.

BOX 2: Key climate change scenarios as defined by the IPCC

RCP 8.5: Business-as-usual climate change scenario or the worst-case scenario where the climate changes without any mitigation actions.

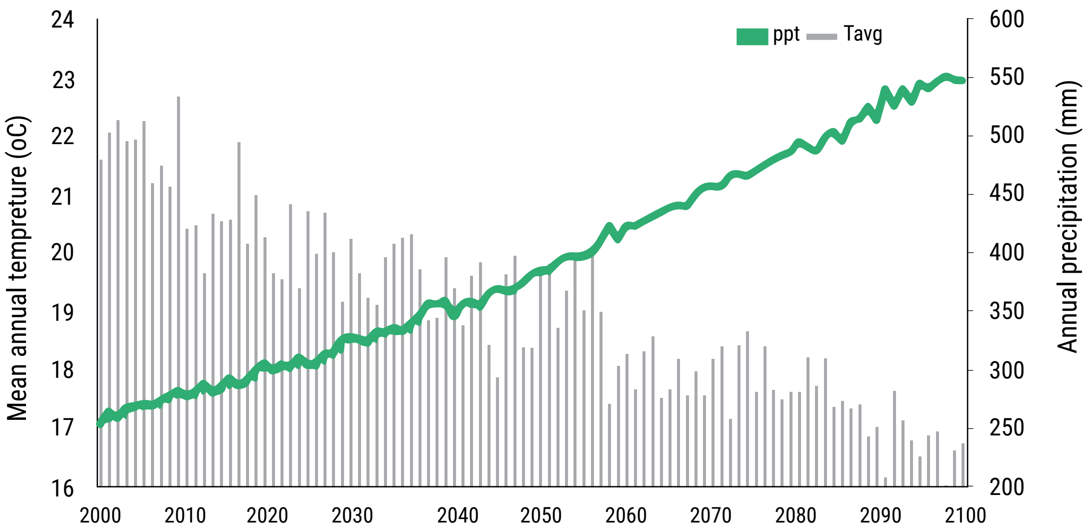
RCP 4.5: Best case scenario where the climate change happens with very good mitigation actions.

SSP5-8.5: Fossil-fuelled development, leading to very high greenhouse gas (GHG) emissions. Carbon dioxide (CO_2) emissions triple by 2075.

D. Climate dynamics in Morocco, Iraq and Jordan

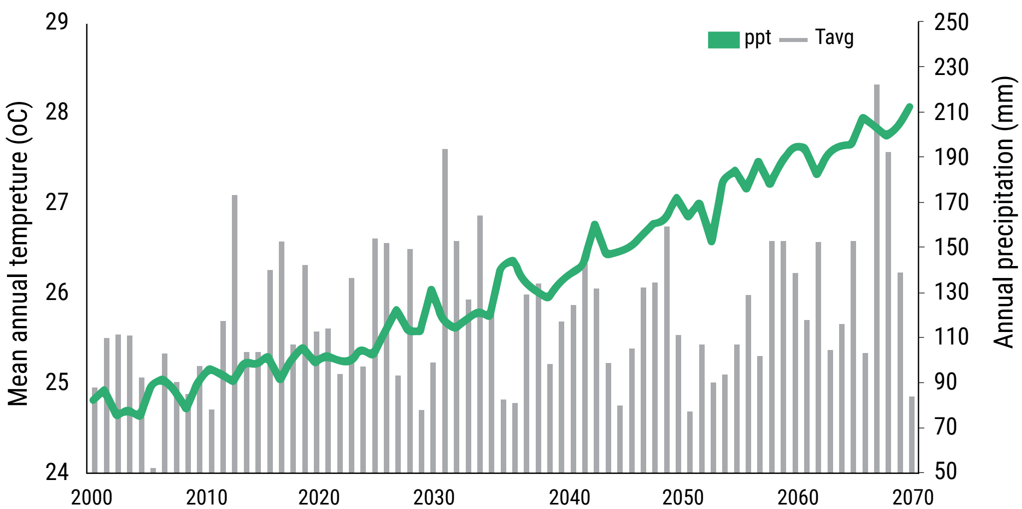
A brief narrative on the plausible pathways of climate change at the three test case sites are shown. The RCP 8.5 scenario is displayed here because it corresponds to the "business-as-usual" scenario of climate change. The climate change trends are briefly explained in the adjacent boxes.

FIGURE 1: Interannual variability of the mean annual temperature and annual precipitation in the business-as-usual scenario (RCP 8.5) in the three test cases



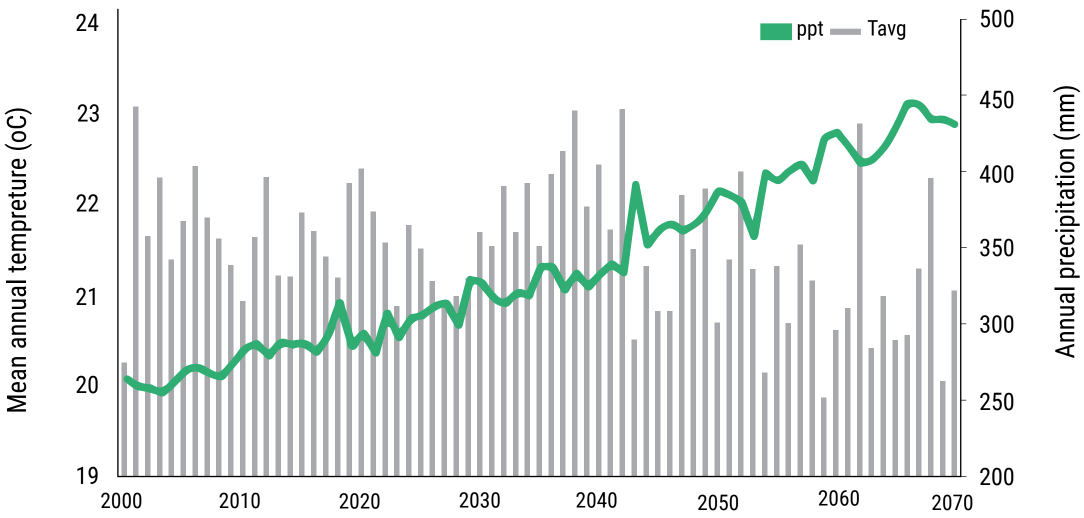
Morocco

The mean annual temperature is projected to change from 17°C during the baseline period to as much as 23°C by 2100. A steady decline of precipitation from 480 mm in 1980 to as little as 250 mm in 2100 is expected.



Iraq

The mean annual temperature is projected to change from 25°C in the baseline period to as much as 28.5°C by 2100. Regarding precipitation, the variability with climate change is very uncertain. The general trend shows a slight increase.



Jordan

The mean annual temperature is projected to change from 20°C in the baseline period to as much as 23°C by 2100. Regarding precipitation, there is a general decline after 2040, although there is a slight increase between 2020 and 2040.

2. THE APSIM CROP SIMULATION MODEL

A. Introduction to the APSIM model

APSIM, the Agricultural Production Systems Simulator is a dynamic, daily time step modelling platform that combines biophysical and management modules within a central engine to simulate the production and resource consequences of agricultural systems. It simulates biophysical processes in cropping systems, particularly those relating to the production and ecological outcomes of management practices in the face of climate risk. It contains a suite of modules that enable the simulation of systems that cover a range of plant, animal, soil, climate and management interactions. The APSIM (Keating et al., 2003, Holzworth et al., 2014) cropping systems model has a proven track record in modelling the performance of diverse cropping systems, rotations and fallowing, as well as crop and environmental dynamics (Whitbread et al., 2010, Hochman et al., 2017). A distinctive innovation and philosophical departure from most other "crop models" is the primary focus of APSIM on simulating crop resource supply (rather than a primary focus on resource demand), with the soil forming the central simulation component. Crops, with their resource demands impacted by weather and management, find the soil in one condition and leave it in another condition for the next crop (McCown et al., 1996). This emphasis on simulation of soil resource dynamics positions APSIM strongly in comparison with other models for investigations into long-term changes to soil conditions and sustainability associated with different cropping strategies and practices. With a particular focus on research into adaptation strategies, another notable strength of the APSIM model is its unique capacity to capture intricate detail and subtleties of dynamic farmer management practices through a highly flexible "Manager" module allowing the user to specify detailed farmer decision-trees using simple "if-then-else logic" (Holzworth et al., 2014). Evaluation of APSIM is well-established and well-documented in Australia, Africa and Asia. The first step in evaluating a model's credentials is to define model capacities required for addressing research questions around some of the issues. A model for the simulation of cropping system performance should be capable of several key functions: (i) robust crop development and yield simulation for a wide variety of crops; (ii) the ability to simulate cropping sequences and the effect of different fallow, tillage and residue management strategies on system performance; (iii) robust simulation of soil water and nutrient dynamics in conjunction with crop performance; (iv) flexibility to capture detailed management practices, including subtle changes to farmer decisions and strategies, and evaluate their impact on system performance; and (v) robust simulation of crop response to CO_2 and temperature variation (Rötter et al., 2011).

B. The developmental history of APSIM

The APSIM framework was originally developed by the Agricultural Production Systems Research Unit (APSRU), based in Toowoomba, Queensland. APSRU was a partnership involving researchers from Australian Government research agency CSIRO (the Commonwealth Scientific and Industrial Research Organization), the University of Queensland and the Queensland State Government, established in 1990. The APSIM model has been the result of this collaboration. Ever since its start in the early 2000, APSIM has evolved into a framework containing many models required to explore changes in agricultural landscapes.

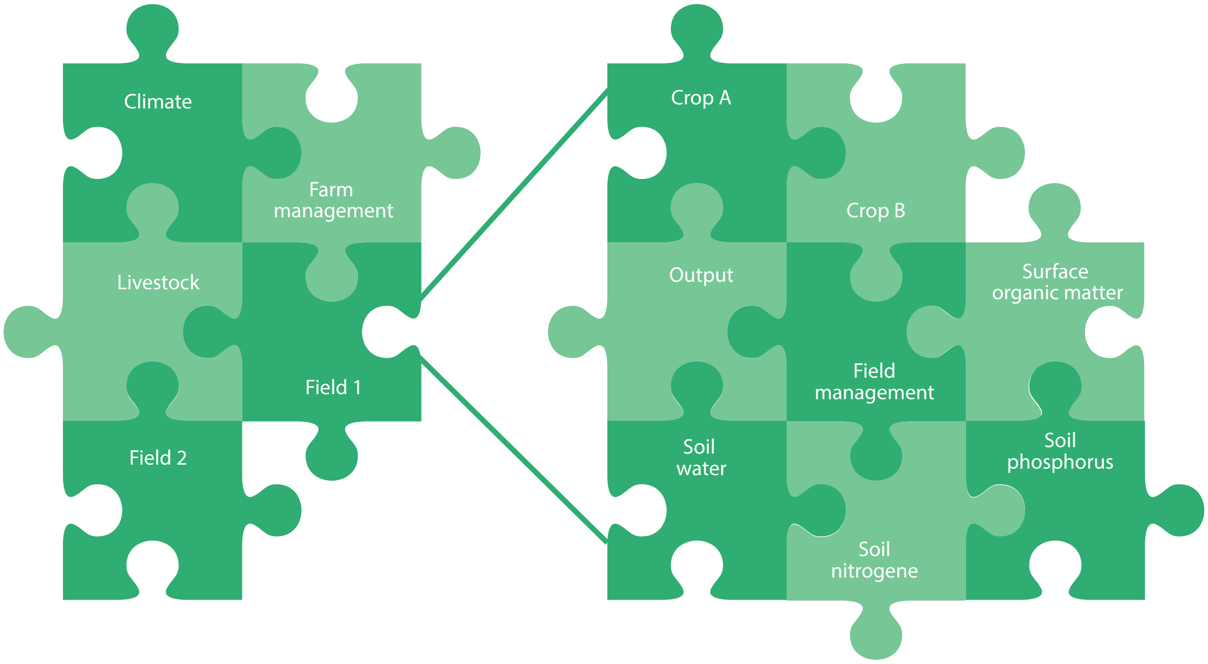
C. The modular structure of APSIM

APSIM has a modular framework consisting of numerous individual modules that describe the plant, soil, climate and management processes. These modules include a diverse range of crops, pastures, trees, soil processes including water balance, nitrogen (N) and phosphorus (P) transformations, soil pH, erosion and a highly flexible range of management controls. It is also used in a broad spectrum of research applications from cropping systems to agroforestry and ecology. In this sense, APSIM is a highly customizable modelling framework that can do different things for different users. The APSIM modelling framework is made up of the following components:

- A set of biophysical modules that simulate biological and physical processes in farming systems.
- A set of management modules that allow the user to specify the intended management rules that characterize the scenario being simulated and that control the simulation.
- Various modules to facilitate data input into and output from the simulation.
- A simulation engine that drives the simulation process and facilitates communication between the independent modules.

- Various user interfaces for model construction, testing and application, database tools for visualization, and further analysis of output.
- A web-based user and developer support facility that provides documentation, distribution and defect/change request tracking.

FIGURE 2: A conceptual representation of the modular approach adopted in the APSIM model. Various modular approaches can be plugged-in as and when needed



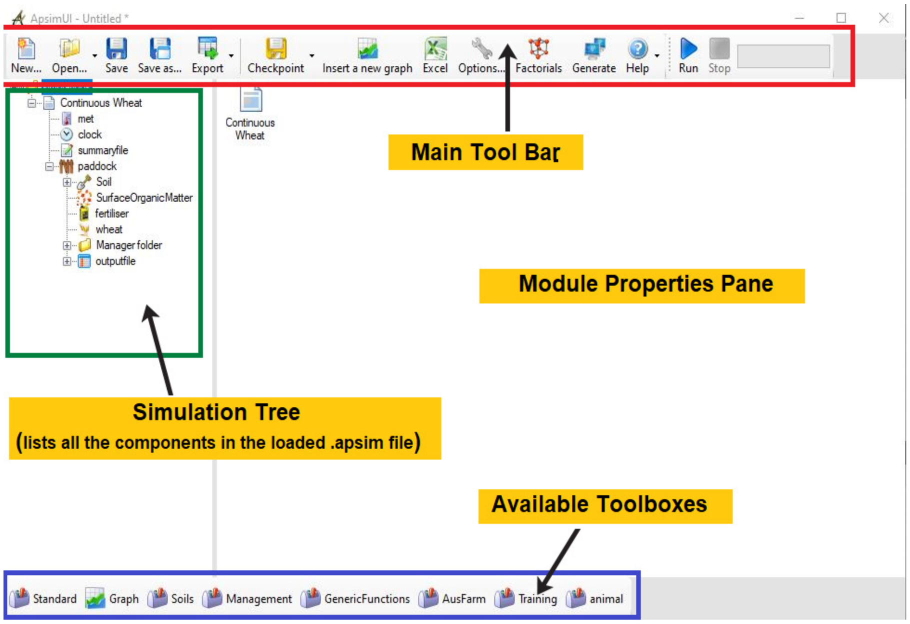
D. Familiarizing users with the APSIM Interface

This section will introduce the APSIM user interface (Apsim UI) and described the process of building, running and graphing a typical simulation. This section is not comprehensive regarding the overall capability of APSIM UI as its purpose is to shed light on what APSIM UI provides, after which the user may explore and self-learn using this section as a base. The primary buttons that users will be working with are highlighted below. They will be used frequently throughout the tutorials in this manual.

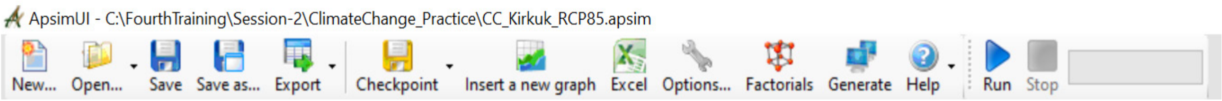
The APSIM UI consists of four panels:

- The main toolbar at the top.
- A simulation tree on the left that lists all the components in the loaded file.
- A module properties pane on the right.
- A bar at the bottom that lists available toolboxes.

FIGURE 3: Screenshot showing the APSIM UI panels



Zoom into main toolbar components



The main toolbar items include:

- **Export** – this exports a graph created in the APSIM UI in several formats (.jpeg, .png, .bmp etc).
- **Checkpoint** – this creates a snapshot of a simulation allowing the user to do before and after comparisons or to revert a change.
- **Inserting a new graph** – this brings up the "add new" graph wizard.
- **Excel** – this allows output files to be exported as comma-delimited text files.
- **Factorials** – this is an advanced topic that will be looked at in a separate module.
- **Generate** – this generates a ZIP file required for running remotely.
- **Help** – this directs the user to the local help files; however, there are many support options that are discussed in a separate module.

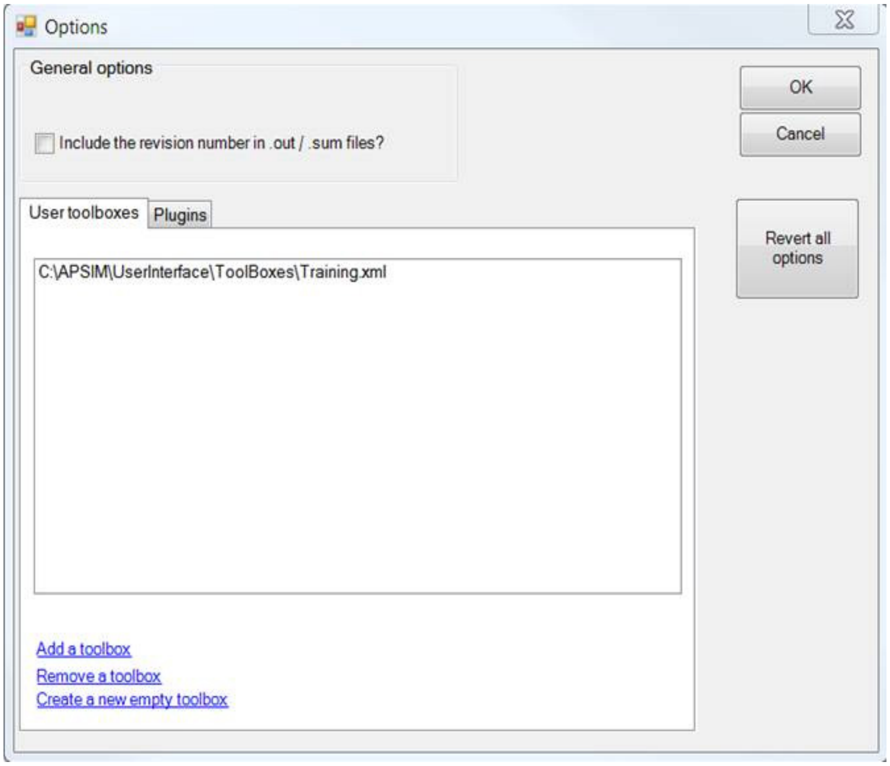
To familiarize the interface, we will walk through a simple simulation initially.

1. The APSIM toolbox

All available components in APSIM are included in toolboxes. Whenever the user needs to add a new component to the simulations, one of the toolboxes along the bottom of the screen is to be used. It is possible to add toolboxes; for instance, components that users need often and want to make easier to access can be added, including written scripts that the user would like to share with a colleague or a customization of some of the standard components.

Use the following instructions to add a toolbox:

- **Load** a premade toolbox to make it easier to access some soil data.
- **Click** the **Options** button. **Click** on **Add a toolbox**.
- **Navigate** to the APSIM installation folder (by default it will be in **C:\Program Files (x86)\Apsim[version]-r[revision]\UserInterface\Toolboxes folder**.
- **Click** **Training.xml** and **click** **Open**. You should now see the following (your path will be different):



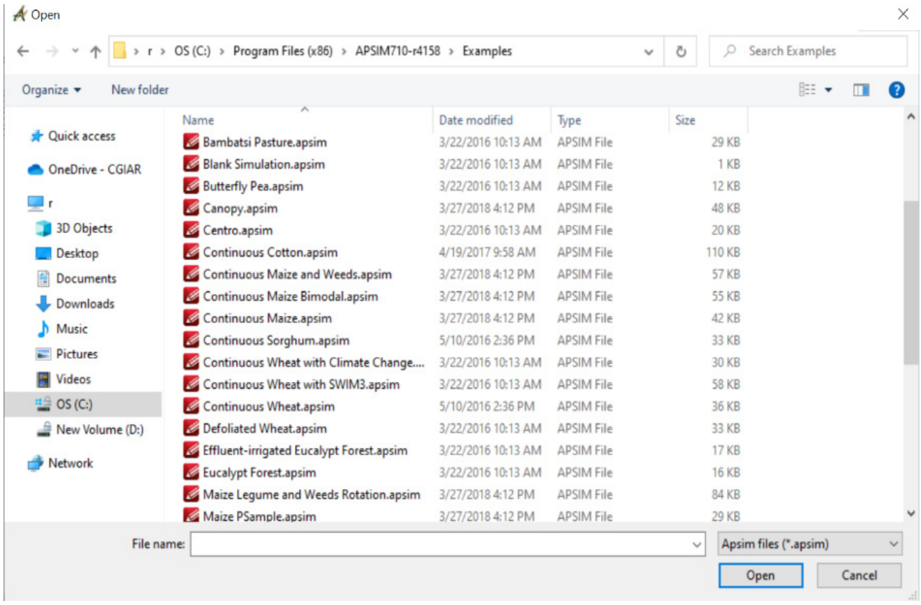
- **Click** **OK** to see the new toolbox in the toolbox bar at the bottom of the APSIM window. This toolbox contains components to be used in the training session.

You can add your own components to toolboxes by dragging and dropping them from a simulation. Alternatively, you can also copy them directly from another toolbox. **Note that you can't add anything to this training toolbox as the Program Files folder is write-protected.**

2. Running a typical APSIM simulation

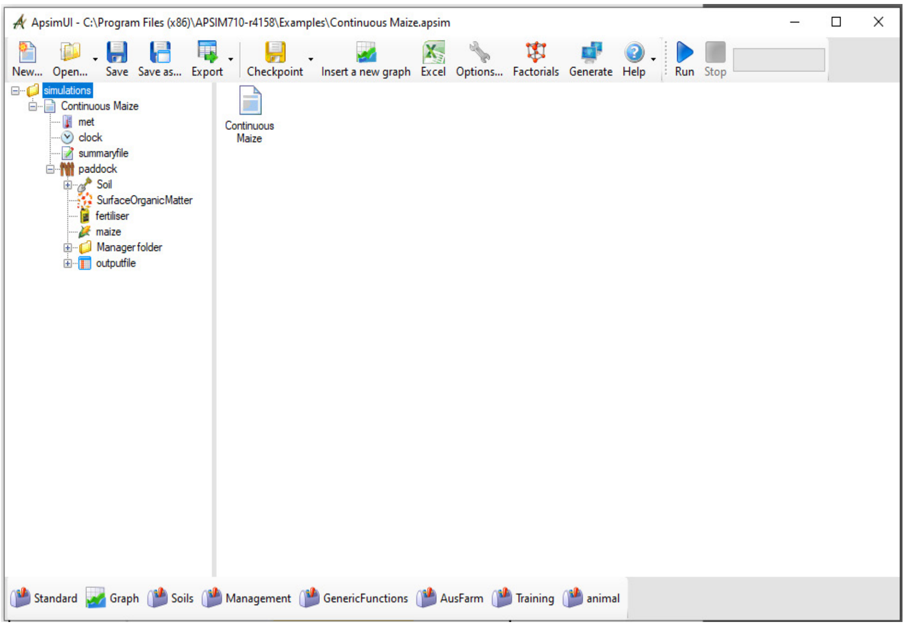
The first step is to familiarize users with the APSM UI and understand how to run a typical simulation in APSIM so that users get an idea of how things work. As it takes some effort to prepare site-specific data and soil input, in the APSIM familiarization step, we will just go through an inbuilt example so that the user can seamlessly practice. As we familiarize the interface, we will deal with our specific cases with context-specific inputs.

- **Click** the **New** button to create a new simulation. You will be presented with the following screen:

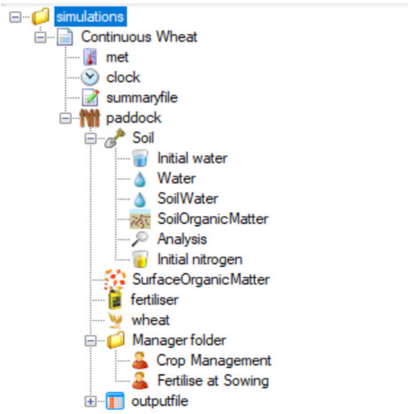


Because all simulations generally share the same base components, we do not recommend starting from scratch. The best method is to choose the simulation closest to the one you want to build then modify it. For this exercise, we will use the "Continuous Wheat" simulation.

- **Click** **Continuous Wheat.Apsim** then **click** **Open**.
- **Click** **Save**.
- **Create** a new folder in your C drive called **Apsim Training** to save all of your work in. Remember this location; all training modules will be saved in this location.
- **Save** the file as **Training_Lesson1.apsim**. You will now see the new simulation loade

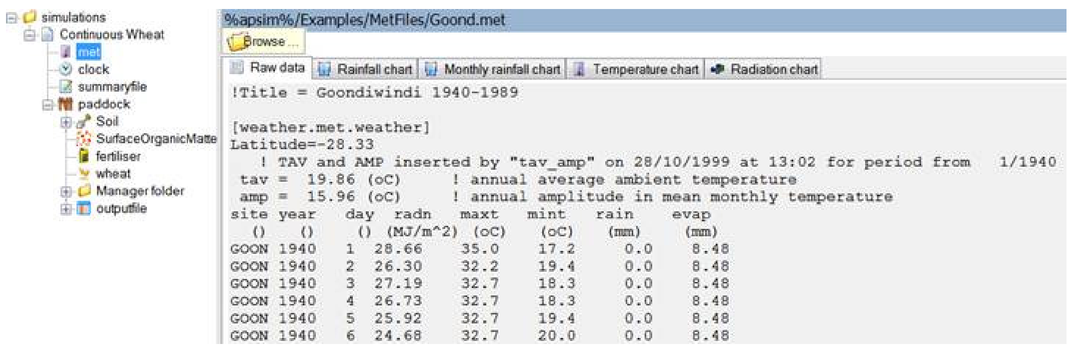


- **Closely examine** the simulation tree on your left panel that describes the components pictorially. The hierarchy of the modules in the simulation tree is shown. Roughly speaking, each simulation tree has four components (**met**, **clock**, **summary file** and **paddock**) of which the **paddock** is the most elaborate component with several subcomponents such as **Soil**, **Surface Organic Matter**, **Crop**, **Manager** and **outputfile**.

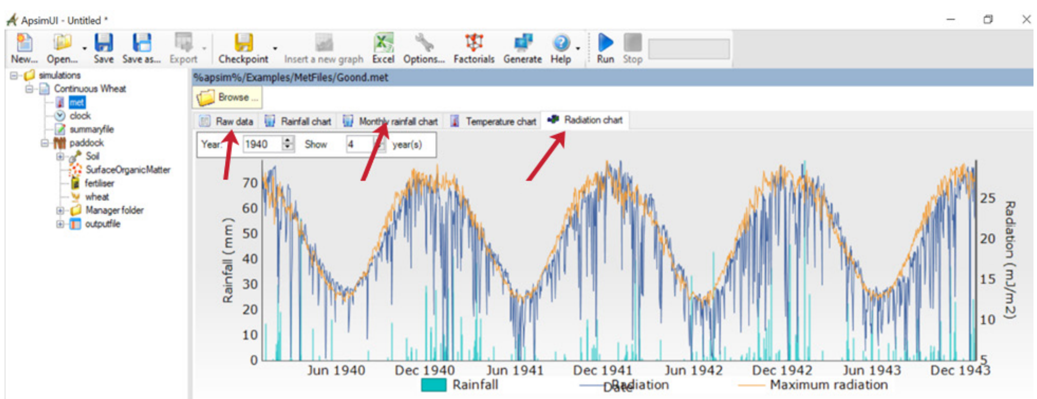


First make sure the user is using the right weather data. To do this:

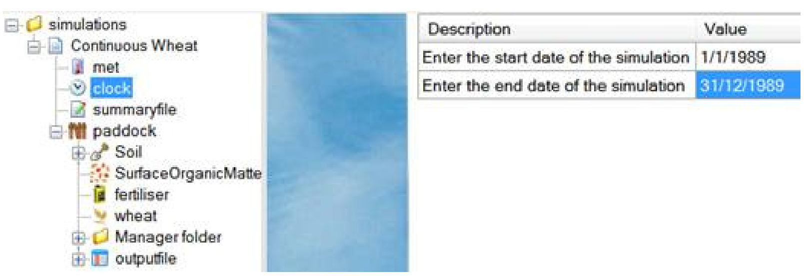
- **Click** the **met** component in the simulation view. Now it is possible to see the weather data for **Goondiwindi** loaded.



- **Click** the other tabs in this window to visualize the climate (meteorological) data. The user may click the **Radiation chart** to see solar radiation, radiation, etc., superimposed as shown in the next screenshot.

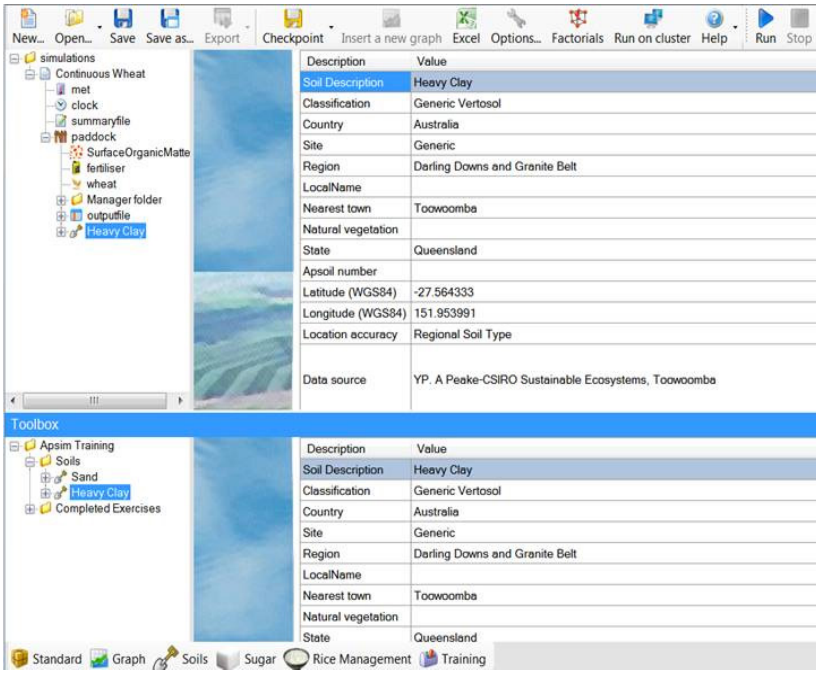


- **Define** which section of the available meteorological time frame the user would like to run the model on. In the simulation tree below the **met**, one can see the **clock**, with the **start date** as 1/1/1989 and the **end date** as 31/12/1989.



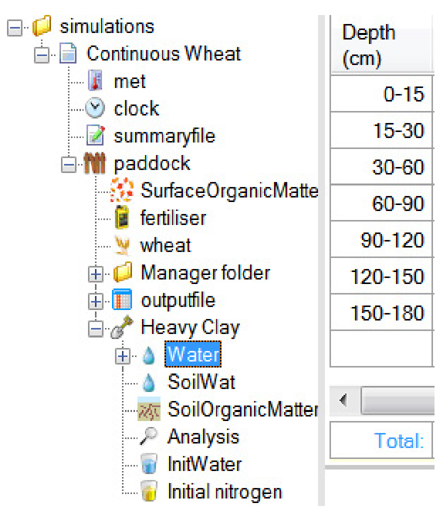
To change the soil:

- **Click** the **Training toolbox** that you loaded earlier.
- **Drag** the **Heavy Clay** soil node from the toolbox.
- **Drop** it on the **paddock** node in your simulation.
- **Delete** the **old soil** by clicking it and clicking **Delete**. **You can reorder components by right-clicking and choosing Move Up/Down.**
- **Set** the starting water and nitrogen conditions for the soil.
- **Expand** the **new soil** node and **click** **Initial Water**. Make sure **Filled from top** is selected.
- **Set** the fraction available to **10 per cent.**



To find out how deep the profile is:

- **Click** the **Water** module. You will see that the soil profile is 180 cm deep and is split into seven layers.



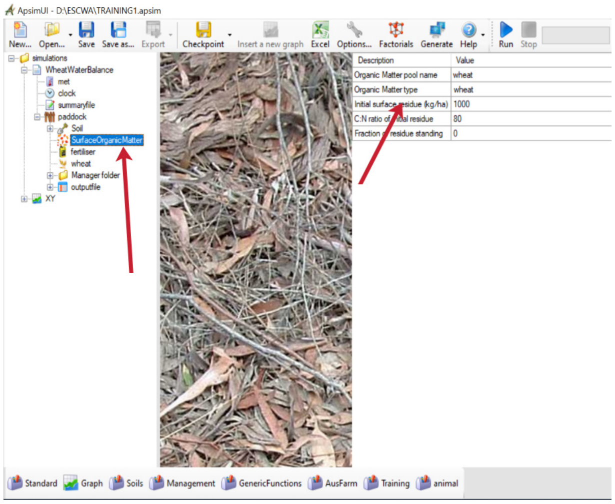
- **Click** the **Initial Nitrogen** module.
- **Set** the starting **NO_3** to 50 kg/ha and **starting NH_4** to 3 kg/ha.
- First, it is essential to identify the working unit in APSIM. In this case it is kg/ha, not ppm. Notice the colour of the column header text. This indicates that the user can change units by right-clicking the column header.
- **Change** **NO_3** and **NH_4** to kg/ha, then enter the values below.

Depth (cm)	NO3 (kg/ha)	NH4 (kg/ha)	SW (mm/mm)
0-10	50	3	0.000

- For this exercise, the nitrogen should be spread evenly through the entire soil profile, so **enter the same values** for all the layers.

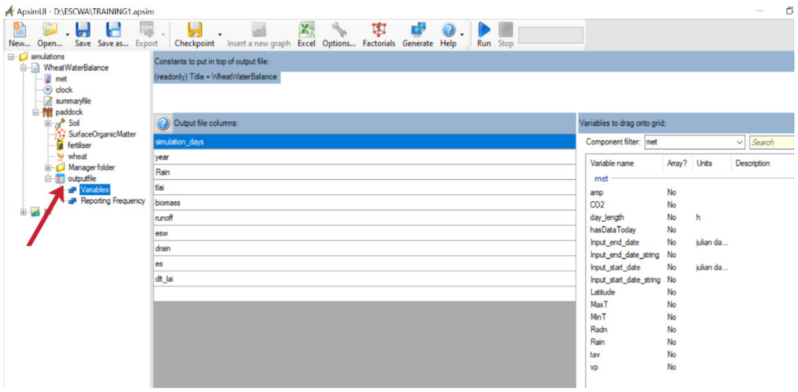
Next, in the **SurfaceOrganicMatter** node:

- **Check** that the **Organic Matter type** is wheat and the **Initial surface residue** is 1,000 kg/ha. This means we start the simulation with 1,000 kg/ha of wheat stubble on the surface. This will decay over time putting nutrients back in the soil. It will also reduce surface evaporation.



To rename the simulation:

- **Right-click** **Continuous Wheat** and choose **Rename**. Type in **Wheat Water Balance**.
- Results for the simulation are found in the **outputfile** node. This is also where the user will specify what variables they want to be reported and how often.
- **Click** the **outputfile** node and delete all the variables except the first one (**dd/mm/yyyy** as date).



There are two ways to enter new variables:

1. Type them directly into the **outputfile columns** list, or

2. Select them (double-click or drag) from the pane on the right.

This panel shows all the available variables for the chosen component. You can change their order in the list by right-clicking and choosing Move Up/Down, or use the keyboard shortcut (Ctrl + Up/Down arrows). Enter the following variables to report:

TABLE 3: Variables selected to customize the output file for this simulation

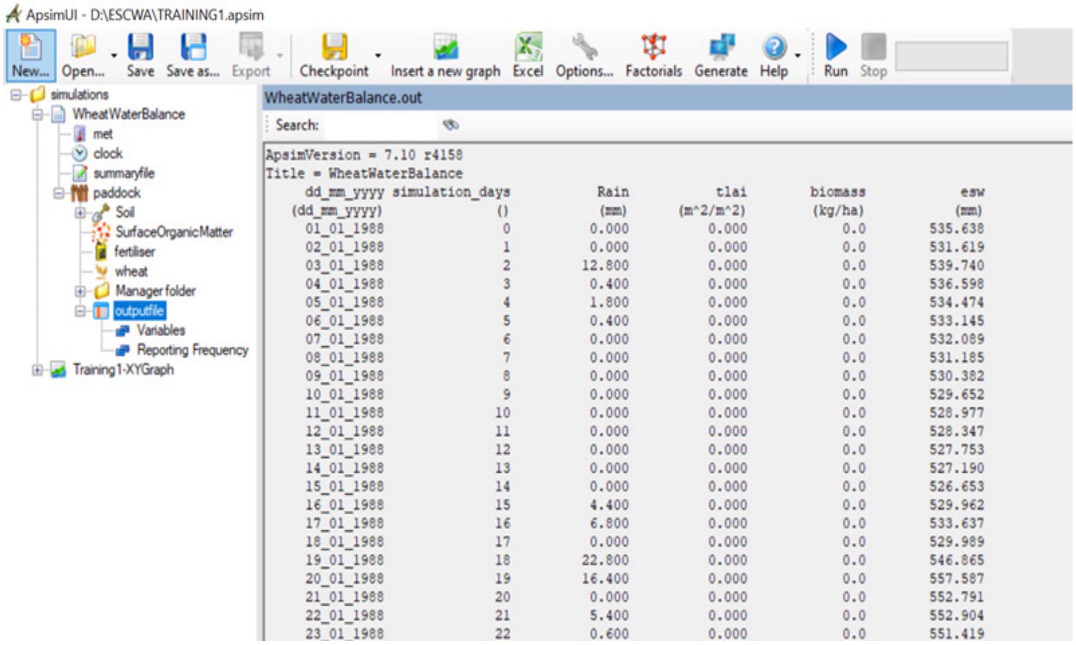
Variable	Unit	Explanation	Variable family
Dd_mm_yyyy	NA	Date	Clock
Simulation_days	NA	Day since simulation started	Clock
Rain	mm	Daily rain	Met
Tlai	m^2/m^2	Total leaf area index	Wheat
Biomass	kg/ha	Total biomass	Wheat
Extractable soil water (ESW)	mm	Extractable soil water	Soil

- **Click** **Reporting Frequency** to specify how often you want the variables written to the output file.

The user may choose a regular interval such as every day or once a month/year. It is also possible to specify an event. For instance, you might want to write the output **on sowing, harvesting or fertilizing**. For this simulation, the needed output is daily, so delete **harvesting** and type in **end_day**.

This is the end of building the simulation:

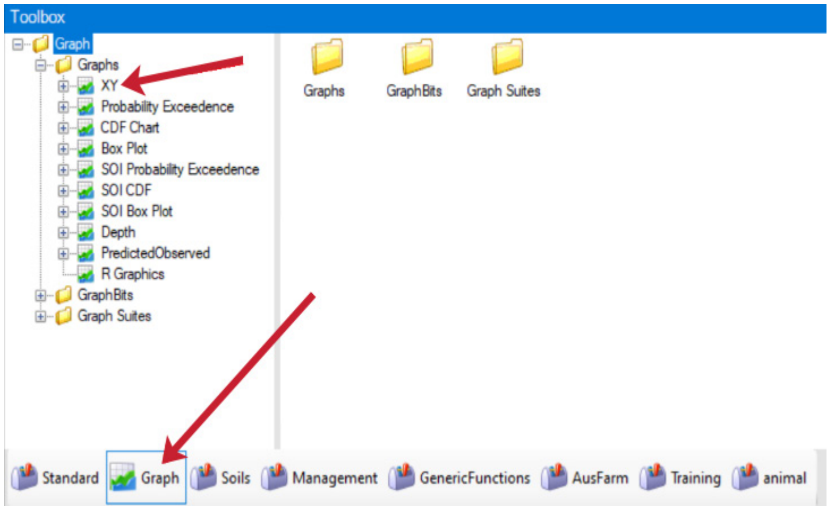
- **Click** the Run **Run** button on the main toolbar.
- Once the run is complete, **click** the **outputfile** component to view the results.
- This is just a text file so users can easily import it into other programs for analysis. It will be saved in the same directory your simulation is in with the file name being <simulation_name>.out. If there is no file available, it means the run failed. Check the **summary file** for errors.



3. Creating graphics

APSIM UI can do basic visualization and analysis right in the user interface. Several types of graphs can be developed. This section will use the inbuilt APSIM graphs to display the data in the output file in a graph and create a graph showing **ESW** and **rain** (Right Hand Axis) by **simulation day**. To do this:

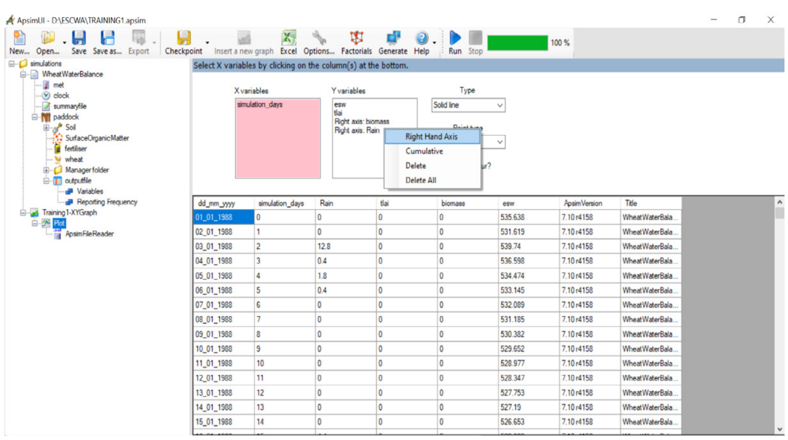
- **Click** on the **Graph toolbox** to open it.



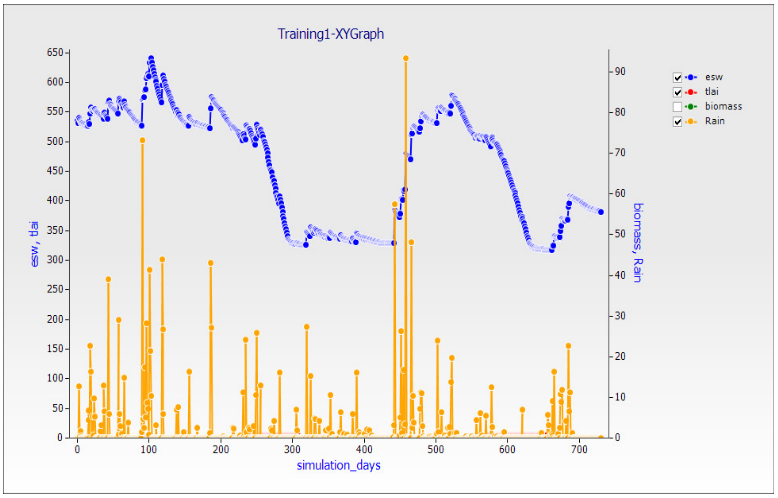
- **Expand** the **Graph** folder then the **Graphs** folder. **Click** on the **+** symbol next to the **Graphs folder** to expand it.
- **Drag** an **XY component** onto the output file in your simulation.
- **Right-click** on the **XY** node, and rename it to **Training1-XYGraph**. This updates the chart title.
- **Expand** the **Training1-XYGraph** component.
- **Click** on the **Plot** subcomponent.
- **Click** on the **X variables** square to make sure the background of the square is pink (variables can only be added to it when the background is pink).
- **Click** on the **simulation_days** column heading. It should appear in the list in the square.
- **Click** on the **Y variables** square to make its background pink.
- **Click** on the **ESW, tlai, biomass**, and the **Rain** column headings. They should be added to the list in the square.

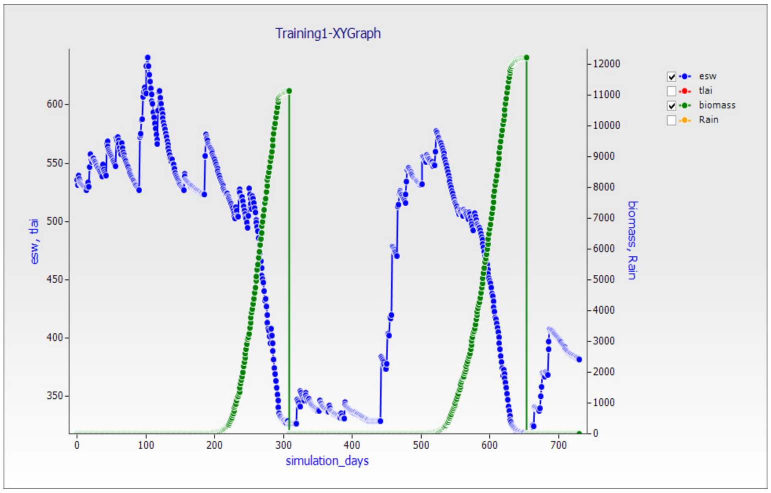
To make Rain and biomass appear on the right-hand axis:

- **Click** **Rain** in the square to highlight it and **right-click on it**. In the popup menu **click on** **Right Hand Axis**.



- **Click** **Training1-XY Graph** to see the following graph that shows the dynamics of ESW plotted with Rainfall.
- **Click** the legend items on the right for other variables to be plotted.





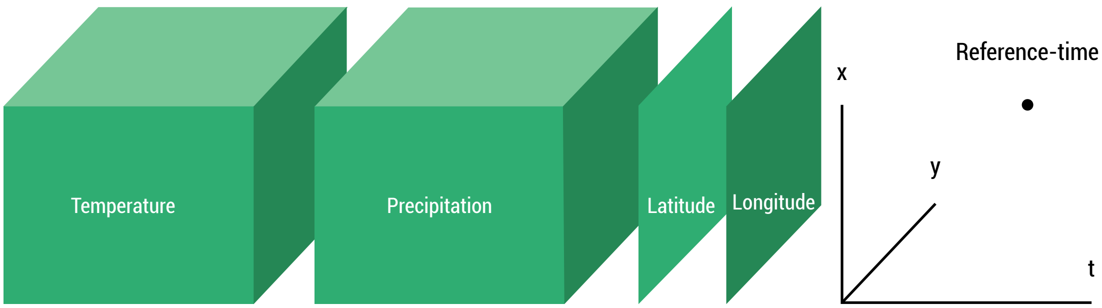
The user is encouraged to explore other graph options on their own.

- **Right-click** the graphs to explore various saving options. **Explore** the **Excel** icon in the main toolbar to export the data of simulations.

3. PREPARING INPUT CLIMATE DATA TO RUN APSIM USING RICCAR PRODUCT

Although climate data is vital to many applications in many disciplines, handling climate data is often difficult for the non-expert user owing to its complex structure due to its spatiotemporal nature along with several variables arranged together. There are also variable-specific conversion requirements (coefficients and units). Most of the time climate data exists in NetCDF (Network Common Data Form) format. A NetCDF is a set of software libraries and self-describing, machine-independent data formats that support the creation, access and sharing of array-oriented scientific data. This means that there is a header that describes the layout of the rest of the file, in particular the data arrays, as well as arbitrary file metadata in the form of name/value attributes. The format is platform-independent, with issues such as endianness[3] being addressed in the software libraries. The data is stored in a fashion that allows efficient sub-setting with several variables in space and time. Figure 4 shows an example of a complex climate data structure.

FIGURE 4: A conceptual representation of the NetCDF climate data

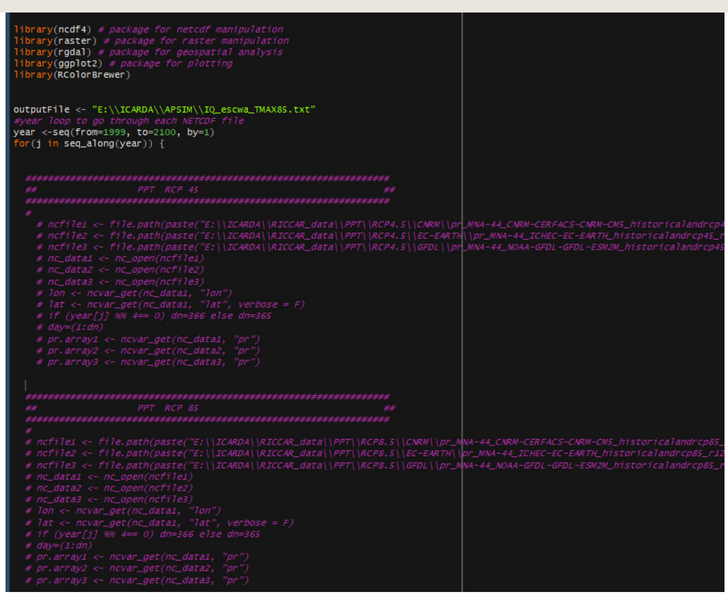


Source: Hoyer and Hamman, 2017.

A. Extracting RICCAR data for a location or region in simpler formats

To understand the impact of climate change, the first step of long-term climate/weather data preparation for running APSIM is to extract climate data from the RICCAR in a format that is usable by the APSIM model. Usually, this is done using programing tools that can handle the NetCDF files. A code was developed for extracting the time series of a given variable and for a given RCP for any location in the RICCAR Domain. This source code is compiled in the R platform. The source code is provided in Appendix 1 for users who are interested. The user need not necessarily use this method to extract the time series for a location from the RICCAR data. Alternative time series extraction codes written in other languages such as C, Python, etc., may be used.

FIGURE 5: Example of a program written in the R language to extract time series of data from a location from the RICCAR (NetCDF) data. This code is provided in Appendix 1



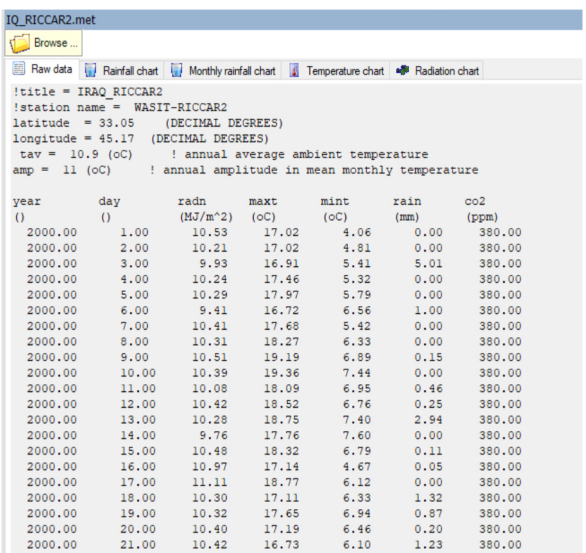
B. Developing derived weather variables from RICCAR

It is possible to extract daily maximum temperature (Tmax), daily minimum temperature (Tmin), and daily precipitation (Ppt) from the RICCAR database. However, incoming short-wave radiation (Rsw) is an essential variable for crop modelling. If the user is using climate data from other sources, then it is recommended that they use Rsw directly. In the event that Rsw data is not available, it is possible to calculate a value for Rsw using the basic meteorological variables, the latitude of the location and the time of the year. However, this is a modelled estimate of radiation. The necessary equations that can be used to calculate Rsw are provided in Appendix 1. On the other hand, if Rsw data is readily available, it is highly recommended to use that directly. Some crop simulation models also require the use of data on relative humidity and wind speed.

C. Preparing APSIM-specific climate data

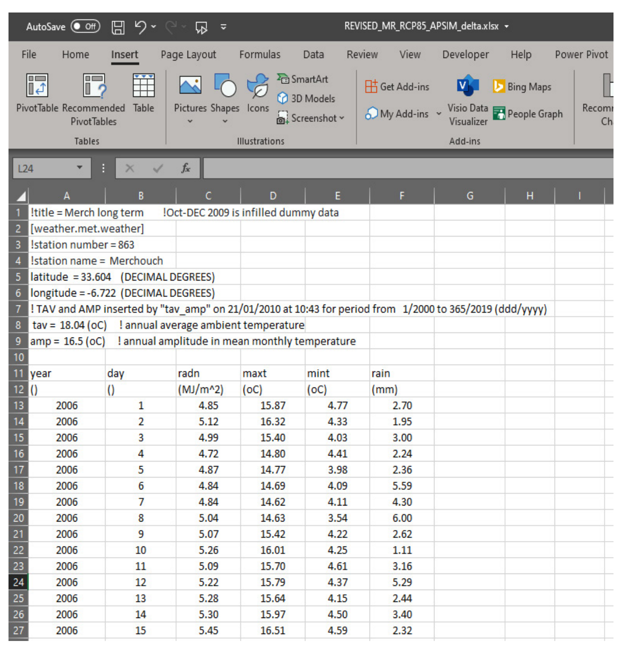
APSIM met files (meteorology input files) consist of a section name, which is always **weather.met.weather**, several constants consisting of "name = value", followed by a headings line, a units line and then the data. Spacing in the file is not relevant. Comments can be inserted using the ! character. As a minimum requirement, three constants must be included in the file: latitude, mean average temperature (tav), and amplitude in mean monthly temperature (amp). The met file must also have a year and day column, as well as columns for incoming solar radiation (MJ/m^2), maximum temperature (oC), minimum temperature (oC) and rainfall. In APSIM nomenclature, the column headings used for these are year and day, radn, maxt, mint, rain, respectively. The user may instead use RICCAR-based Tmax for maxt; Tmin for mint and Ppt for rain. The calculated Rsw can be used for radn. Other constants or columns can be added to the file. These then become available to APSIM as variables that can be reported or used in the manager script.

FIGURE 6: Example of a typical APSIM meteorology input file



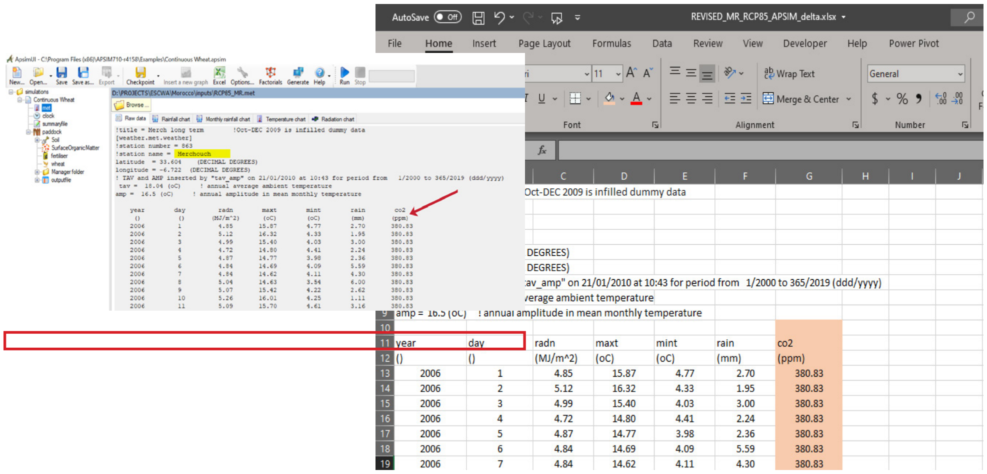

```
!title = IRAQ_RICCAR2
!station name =  WASIT-RICCAR2
latitude  = 33.05    (DECIMAL DEGREES)
longitude = 45.17  (DECIMAL DEGREES)
 tav =  10.9 (oC)     ! annual average ambient temperature
amp =  11 (oC)      ! annual amplitude in mean monthly temperature

year        day        radn      maxt      mint      rain      co2
()          ()         (MJ/m^2)  (oC)      (oC)      (mm)      (ppm)
  2000.00      1.00     10.53     17.02      4.06      0.00     380.00
  2000.00      2.00     10.21     17.02      4.81      0.00     380.00
  2000.00      3.00      9.93     16.91      5.41      5.01     380.00
  2000.00      4.00     10.24     17.46      5.32      0.00     380.00
  2000.00      5.00     10.29     17.97      5.79      0.00     380.00
  2000.00      6.00      9.41     16.72      6.56      1.00     380.00
  2000.00      7.00     10.41     17.68      5.42      0.00     380.00
  2000.00      8.00     10.31     18.27      6.33      0.00     380.00
  2000.00      9.00     10.51     19.19      6.89      0.15     380.00
  2000.00     10.00     10.39     19.36      7.44      0.00     380.00
  2000.00     11.00     10.08     18.09      6.95      0.46     380.00
  2000.00     12.00     10.42     18.52      6.76      0.25     380.00
  2000.00     13.00     10.28     18.75      7.40      2.94     380.00
  2000.00     14.00      9.76     17.76      7.60      0.00     380.00
  2000.00     15.00     10.48     18.32      6.79      0.11     380.00
  2000.00     16.00     10.97     17.14      4.67      0.05     380.00
  2000.00     17.00     11.11     18.77      6.12      0.00     380.00
  2000.00     18.00     10.30     17.11      6.33      1.32     380.00
  2000.00     19.00     10.32     17.65      6.94      0.87     380.00
  2000.00     20.00     10.40     17.19      6.46      0.20     380.00
  2000.00     21.00     10.42     16.73      6.10      1.23     380.00
```

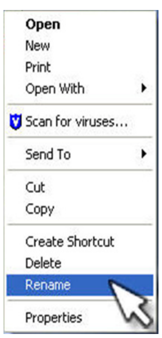


	A	B	C	D	E	F
1	!title = Merch long term !Oct-DEC 2009 is infilled dummy data					
2	[weather.met.weather]					
3	!station number = 863					
4	!station name = Merchouch					
5	latitude = 33.604 (DECIMAL DEGREES)					
6	longitude = -6.722 (DECIMAL DEGREES)					
7	! TAV and AMP inserted by "tav_amp" on 21/01/2010 at 10:43 for period from 1/2000 to 365/2019 (ddd/yyyy)					
8	tav = 18.04 (oC) ! annual average ambient temperature					
9	amp = 16.5 (oC) ! annual amplitude in mean monthly temperature					
10						
11	year	day	radn	maxt	mint	rain
12	()	()	(MJ/m^2)	(oC)	(oC)	(mm)
13	2006	1	4.85	15.87	4.77	2.70
14	2006	2	5.12	16.32	4.33	1.95
15	2006	3	4.99	15.40	4.03	3.00
16	2006	4	4.72	14.80	4.41	2.24
17	2006	5	4.87	14.77	3.98	2.36
18	2006	6	4.84	14.69	4.09	5.59
19	2006	7	4.84	14.62	4.11	4.30
20	2006	8	5.04	14.63	3.54	6.00
21	2006	9	5.07	15.42	4.22	2.62
22	2006	10	5.26	16.01	4.25	1.11
23	2006	11	5.09	15.70	4.61	3.16
24	2006	12	5.22	15.79	4.37	5.29
25	2006	13	5.28	15.64	4.15	2.44
26	2006	14	5.30	15.97	4.50	3.40
27	2006	15	5.45	16.51	4.59	2.32

- **Create** an Excel file using the required variables on a daily time step exactly in the same sequence as shown above. Ensure that header elements are entered as shown above by writing continuously in the first cell of a row. Ensure that you list the variables in APSIM notation (**year**, **day**, **radn**, **maxt**, **mint** and **rain**) and in the next line their units within brackets. It is important that the column widths are a bit wider than the data in them. Please note that in the screenshot, the **maxt** column is wider than it needs to be.
- **Save** the file as a Formatted Text (Space delimited) (*.prn) file, giving it a **.met** file extension. It is recommended that you keep your toolboxes, met files, etc., in a separate folder from the APSIM installation directory. Perhaps you could create a folder called **c:/apsim_toolboxes** for storing these types of files. It is advised that the first two columns (**year** and **DOY**) do not have any decimal places. The first several lines that represent the header file may be written as continuous text in the first column. You can first save it as a **.prn** file.



MERCHOUCHEMOROCCO_RICCAR_RCP4.5.prn.



- **Rename** the file extension as **.met** as shown above: **MerchoucheMorocco_RICCAR_RCP4.5.met**.

D. Preparing a typical APSIM soil profile

Inputting soil characteristic data is vital to simulate plant growth adequately. There are several physical, chemical and biological properties that need to be parameterized adequately. In APSIM, there are two methods to characterize a soil profile so that it matches the study context.

Option 1: Modify the soil profile of an existing simulation (for example, **ContinuousWheat.apsim**) in the examples folder using the huge selection of soil profiles available in the APSIM database. Then modify the soil characteristics of the selected soil profile to further suit the context as the model set-up steps are carried out, as needed.

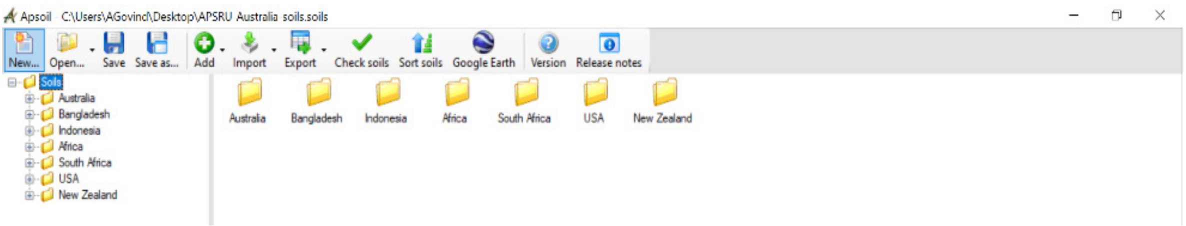
Option 2: Develop a soil library suited to your situation using an external program called APSoil. This also works similar to the method explained above. In other words, the user can use the extensive library already available as a template and develop a new soil profile by modifying it. The relative advantage is that the user can save it as a unique soil library. Because of this, this soil profile can be reused for other simulations directly or shared with other users without necessitating that the new user develops or parameterizes a new soil profile. A new soil library developed using APSoil can be imported into the APSIM UI through the main toolbar.

E. Developing a soil library using APSoil

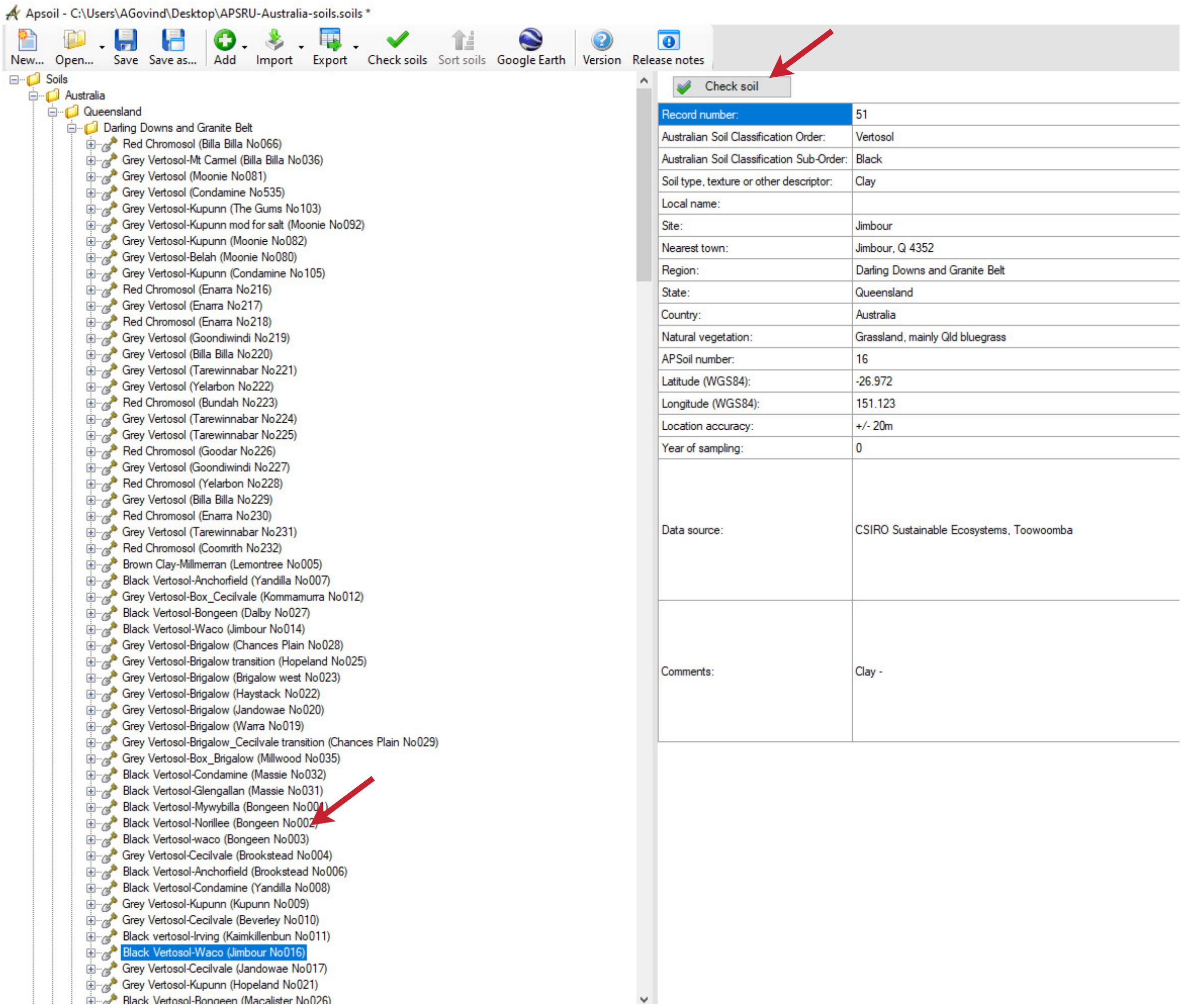
APSoil is a database of soil water characteristics that enables the estimation of plant available water capacity for individual soils and crops. This platform covers many cropping regions of the world including Australia, Africa, North America and South-East Asia, and is regularly updated. As a wide variety of soil profiles are available in this database, it is suitable for parameterizing any type of soil profile across the world, with some modifications. It is designed for use in simulation modelling and agronomic practice. APSoil enables the user to view individual soil and crop species data in spreadsheet and graph formats. Users can download the APSoil database, which can be opened with the APSoil interface to visualize, modify and create new libraries.

FIGURE 7: The homepage of the APSoil interface

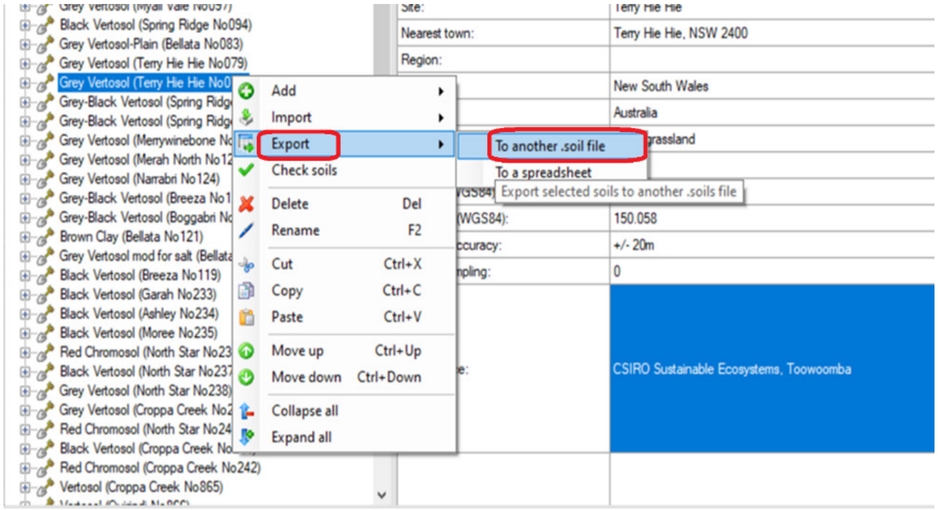
- **Open** the **APSoil interface** to see the screen as shown below.



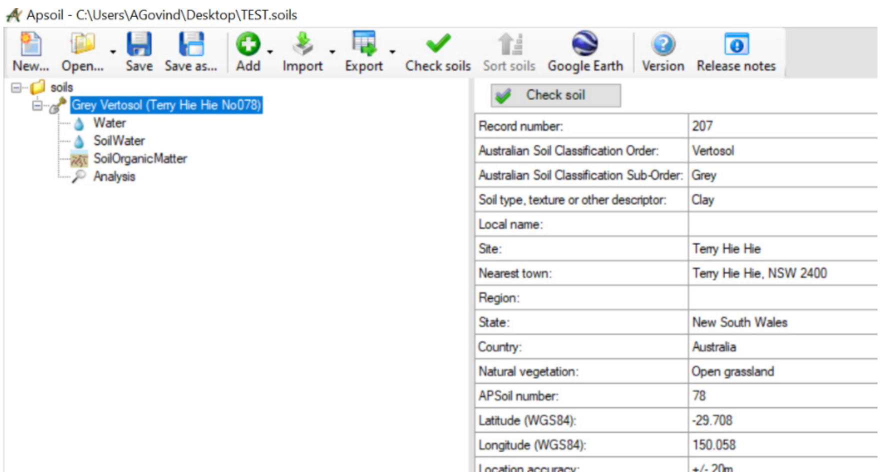
- **Open** the **APSoil database** by browsing the interface.



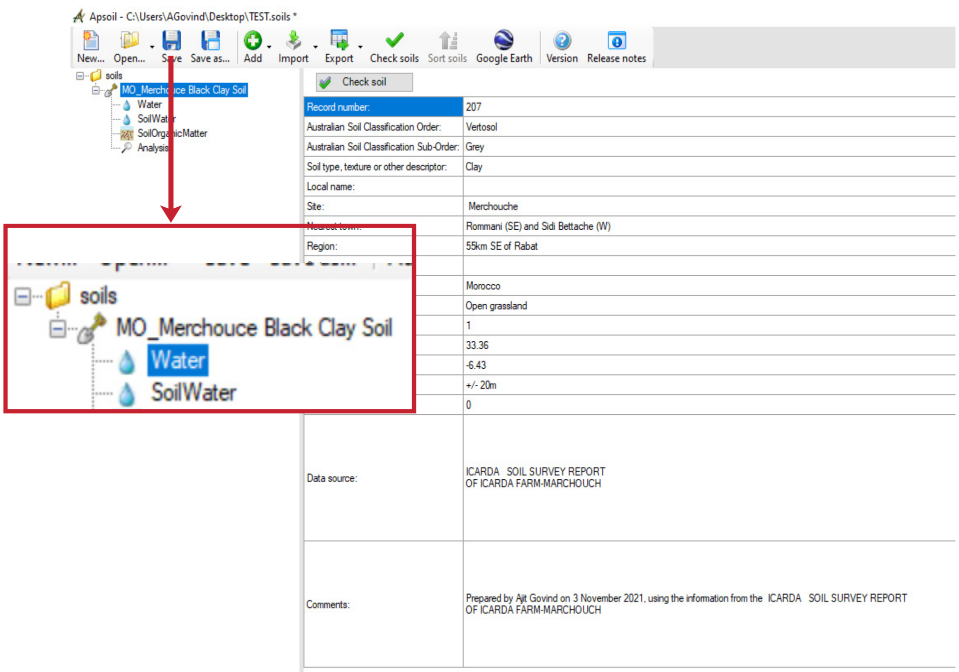
- **Select** a soil that resembles your situation. In this case choose **Black Vertisol-Waco (Jimbour No016)**.



- **Close** the currently open large database and open the exported **.soil file**. Note that within a given **.soil file**, it is possible to have several soil profiles. For example, when creating a **.soil file** for the MENA region, it is possible to create several soil profiles within this library. When opening the new exported **.soil file**, users can see the following:



- **Rename** all the necessary components on the panel to the right as required by right-clicking and selecting **Rename**. For example, you may rename the soil profile, change the details in the metadata, etc. See below for an example of how to change the details.



- **Click** the various components of the soil profile to edit them based on local needs. You can save this and use it for future modelling needs. The user may create several soil profiles under this library.

4. CLIMATE ADAPTATION IN A RAINFED AGROECOSYSTEM: SUPPLEMENTARY IRRIGATION IN MOROCCO

A. Problem statement

One of the wettest areas in the MENA region is the Maghreb region encompassing northern Morocco, Algeria and Tunisia. Under a changing climate, the region is experiencing a rapid decline in precipitation in recent years (Mohamed & Saeid, 2021). Analysis of the long-term climate data using RICCAR, and other climate datasets have demonstrated that, at the regional scale, the Maghreb region has a high probability of precipitation decline under a changing climate (Filahi et al., 2017). Most of the farming in this region is rainfed although there is sizable acreage of irrigated agriculture. As the annual rainfall patterns are changing under climate change, it is expected that rainfed agriculture may not be viable in the long run. Often supplementary irrigation is required to secure a good crop yield. There are many reports of increasing drought frequency and related crop failures in Morocco (Driouech, et al. 2017). This may have a profound implication on the sustainability of the agrifood system and has implications on regional food security.

To address this, the APSIM model is used to simulate the crop production trends under long-term climate data using the RICCAR climate product.

Taking wheat as a representative crop, this section will:

1. Simulate how a typical wheat crop in Morocco would behave under the two IPCC scenarios (RCP 4.5 and RCP 8.5).

2. Compare the crop yield evolution under RCP 8.5 (the business-as-usual climate scenario) and a scenario in which a climate adaptation measure is applied: "supplementary irrigation".[4] Comparing the simulation of the evolution of interannual wheat yields in a rainfed scenario (under RCP 8.5) with the simulation of supplementary irrigation (under RCP 8.5) will provide an idea of how valid this climate adaptation intervention for Morocco is.

FIGURE 8: Supplementary irrigation being applied in a field in Morocco

Source: International Center for Agricultural Research in the Dry Areas (ICARDA), "Climate-resilient supplementary irrigation", n.d. https://www.icarda.org/research/innovations/climate-resilient-supplementary-irrigation.

In the following sections, a step-by-step procedure is presented. The assumption is that users have already practised the APSIM interface based on the previous chapters. If not, it is highly recommended that users practise the interface using the simple case provided as an example. The climate files required to run APSIM for the specific case have to be prepared as instructed in chapter 3.

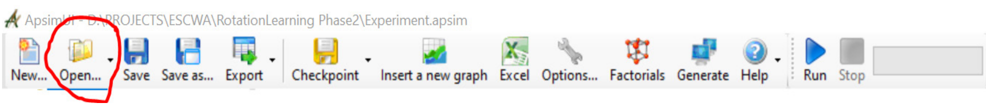
B. Setting up and parameterizing weather, soil, crop and management

First, simulate the interannual variability of a hypothetical wheat crop in the Morocco context for several years under the effects of climate change to understand how the wheat yields might change. Unlike the introductory exercise in chapter 1, where the crop growth simulation for a single year was done on a daily time step, in this section the simulation is for 100 years but the outputs will be analysed using an annual time step.

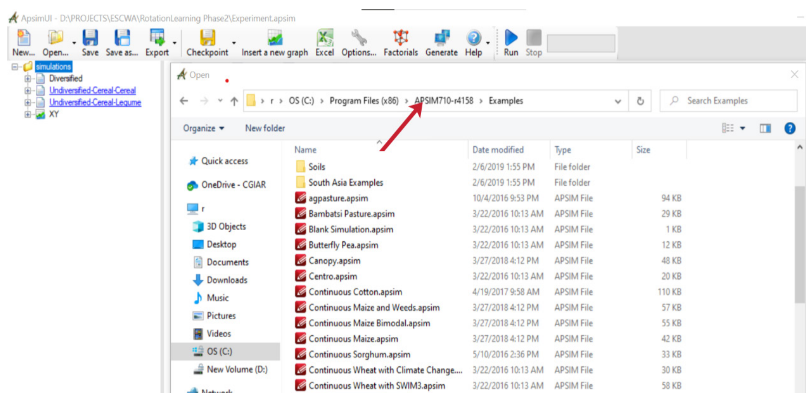
Launch APSIM and select an example simulation file already available in the APSIM database. Use it as a template simulation first and then customize it for our needs rather than building a simulation from scratch. When you launch APSIM UI, you will see the previously worked simulations (if any) on the left panel.

- **Click** **Open** and browse for the APSIM example folder in the following file path.

C:\Program Files (x86)\APSIM710-r4158\Examples.

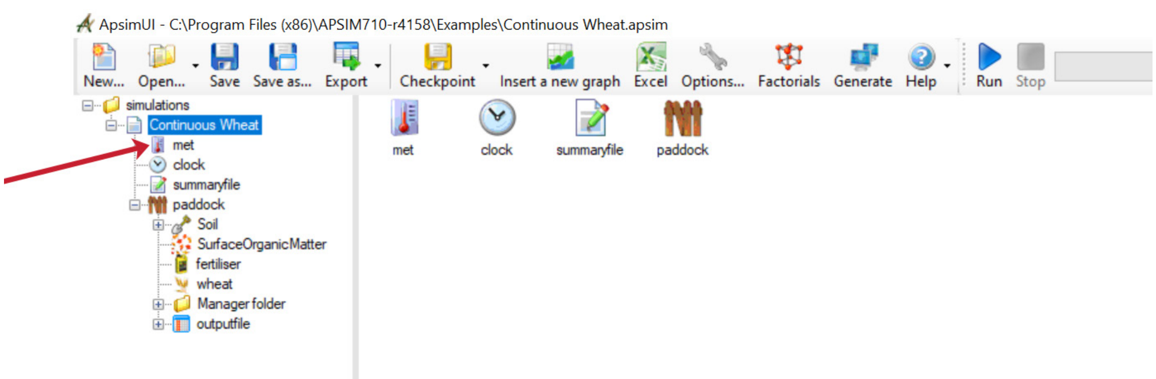


- **Open** the **.apsim** file called **Continuous Wheat.apsim**.



If you are not familiar with the simulation tree and the components, it is recommended that you revisit chapter 2.

The first step involves two main alterations to the **Continuous Wheat** example that was loaded as a template, and which will be customized for this exercise:

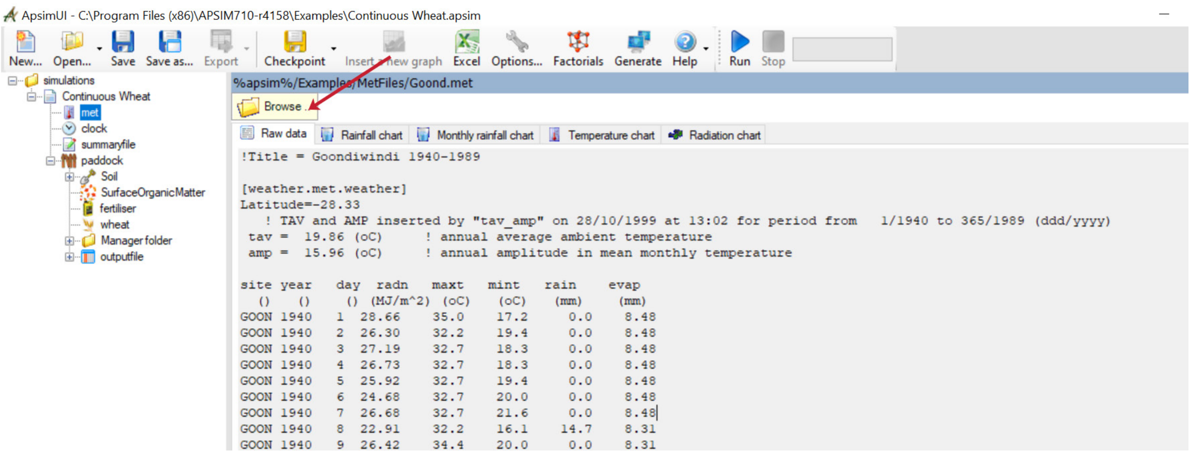


The first alteration involves replacing the meteorological file with the one relevant for our case study (Morocco).

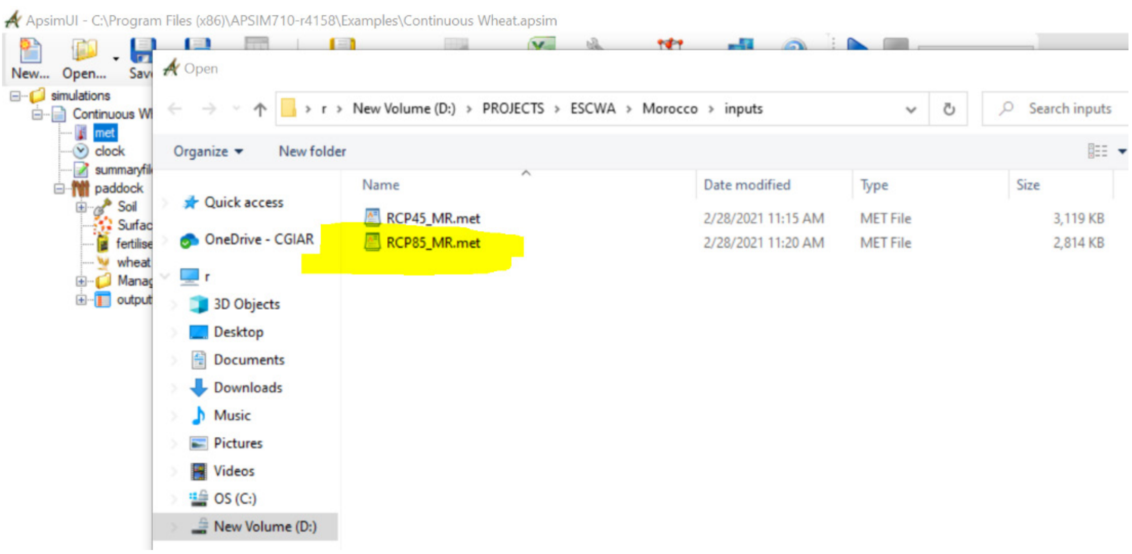
The second alteration involves replacing the soil profile.

To replace the meteorological file:

- **Click** the **met** icon in the **simulation tree**.
- **Save** this as a new simulation giving a New File Name.
- **Save** this **Continuous Wheat** simulation as **MoroccoSupplementary Irrigation.apsim**.
- **Replace** the meteorological station file for the example simulation (**Goondiwindi, Australia**) with the meteorological file created for the site in Morocco by browsing for it and opening it in the relevant location.

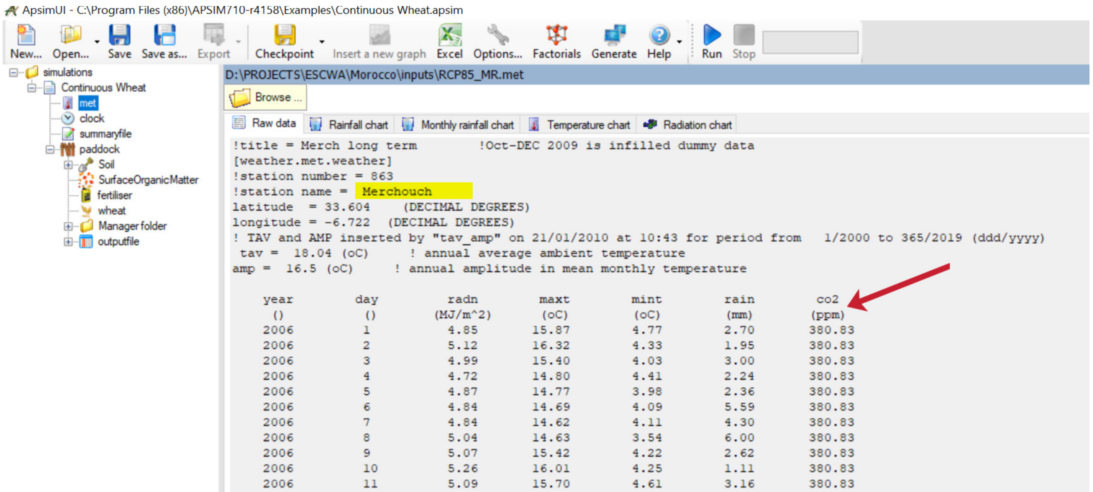


- **Replace** the dataset with Morocco data. In the Morocco input folder, two meteorological files should be created, each one corresponding to each IPCC scenario (RCP 4.5 and RCP 8.5).
- **Load** RCP 8.5 as it is the business-as-usual scenario.

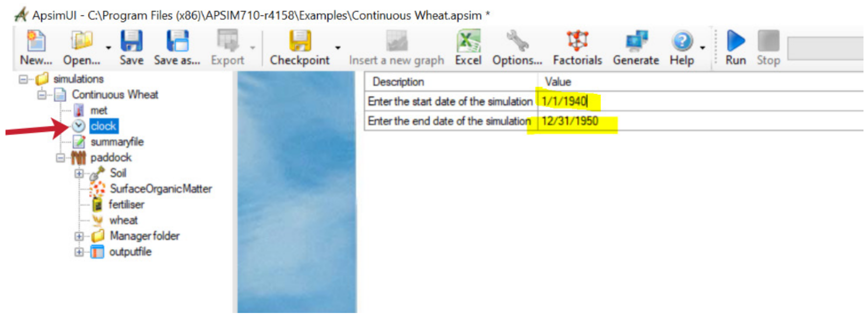


When the selected file is loaded, the name **Merchouch** can be seen, which is a field location in the Moroccan plains.

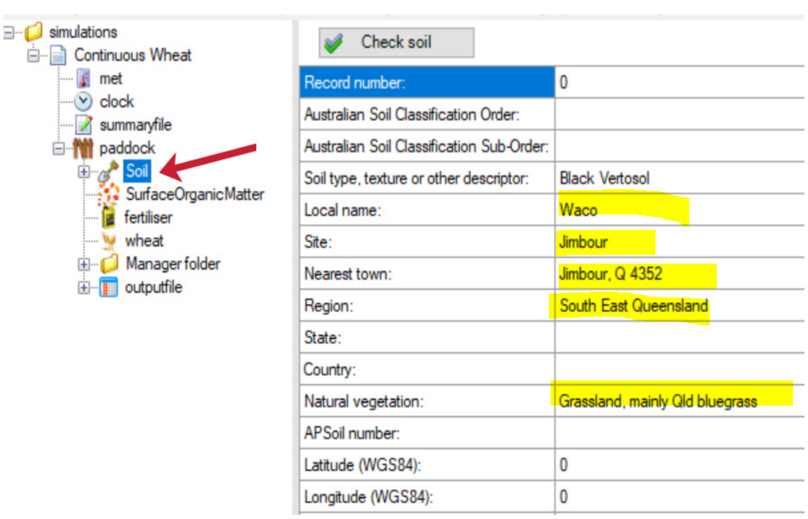
Scroll down through the data to see that the data ranges from 2006 to 2100. An additional column can be seen called **CO_2 (ppm),** which was not there in the previous meteorological file example. In this exercise, we will be simulating the long-term effect of climate change (2006-2100) on the wheat yield in Morocco. This is a function of changing climate as well as the atmospheric CO_2 concentration. Thus, it is beneficial to take CO_2 concentration into account in the datasets throughout the modelling period. This data can be obtained from IPCC and can be incorporated into the meteorological file directly.



- **Adjust** the simulation clock. In APSIM, although a long range of climate data is available, we can simulate for subset periods (such as 2010-2015) from a temporal domain ranging from 2006 to 2100. We will, however, simulate for the entire duration in this case. Thus we will need to adjust the clock accordingly with the **start date** as 1/1/2006 and **end date** as 12/31/2100.

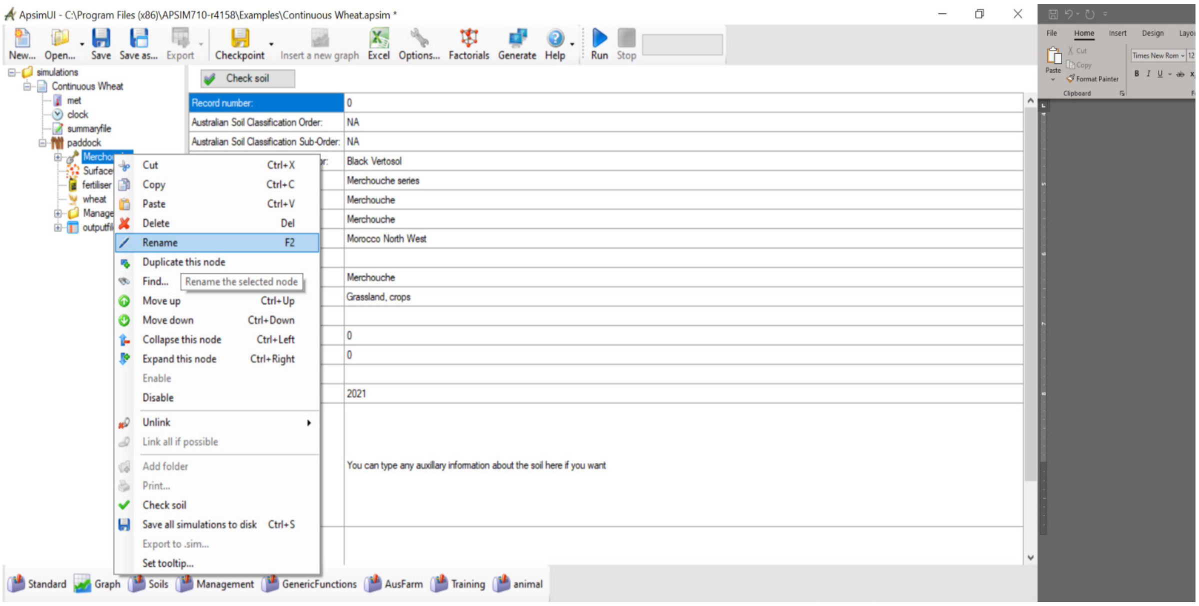


- The next set of parameterizations is to **set up** the **paddock**. In APSIM, the **paddock** is the modelling unit that consists of soil, crop and management each of which has a complex set of parameterizations for various components within each of these broad categories.
- **Replace** the soil profile with the one created. There are two solutions to parametrize the soil profile in APSIM. Either choose a soil profile from the huge database of soils already in APSIM and then parameterize as the simulation proceeds or externally develop a soil profile (using APSoil software) as described in chapter 2 and include them in the simulation through the **Add a toolbox** option. For this exercise, we will continue using the soil profile that came along with the **Continuous Wheat** simulation and parameterize it to suit the Merchouche (Morocco) conditions. This also has the same effect as the above, with the only difference being soil file is not separately provided.

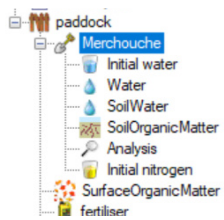


If you keep the cursor on the soil and right-click, you can rename the soil (optional). You can also edit the auxiliary information on the right panel (replacing the highlighted text).

- **Click Save**.

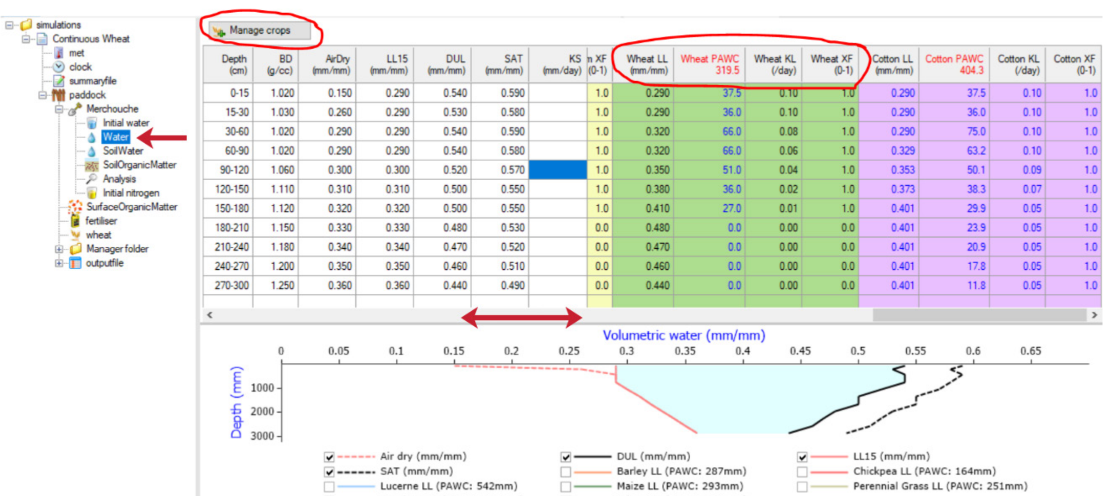


- **Click** the **+** beside the Soil (renamed now as **Merchouche**) to expand the list. Several modules can be seen for parameterization of the soil characteristics. The next requirement is to parameterize each of these to suit the soil characteristics of the study site.

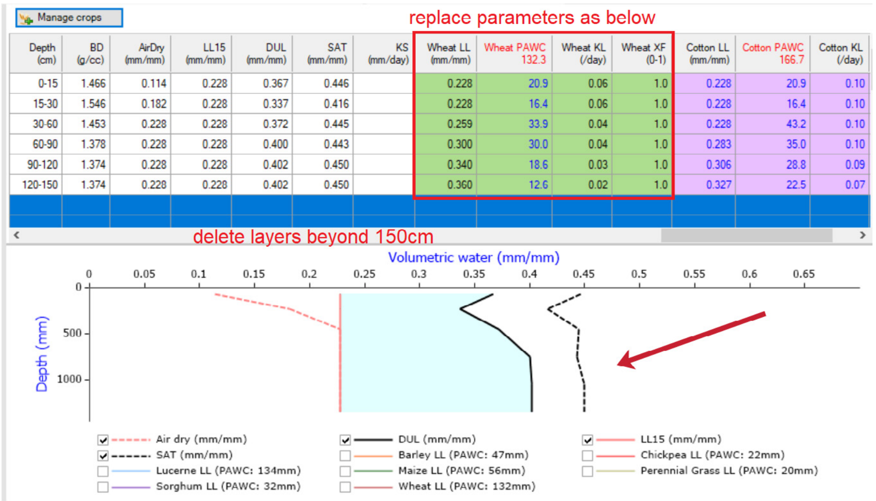


The parameterizations of these modules are quite similar to the procedures mentioned in chapter 2 and may be followed if needed to suit your site soil parameterization. The most important is the soil module called **Water** where the plant water relations are parameterized.

Click the **Water** icon to see the parameterizations available for various crops. Here we see that this soil is a 3 m deep soil profile that has 11 layers. Here you can edit the values of soil-plant water relations specific to each layer as a function of the crop that you are planning to simulate. Let us edit this soil profile for our needs.



Delete the layers from 150 cm onwards such that only 6 layers are there in the soil profile. Then, edit the values in the wheat plant water relations as shown in the screenshot below. Scroll right to see the wheat parameterizations.



Likewise, the user may parameterize other aspects of the soil such as **Soil Water**, **Soil Organic Matter**, **Analysis** and **Initial Nitrogen** to better suit the site. Most of these parameterizations and their distribution on the vertical characteristics of the soil can be visualized graphically and are displayed in the panel below. Such visualization is good for efficient parameterization of the soil characteristics.

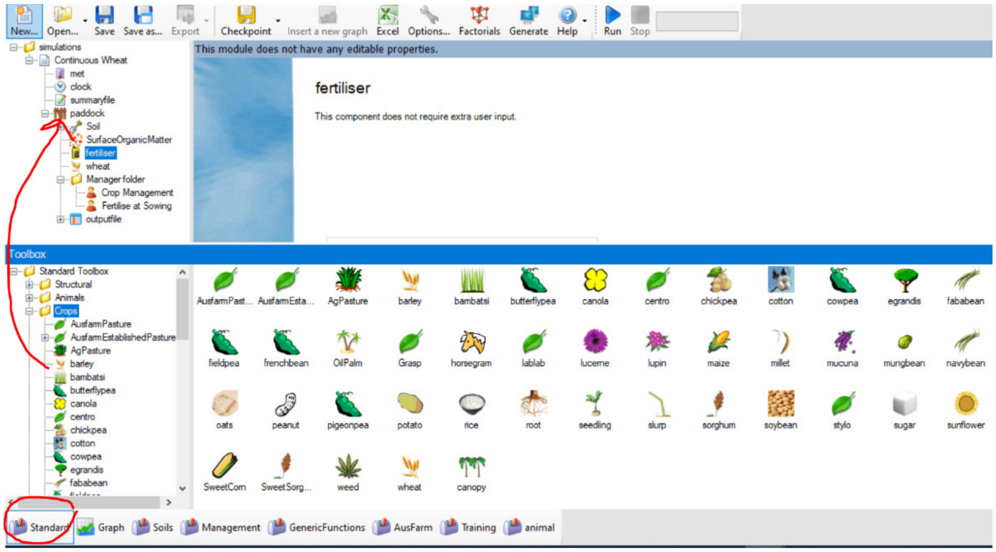
Moving to other components of the **paddock**. In APSIM there are specific modules for various crop management topics such as the choice of **Surface Organic Matter**, **Crop**, **Fertilizer**, **Irrigation**, etc. Each of these modules needs to be listed under the **paddock** to be used in a simulation. Each of these modules can be given one or more specific management rules, which are listed in the **Management folder**. For example, instructions can include explicitly adding crops and fertilizer.

- First, **edit** the **Surface Soil Organic Matter** module. Change the **C:N ratio** of the initial residue to 90 and the **fraction of residue standing** to **0.15**.

BOX 3: Alternative climate data sets to run APSIM

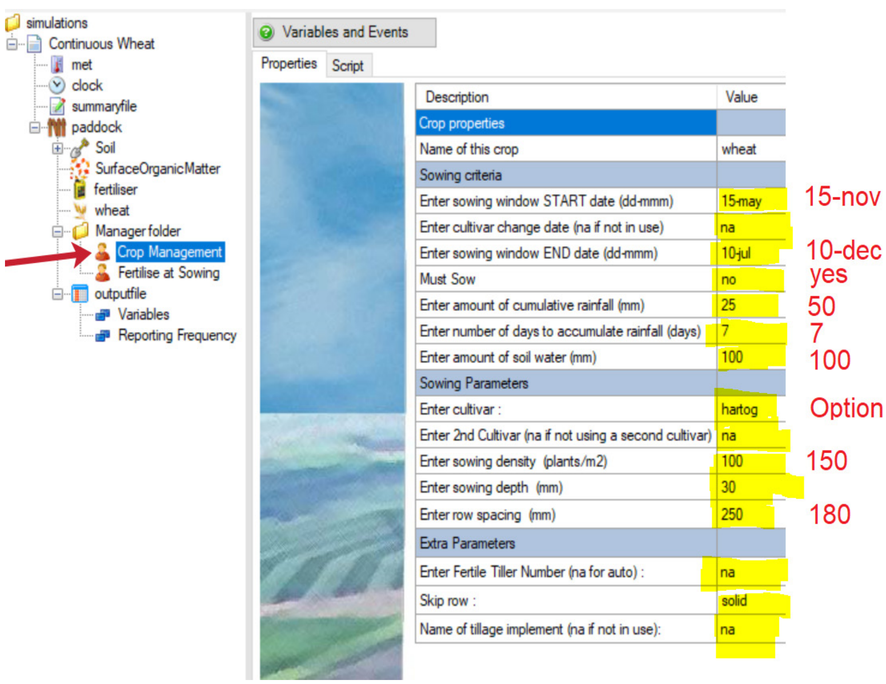
The procedure set out in this training manual may be used, even if you are using climate data from sources other than the RICCAR database (including climate products such as ECMWF, TerraClimate or measured meteorological datasets). It is always advised to do modelling with measured datasets, do calibration and validation (CALVAL), and use long-term climate data for ex ante assessments.

- **<u>Ensure</u>** that the right crop module is present. In this case, the crop **Wheat** is already there. To change the crop, drag and drop any crop that is available in the APSIM environment from the panel below (by selecting **Standard**, **Standard Toolbox** and then **Crops**).



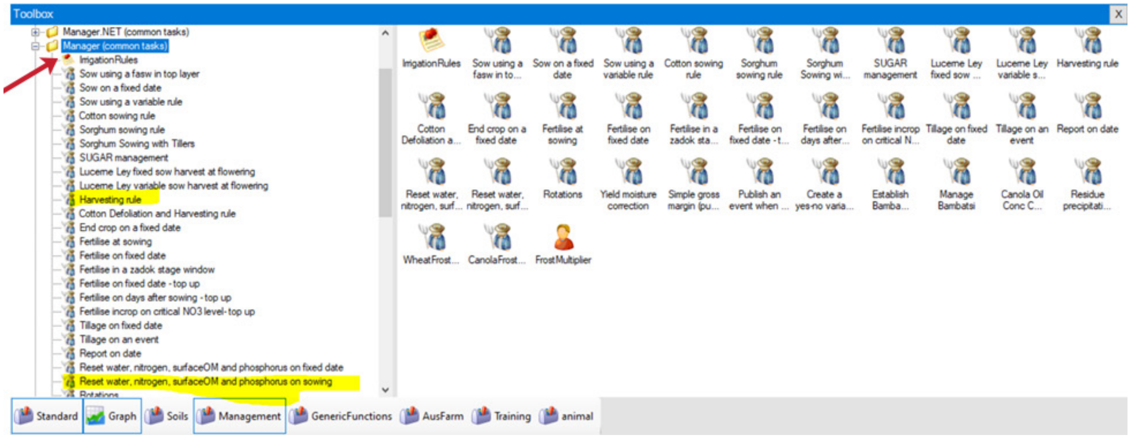
- **<u>Ensure</u>** that the **fertilizer** module is also listed as a module. Now, under the **Management folder**, we see two management actions: (1) **Crop Management** and (2) **Fertilize at Sowing**.

- **<u>Click</u>** on **Crop Management**. The following tables will appear. Edit it using the text shown in red below:

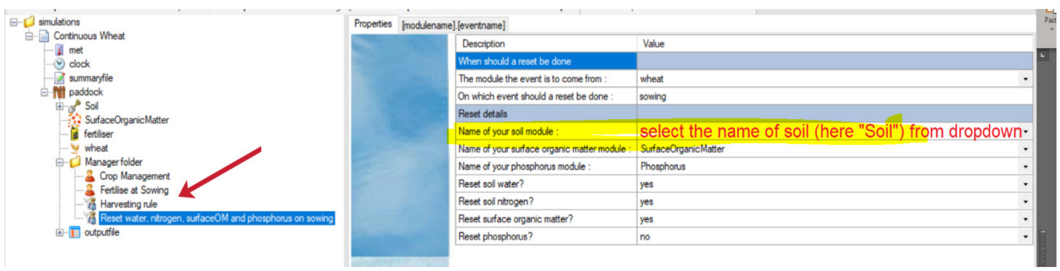


As this is a multi-annual simulation running for many years to clearly understand the long-term effects, two more management options are needed.

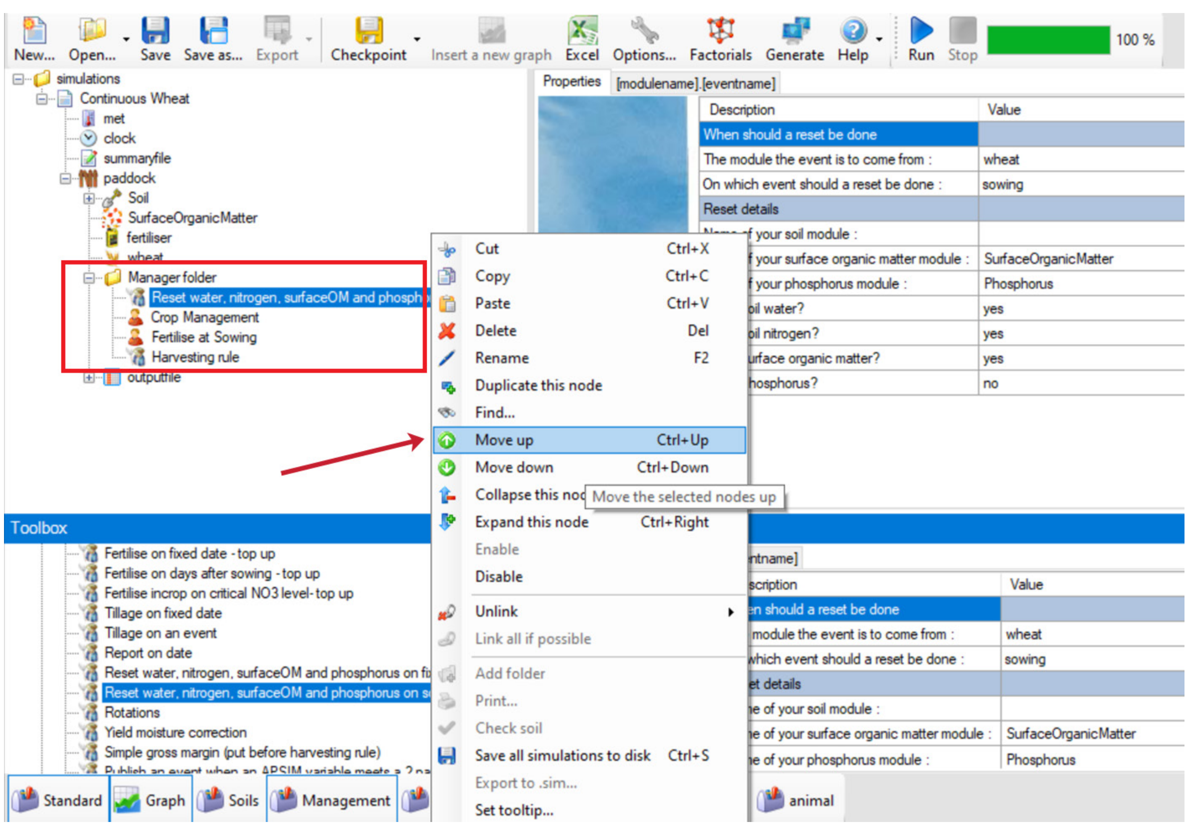
- **<u>Locate</u>** the common management functions on the lower panel of the APSIM interface that can be brought into the simulation. **<u>Select</u>** the **Management folder**, then **<u>open</u>** **Manager (common tasks)** and drag the two highlighted management functions and bring them to the **paddock** of the simulation tree.



- **Go back** to the **paddock** to see these management functions and edit the details.



Care should be taken to sequence the management actions. The sequencing can be managed by right-clicking on a management tool and moving it up or down as needed. The sequence of events in the management folder is important and should be sequenced as shown in the picture below.



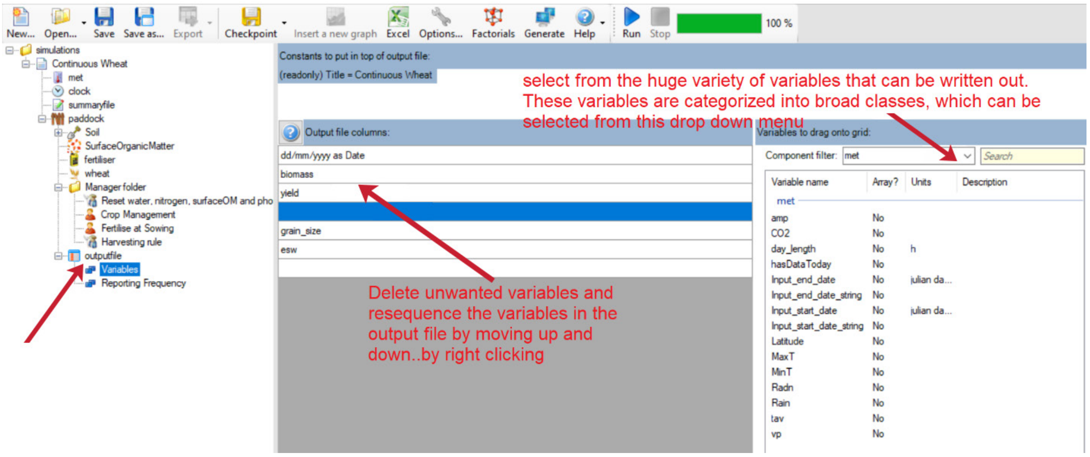
Note that although the simulation name is **Morocco_Suppl_Irrig.apsim**, the name of the specific simulation tree is still named Continuous Wheat.

- **Right-click** the simulation name, **Continuous Wheat** and rename it as **Morocco_Rainfed_RCP85**. This will be just one experiment listed under the simulation file. More than one experiment under this simulation can be added as a **scenario**.

C. Setting up output variables and reporting frequencies

So far, the modelling environment and the necessary parameterizations have been set up. This lengthy and tedious process is now finalized. The following steps are to be followed to determine which variables to write out as outputs and the frequency of their reporting. This is a critical step, especially when we want to intercompare different simulations.

- In the simulation window, **click** **Variables** under the **outputfile**. This should be the first module listed under the **outputfile**.

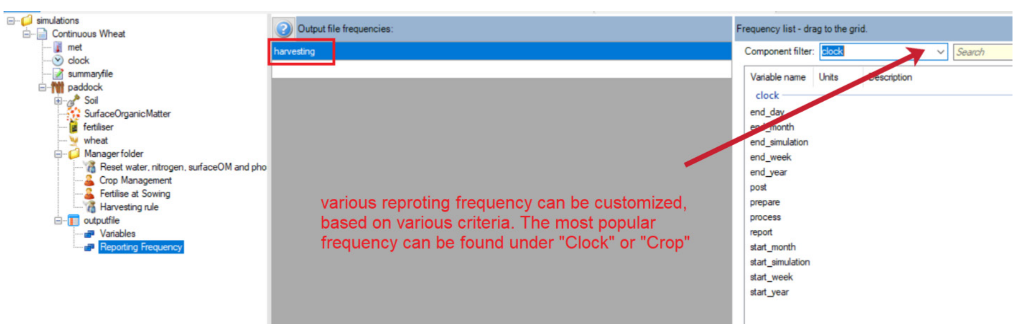


Although the APSIM simulation runs at daily time steps, the results can be written out at different temporal resolutions. This is often helpful while doing long-term experiments such as the current exercise where the daily results for 100s of years for different variables are difficult to manage and analyse. This is more relevant when different scenarios in the numerical modelling experiment are available.

- In this simulation, **delete** **dd/mm/yy** as date in the variable list and **replace** it with **Year**.
- **Find** **Year** under the **Clock** on the right panel.
- **Delete** **grain_size** and **ESW** variables.

BOX 4: Good modelling practices #1

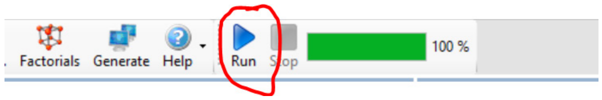
It is advised to have a thorough understanding of the system that you are trying to model. This means that you should have a clear understanding about the soil characteristics and general climatology of the location you are modelling. This means you should know the start and end timings of the seasons, maximum and minimum magnitudes of various meteorological variables and the nature of their seasonal patterns.



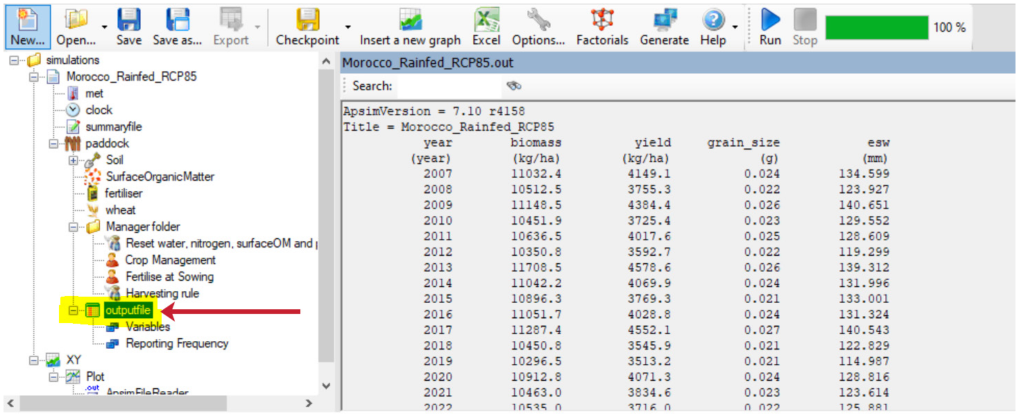
D. Running the simulation (first scenario) and visualization

Up to this step, the user has adequately set up the modelling environment and provided the necessary parameterization and also customized the output file. It is now time to run the Morocco_Rainfed_RCP85 experiment.

- **Click** the Run button in the main toolbar.

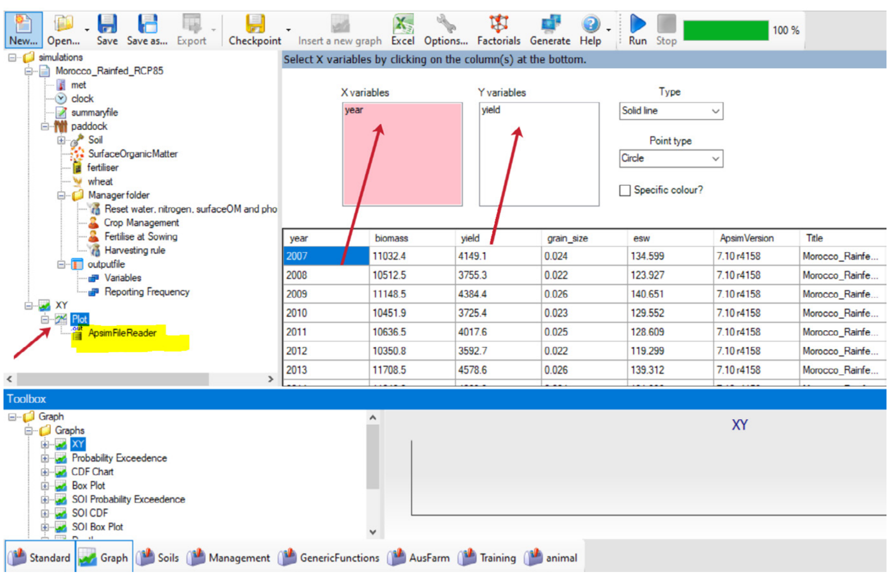


- Once the simulation has loaded to 100 per cent , **click** on the **outputfile** (not the subcomponents) to see the output file based on the configurations that were designed during the simulation set-up phase.



To plot this data, recollect the procedure mentioned in the chapter 2.

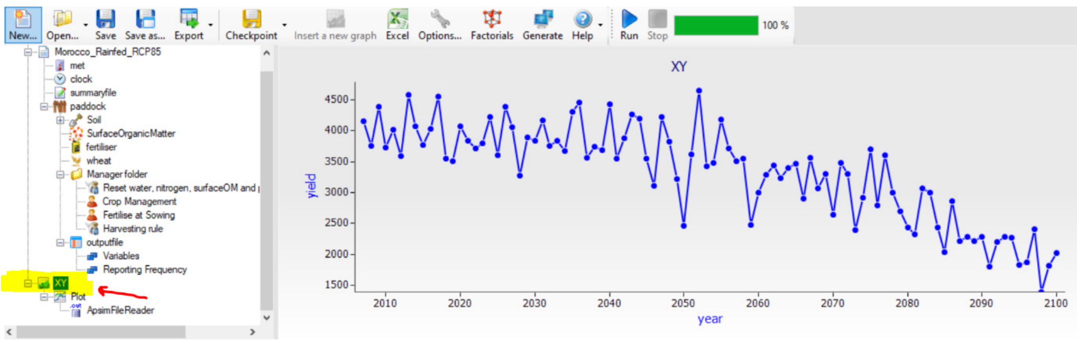
- From the bottom panel, **click** the Graph button.
- **Select** XY and drag it and keep it under the Simulations folder.
- **Click** the + next to the XY graph icon to expand the list and see two child icons: Plot and AspimFileReader.
- **Browse** for the output file Morocco_Rainfed_RCP85. It should be in the same folder where the simulation was saved as Morocco_Suppl_Irrig.apsim. You can see that it is loaded into the Plot icon.
- **Click** on the X variable to activate it (the background should turn pink) and click on the relevant year to list it in the X variable box.
- **Click** on the Y variable to activate it (the background should turn pink) and click on yield so that it is listed in the Y variable box. Note that the X variable box will be white now.
- To visualize the graph, **click** on the main XY icon.



E. Explanation of results

The user has now successfully simulated the trends in wheat yields in Morocco under the IPCC RCP 8.5 scenario with the assumption of rainfed agriculture. The yield shows a significant decline from 4,000 kg/ha (4t/ha) to as low as 1.5 t/ha towards the end of the century if no climate adaptation measure is taken.

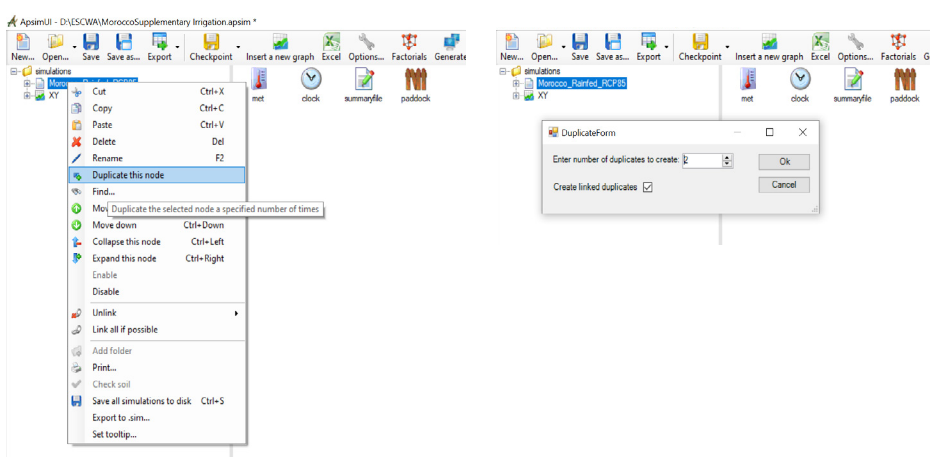
The next step is to explore how supplementary irrigation may improve the situation.



F. Adding scenarios

Adding scenarios is an easy process in APSIM. Once a standard simulation is established, the user can duplicate it and use it to create another scenario by changing specific elements and keeping other elements the same.

- **Right-click** on the experiment **Morocco_Rainfed_RCP85**.
- **Click** **duplicate this node**.



As soon as you click this, a pop-up window appears and asks how many duplicates are required and if they should be **linked**. This is a very critical step. If the **linked** option is pressed, all the duplicates will have all the variables linked (this means that a change made in one version will be reflected in the other versions). It is possible to **unlink** the selected portions later on to create specific scenarios. But, to start the process of creating scenarios, it is recommended that all the duplicates are **linked** initially when they are created.

- **Create** 2 duplicates that are linked.

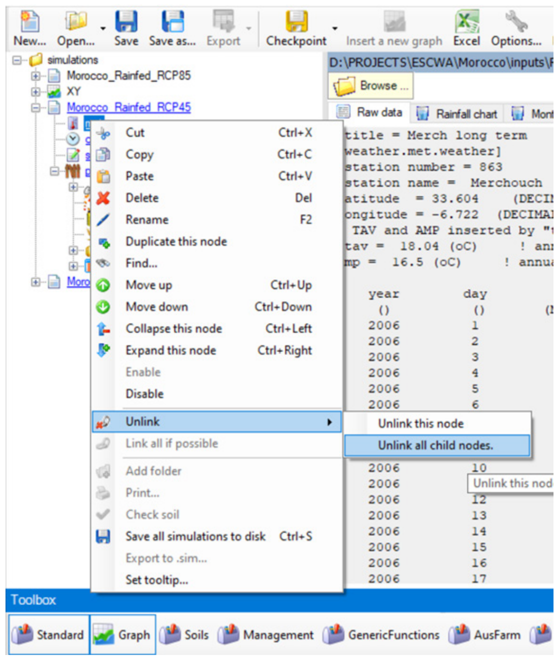
You will now see that two copies of **Morocco_Rainfed_RCP85** are created with numbers 1 and 2. These are default names and you may rename the scenarios later on. We can rename them as **Morocco_Rainfed_RCP45** and **Morocco_SI_RCP85**. What we plan to do is to create three scenarios.

TABLE 4: Comparison of the three scenarios considered in the Morocco test case

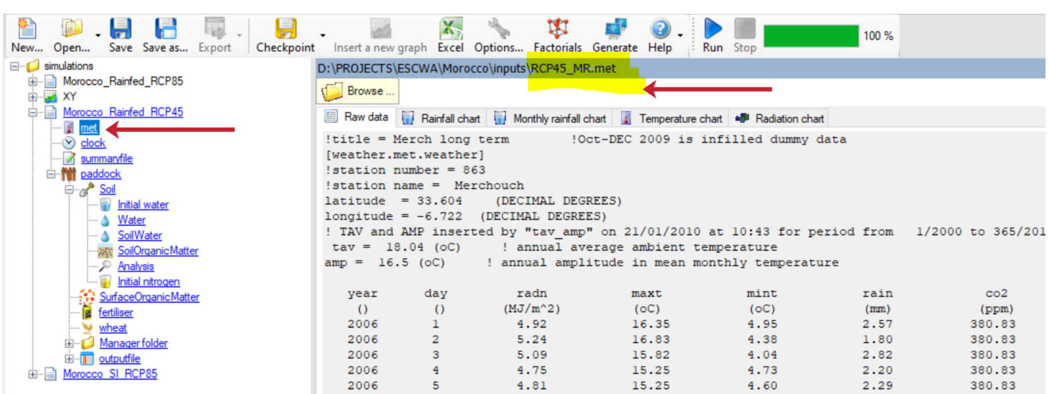
Scenario	Description
MOROCCO_RAINFED_RCP45	Rainfed agriculture under RCP 8.5 climate scenario
MOROCCO_RAINFED_RCP45	Rainfed agriculture under RCP 4.5 climate scenario
MOROCCO_SI_RCP85	Rainfed agriculture with supplementary irrigation as a climate adaptation under RCP 8.5 climate scenario

You may, however, notice that these newly created duplicate scenarios are in blue. The blue colour implies that these are linked. What we will do now is make them into different scenarios. At the moment, all three scenarios have the same characteristics and are only different in their names. We will follow the steps as mentioned below:

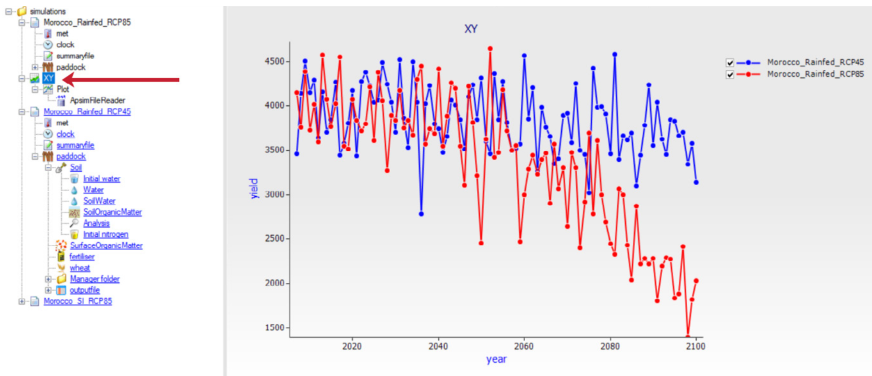
- **Expand** the simulation tree of the **scenario Morocco_Rainfed_RCP45**.



- Since the only changes needed in this scenario are to the meteorology, **click on** the **met** module and unlink it (select **Unlink all child nodes**).
- **Replace** the file in the **met** with another file using the browse option mentioned previously.
- **Click Save**. Now there is another scenario that uses RCP 4.5 climate but the outputs are not yet generated.



- **Press** ctrl or shift, select both the experiments Morocco_Rainfed_RCP45 and Morocco_Rainfed_RCP85 and **click** Run.
- Through the ApsimFileReader under Plot, **read** both Morocco_Rainfed_RCP45.out and Morocco_Rainfed_RCP45.out files.
- **Click** the XY icon to see the following graph that compares how RCP 8.5 and RCP 4.5 simulates interannual wheat yields in Morocco using the RICCAR data in a rainfed situation.

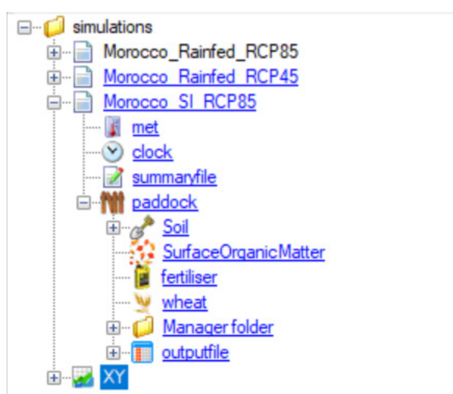


Now that the rainfed scenarios have been created for the two climate scenarios RCP 8.5 and RCP 4.5, a third scenario will be created where climate adaptation under RCP 8.5 (supplementary irrigation) is taken into account.

This will be done using the experiment Morocco_SI_RCP85, which was created as the duplicate of Morocco_Rainfed_RCP85. Note that Morocco_SI_RCP85 is currently a replica of Morocco_Rainfed_RCP85 and is only different in name. It is important to adequately set up the model as the third scenario in this study.

The following three preparatory things is to be done:

- **Bring down (right click to see the option)** the XY module and keep it at the bottom.
- **Contract** the simulation trees of Morocco_Rainfed_RCP85 and Morocco_Rainfed_RCP45.
- **Expand** the simulation tree of Morocco_SI_RCP85 as shown below.



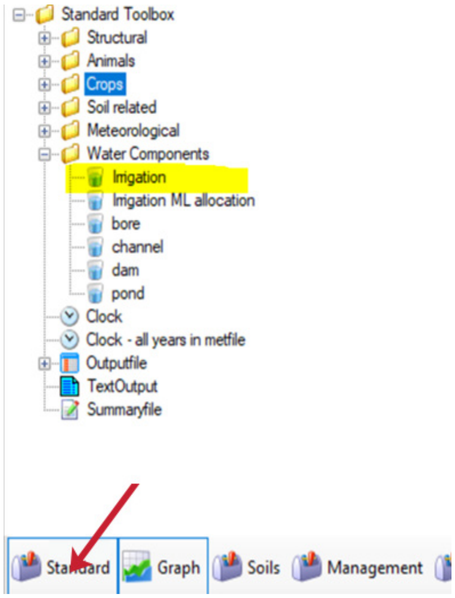
- **Ensure** that Morocco_SI_RCP85 is using the climate of RCP 8.5.

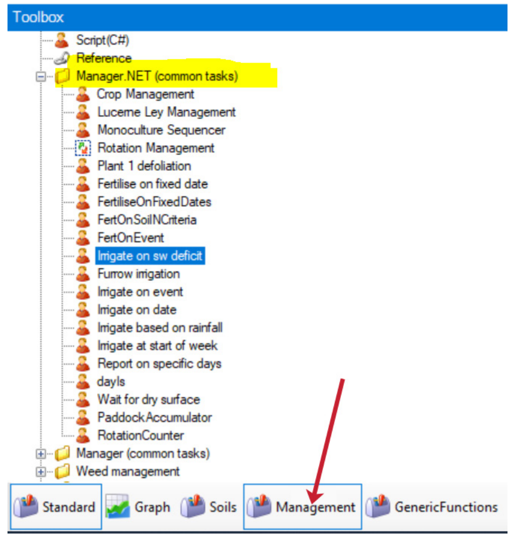
Add an irrigation module to the paddock of Morocco_SI_RCP85. It is found in the lower panel (select Standard, then Standard Toolbox, then Water Component, then Irrigation).

- **Drag** and place the Irrigation module in the paddock. As mentioned earlier, these types of modules can have one or more management tools plugged in.
- **Plug** in a manager for irrigation on soil water deficit in the Manager folder. There are several types of irrigation managers located under the menu below in this folder under Manager.NET (common tasks). The one we will use is called Irrigate on sw deficit.

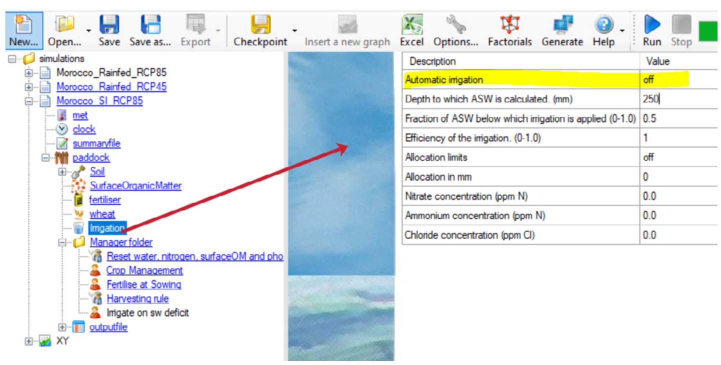
- **Drag and place** **Irrigate on sw deficit** in the **paddock** of **Morocco_SI_RCP85**. See the figure for details.

It is essential to customize the irrigation module as shown so that it mimics a supplementary irrigation mode.

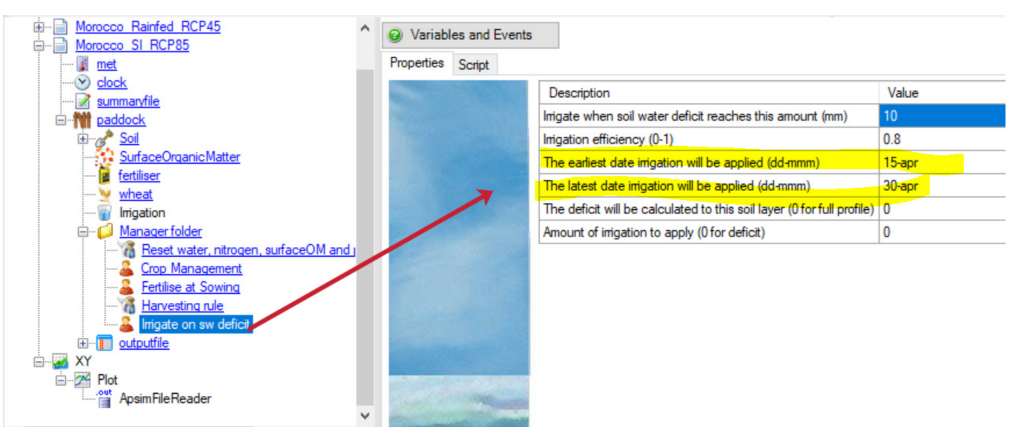




The following parameterization is needed for the **Irrigation** module. Note that **Automatic Irrigation** should be kept in **OFF** mode. Here, we keep the irrigation efficiency as **1 (100 per cent)** but later on, using the specific manager that comes under this module, we can adequately parameterize the efficiency.



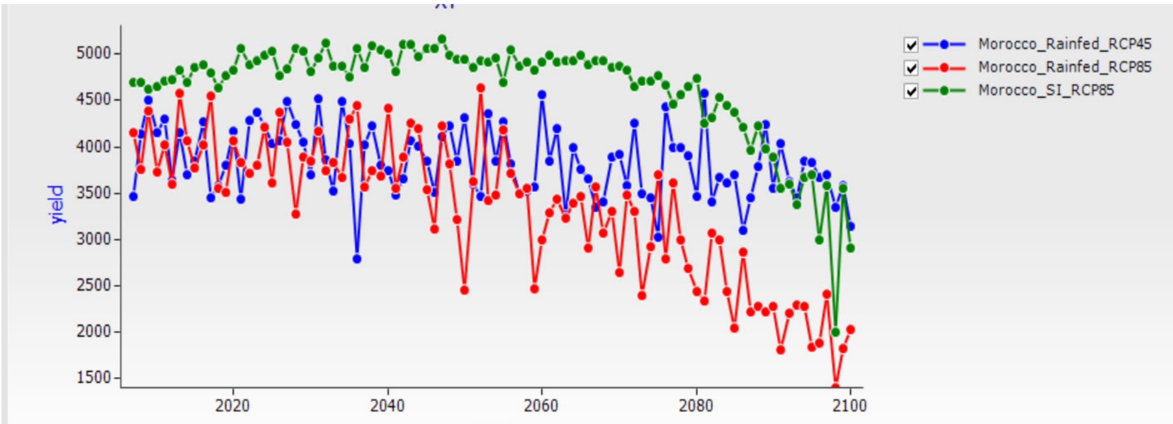
- **Parameterize** the **Irrigate on sw_deficit** irrigation manager as shown below. Note that supplementary irrigation is provided between 15 and 30 April if the soil moisture falls below a threshold.



G. Running scenarios simultaneously and visualization

With these three scenarios parameterized and set up well, now it is time to run APSIM.

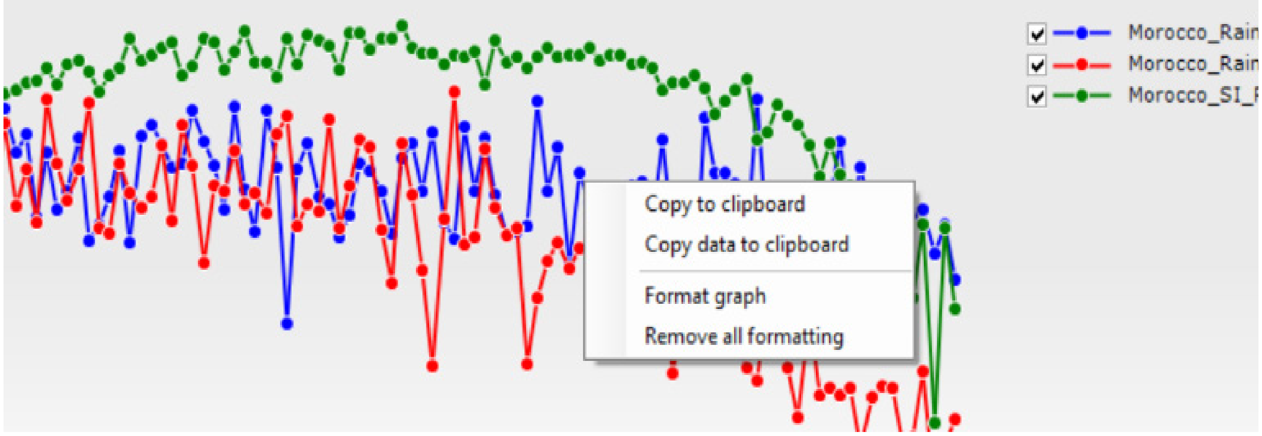
- **Collapse** the modelling trees of all three scenarios.
- **Press** the ctrl button and select all three scenarios.
- **Click** Run. We are now running all three scenarios simultaneously.
- After the scenarios have loaded 100 per cent, **load the three output files** through the ApsimFileReader under Plot.
- **Read** the files Morocco_Rainfed_RCP45.out, Morocco_Rainfed_RCP45.out and Morocco_SI_RCP85.out.
- **Click on** the XY icon.



The following graph compares how RCP 8.5 and RCP 4.5 simulates interannual wheat yields in Morocco using the RICCAR data in a rainfed situation and also how the climate adaptation scenario (with supplementary irrigation applied) effects are manifested.

The Excel icon on the main toolbar can be used to export all of the data contained in the three scenario output files (even the variables that are not graphed) for use externally in spreadsheet software such as Microsoft Excel.

- **Right-click** on the graph to save the graph as an image or copy the data of only those variables used in the graph. The option of customizing the graph according to user preferences is also available.

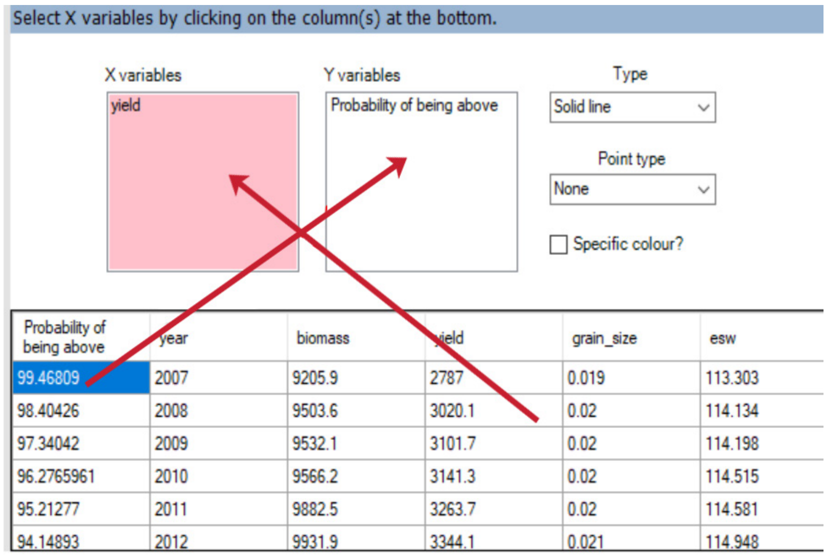


It is important to get familiar with a new type of graphing option available in APSIM called Probability Exceedance. This option is useful in this type of long-term simulation.

- **Drag and drop** the Probability Exceedance plot from the toolbox bar and **place** it under the simulations folder. As with the XY plot, **load** the necessary files first.
- **Place** yield on the X axis and Probabilities calculated on the Y axis.

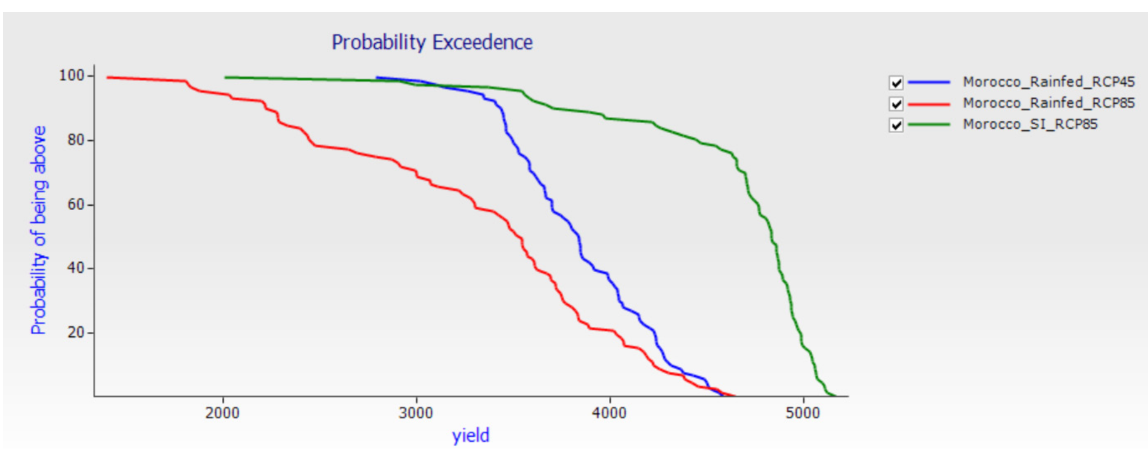
BOX 5: Good modelling practices #2

It is advised to have a thorough understanding of the system that you are trying to model. This means that you should have a clear understanding of the management activities of the location that we are modelling. This includes crop rotation and management factors for each agronomic intervention (including sowing, plant density, irrigation, fertilizer application, intercropping, harvesting and residue management).



Probability of being above	year	biomass	yield	grain_size	esw
99.46809	2007	9205.9	2787	0.019	113.303
98.40426	2008	9503.6	3020.1	0.02	114.134
97.34042	2009	9532.1	3101.7	0.02	114.198
96.2765961	2010	9566.2	3141.3	0.02	114.515
95.21277	2011	9882.5	3263.7	0.02	114.581
94.14893	2012	9931.9	3344.1	0.021	114.948

This will provide a very useful graph, as shown below, that can help us interpret many things.



H. Summary and conclusions of this exercise

In Morocco, in a rainfed agriculture situation and under a business-as-usual climate change scenario (RCP 8.5), the yields of a currently popular wheat variety may decline drastically after 2030 (reducing from approximately 4t/ha in 2020 to as little as 1.5t/ha). However, under the best-case scenario of climate change (RCP 4.5), there is no major threat. Supplementary irrigation is the best climate adaptation in this context and may only lose its efficiency by the 2080s.

5. CLIMATE ADAPTATION IN AN IRRIGATED AGROECOSYSTEM: ENHANCING WATER PRODUCTIVITY IN IRAQ

A. Problem statement

The Arab region is one of the hottest and driest regions on the planet. This region encompasses the great Sahara desert and the Arabian desert. The agroecosystems in the Arab region are predominantly arid and are extremely vulnerable to climate change, and it is believed that they will become warmer and drier as climate change progresses. Agriculture under these circumstances is unsustainable due to the intense heat and water stress (ESCWA, 2017; ESCWA, 2019). Nevertheless, the region possesses large groundwater (large aquifers) and surface water (large river systems) resources. Thus, irrigated agriculture is also widespread in the Arab region. The large river systems include the Euphrates-Tigris river system as well as the Nile river system. If adequate water is available for irrigation, irrigated agriculture is not greatly affected by climate change. However, this is not always the case. Water resources are degrading both in quantity (amount available) and quality (salinity issues). Under climate change, the crop water requirement is greatly increased. This is because of increased evapotranspiration as the atmospheric demand is greatly affected by drier and warmer air. This means that larger amounts of water (possibly more than double) need to be applied to a crop to sustain the comparable yield recovery (Mostafa et al., 2021; Fader et al., 2016; Kang et al.,2009). This means that the water productivity (ratio of yield to water consumed) shows a declining trend. If conventional irrigation practices (such as flooding) with a very low irrigation efficiency are still employed, the water productivity under a changing climate is projected to continue declining. Besides this, several secondary problems emerge which warrant a feedback loop. For example, increased application of irrigation water under arid contexts with high evapotranspiration increases soil salinity (because irrigation water itself is saline and the salt content accumulates in the soil). As the soil becomes more saline, one needs to apply more water than required (due to leaching requirements) and this combined with evapotranspiration (ET) demands makes the soil even more saline, thus demanding more irrigation water needed under a changing climate. This is not sustainable for natural resources (as it leads to depletion of water resources and degradation of the soil). Thus, it is extremely critical that in irrigated systems, the water productivity has to be increased (if not sustained) under a changing climate as an important climate adaptation measure. Improving water productivity is the most influential climate adaptation for irrigated agroecosystems in the Arab region. Water productivity can be increased by several means, including: (1) increasing the irrigation efficiency by employing techniques such as drip irrigation, (2) irrigation scheduling based on crop water demand by either using evapotranspiration as a proxy or understanding the soil water deficit, or (3) a combination of the above.

In this exercise, taking wheat as a representative crop, the objective is to simulate and compare how a typical wheat crop is grown in the lower Mesopotamian plain (LMP) region would behave under the business-as-usual climate scenario (RCP 8.5). The region benefits from the availability of water resources from the Euphrates-Tigris river system in Iraq and is an irrigated situation (using the conventional flooding-based irrigation method). Secondly, a comparison will be made between agriculture using flooding-based irrigation and agriculture with the use of highly efficient drip irrigation combined with soil water need as a climate adaptation measure. The interannual variability of irrigation water use along with the nature of wheat yields will be used as indicators of water productivity. Thus, it is possible to prove that this climate adaptation intervention is valid for an arid, but irrigated ecosystem in the Arab region, such as the LMP region in Iraq.

In the following sections, the trainee will undertake a step-by-step procedure for this task. The assumption is that the user has already become familiar with elements of the APSIM interface based on the previous chapters. If not, it is highly recommended that the user practices the interface using the simple cases provided in previous chapters as examples. In the present chapter, the aim is to introduce certain procedures directly. The climate file (**.met**) and soil file (**.Soils**) required to run APSIM for this case have to be prepared as instructed in chapter 3. In the present chapter the user will be exposed to new options that can be implemented using APSIM (such as exporting data to Excel for external analysis). The climate data for this exercise will be taken from the RICCAR-Mashreq Domain.

FIGURE 9: Improving water productivity in the Arab region is the most influential climate adaptation option in irrigated agroecosystems

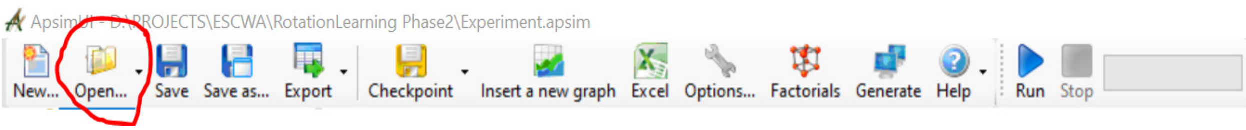
Source: ICARDA, "To improve food security, increase water productivity", 23 October 2018. https://www.icarda.org/media/news/improve-food-security-increase-water-productivity.

B. Setting up and parameterizing weather, soil, crop and management

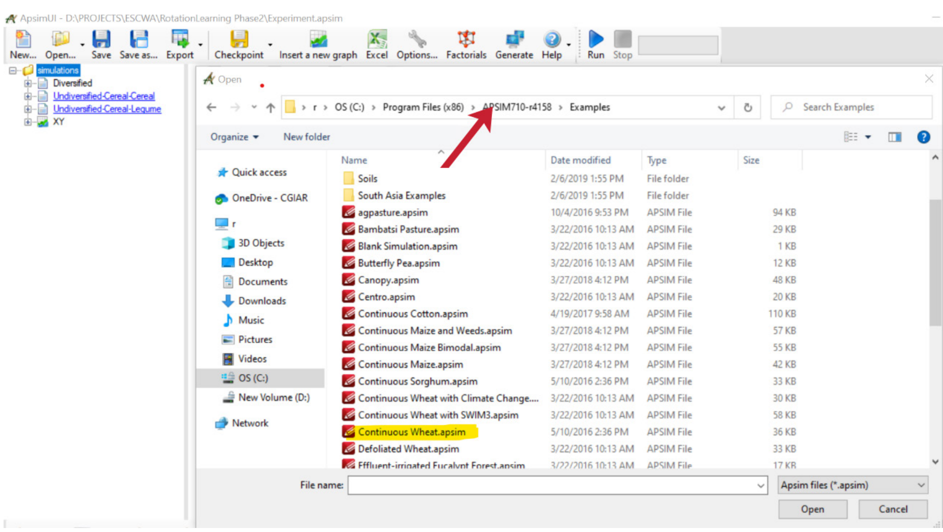
The first step is to simulate the interannual variability of yield for a hypothetical wheat crop grown in the LMP region of Iraq in an irrigated context. The simulation project the effects of climate change over many years to understand how the wheat yields might change. Unlike the introductory exercise, in chapter 1, which was for crop growth over a single year on a daily time step, the simulation in this exercise will be for 70 years, but the outputs will be analysed using an annual time step.

- **Launch** the APSIM UI. When you launch the APSIM UI, you will see the previously used simulations (if any) on the left panel.
- **Click** **Open** and browse for the APSIM example folder using the following file path:

C:\Program Files (x86)\APSIM710-r4158\Examples.



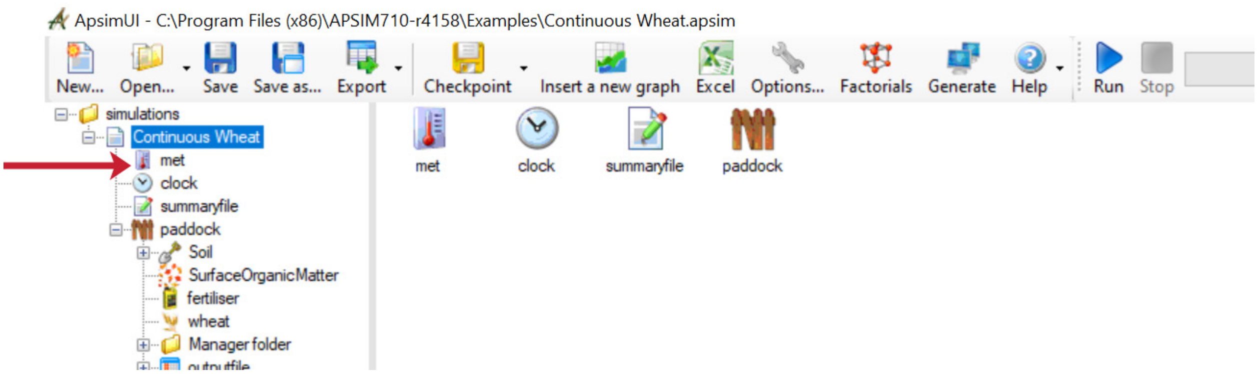
- **Browse for and open** an example simulation file already available in the APSIM database. It will be used as a template simulation and will be customized for the current modelling needs rather than building a simulation from scratch.
- **Open** the **.apsim** file called **Continuous Wheat.apsim**.



It is assumed that you are already familiar with the simulation tree and its components. If not, it is recommended that you revisit chapter 2 and familiarize yourself with the components.

This example simulation will be modified and customized for the needs of this specific exercise. As a first step, two main alterations are required to the **Continuous Wheat** example that was loaded: replacing the meteorological and soil files.

- **Replace** the meteorological file with the one relevant to this case study (Iraq). To replace the meteorological file, **click** the **met** icon in the simulation tree.

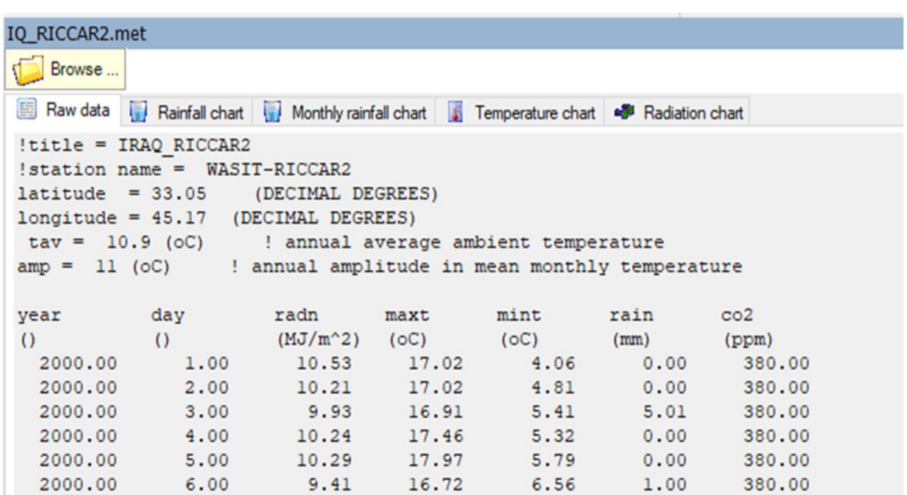


The meteorological station for the example simulation will be shown as **Goondiwindi, Australia**. You may also notice that the dataset is for the period 1940 to 1989.

In the user's Iraq input folder, a meteorological file may be created for a location in Iraq for RCP 8.5 scenario before starting this exercise.

- **Replace** the meteorological file with the one for Iraq (Wasit) by browsing for it and importing it in the relevant location.

When the user loads the selected meteorological file, note that the name is **Wasit-RICCAR2**. Wasit is a field location in the LMP region of Iraq. When scrolled down through the file's data, you will see that the data ranges from 2000 to 2070. You will also see that there is an additional column called **CO_2 (ppm)** listed which was not there in the previous meteorological file example. In this exercise, the long-term effect of climate change (from 2000 to 2070) on wheat crops in Iraq will be simulated as a function of the changing climate as well as the atmospheric CO_2 concentration. It is beneficial to take CO_2 concentration into account in the datasets throughout the modelling period. This data can be obtained from IPCC and can be incorporated into the meteorological file directly.

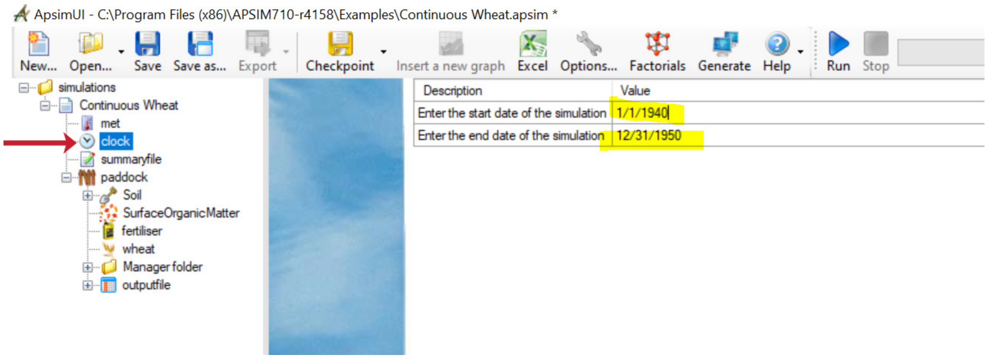



```
!title = IRAQ_RICCAR2
!station name =  WASIT-RICCAR2
latitude  = 33.05    (DECIMAL DEGREES)
longitude = 45.17  (DECIMAL DEGREES)
 tav =  10.9 (oC)      ! annual average ambient temperature
amp =  11  (oC)     ! annual amplitude in mean monthly temperature

year        day        radn      maxt      mint      rain      co2
()          ()         (MJ/m^2)  (oC)      (oC)      (mm)      (ppm)
  2000.00      1.00      10.53     17.02      4.06      0.00     380.00
  2000.00      2.00      10.21     17.02      4.81      0.00     380.00
  2000.00      3.00       9.93     16.91      5.41      5.01     380.00
  2000.00      4.00      10.24     17.46      5.32      0.00     380.00
  2000.00      5.00      10.29     17.97      5.79      0.00     380.00
  2000.00      6.00       9.41     16.72      6.56      1.00     380.00
```

The next step is to adjust the simulation clock. In APSIM, although a long range of climate data is available, we can simulate for subset periods (such as 2010-2015) from a temporal domain ranging from 2000 to 2070. We will, however, simulate for the entire duration in this case.

- **Adjust** the simulation clock, setting the **start date** to 1/1/2000 and the **end date** to 12/31/2070.

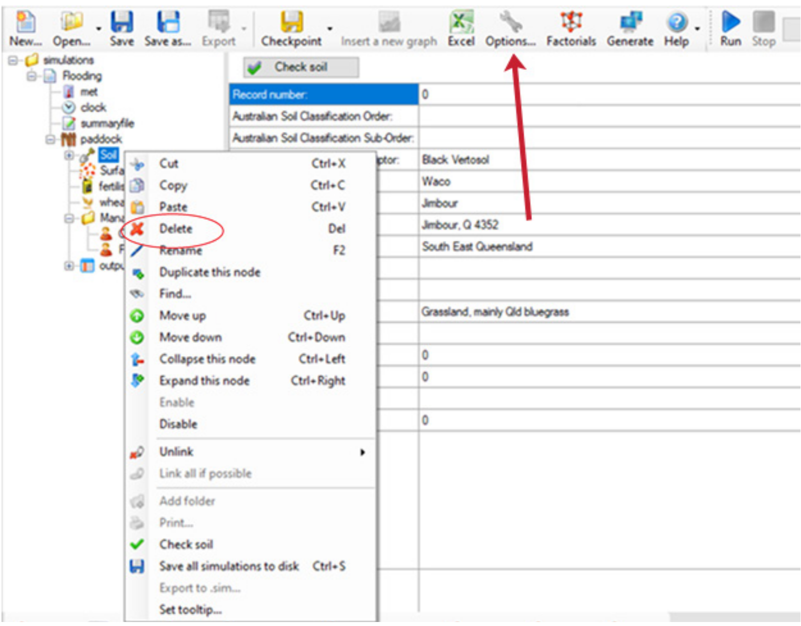


- **Save** this as a new simulation giving a New File Name: **Iraq_WaterProductivity.apsim.**
- **Change** the name of the scenario from **Continuous Wheat** to **Flooding**. This can be done by right-clicking and choosing rename option.
- **Rename** the existing numerical experiment as **Flooding**.

The next set of parameterizations is to set up the **paddock**.

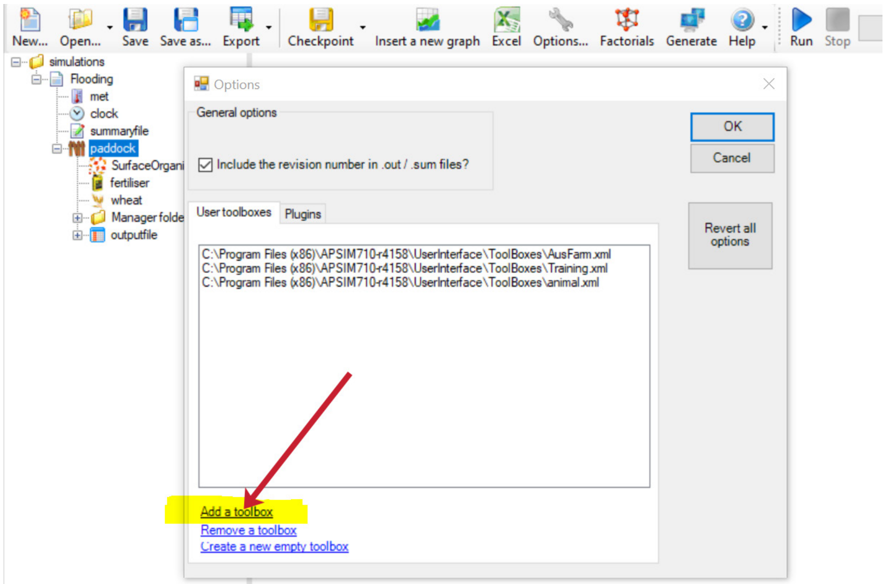
In APSIM, a paddock is the modelling unit that consists of **Soil**, **Crop** and **Management**, each of which has a complex set of parameterizations for various components within each of these broad categories. There are two solutions to parametrize a soil profile in APSIM: either choose a soil profile from the huge database of soils already in APSIM and then parameterize as the simulation proceeds or externally develop a soil profile (using the APSoil software, chapter 3) and include the profile in the simulation though the **Add a toolbox** option. For this exercise, the existing soil that came along with the **Continuous Wheat** simulation will be replaced with a new soil profile that was created using the APSoil to parameterize it to mimic local conditions in Iraq. Please carefully follow the steps.

- **Delete** the soil in the **paddock** of the **Flooding** experiment.



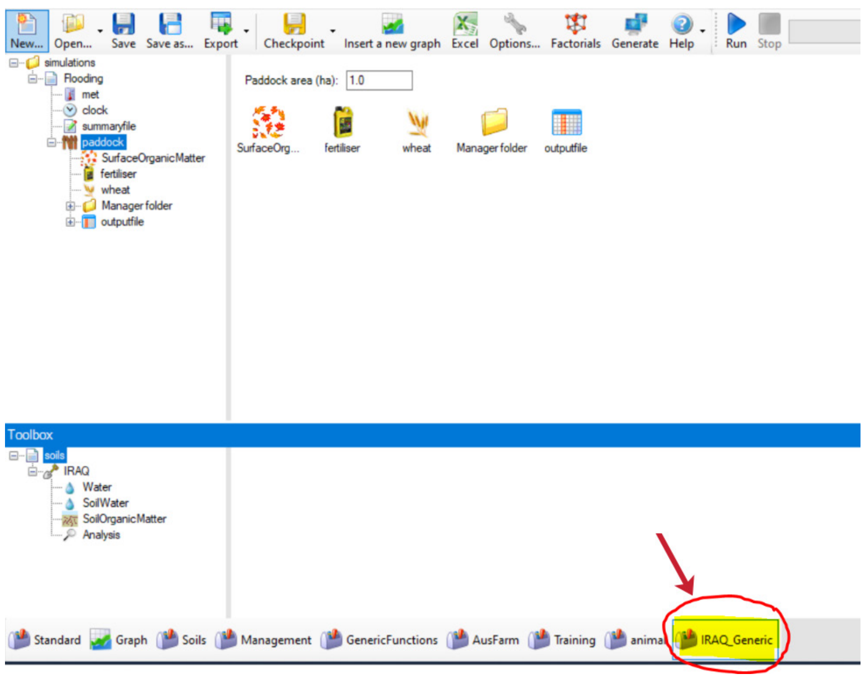
Unlike the previous exercise, this exercise does not require the soil to be parameterized as we are plugging in a soil that is characterized for the location already. To plug in a new soil profile that is externally located (rather than using the soil provided internally by APSIM UI), do the following:

- **Click** the **Options** button on the main toolbar.



- **Click** **Add a toolbox** and **browse** for the soil file (**.soils** file) you created externally and bring it into the APSIM UI.

Now you will be able to see a new item in the toolbox bar. In this case, you will see only one soil profile. However, it is possible to create a library of several soil profiles and plug them in APSIM UI through this approach.



- **Drag and drop** this new soil into the **paddock**.

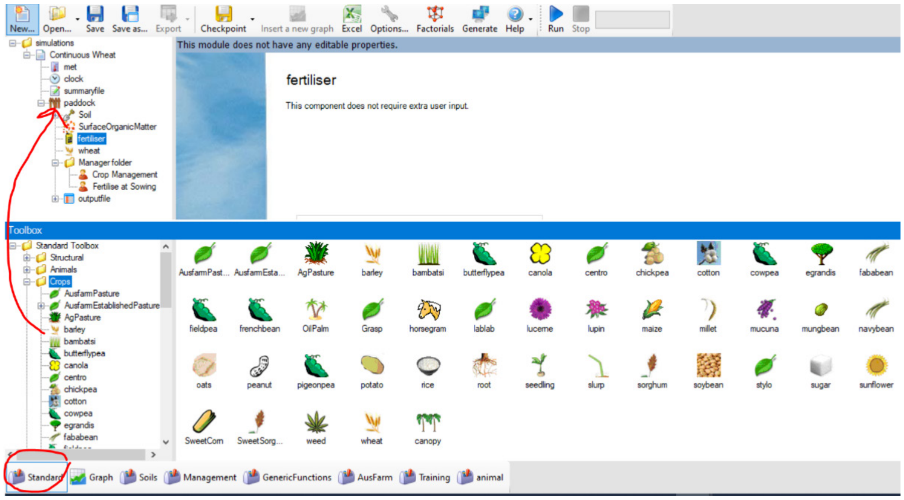
If the soil (here called **IRAQ**) is clicked, the details can be seen on the right panel. If needed, it is possible to adjust these details further in the same way that a soil profile can be modified and parameterized from the inbuilt soil files. It is possible to parameterize all the aspects of the soil profile such as **Soil Water**, **Soil Organic Matter**, **Analysis** and **Initial Nitrogen** to better suit your site characteristics. We are not going to elaborate soil profile parametrization here because we already covered this topic in the previous chapter.

- **Click** the **Save** button.

Now let us move to other components of the **paddock**. In APSIM there are specific modules for various crop management topics such as choice of **Surface Organic Matter**, **Crop**, **fertilizer**, **Irrigation**, etc. Each of these modules needs to be listed under the **paddock** to be used in a simulation. Each of these modules can be given one or more specific management instructions, which are listed in the **Management folder**.

- **Keep** the parameters for the **Surface Soil Organic Matter** as they are.
- **Ensure** that C:N ratio is **90** and that the **fraction of residue standing** to **0**.
- **Click** the **Save** button.

It is important to ensure that the right crop module is available. In this case, the crop **Wheat** is already there. If the crop needs to be changed, it is possible to drag and drop any crop that is available in the APSIM environment from the panel below (by selecting **Standard**, then **Standard Toolbox** and then **Crops**). Simply drag the crop and place it in the **paddock**. But in this exercise, Wheat will be used so there is no need to change the crop.

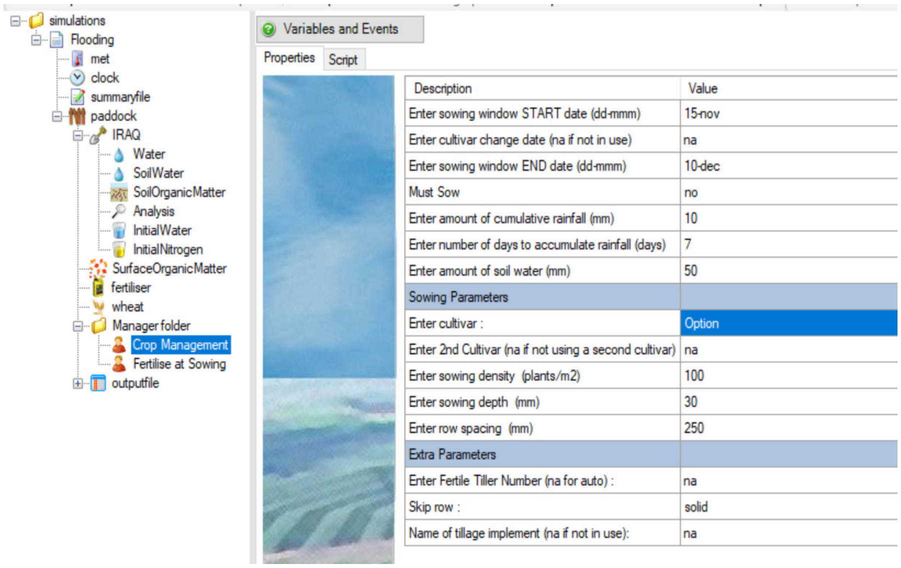


- **Ensure** that the **fertilizer** module is also listed as a module.

Under the **Management folder**, two management actions can be seen: (1) **Crop Management** and (2) **Fertilize at Sowing**.

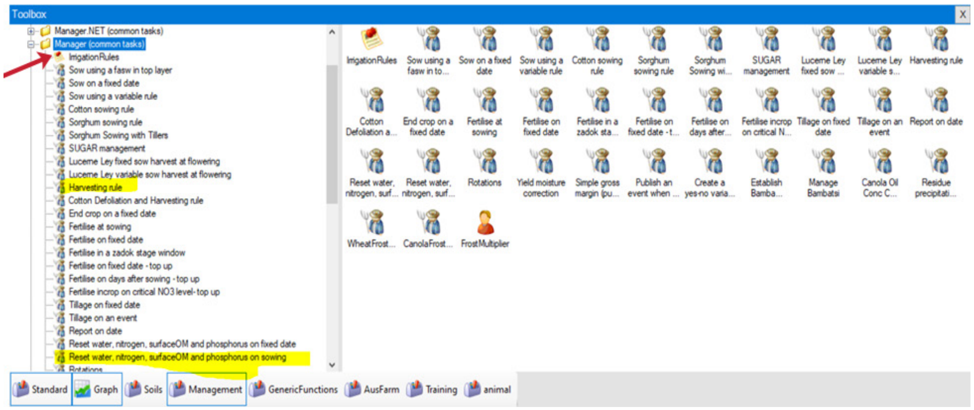
- **Click** **Crop Management** to see the table in the screenshot.
- **Edit** it as shown and **click** the **Save** button.

As this is a multi-annual simulation running for many years to clearly understand the effects, two more management options are needed.

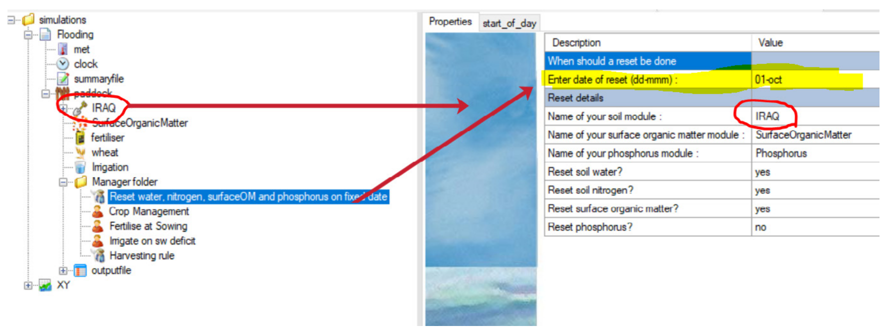


Description	Value
Enter sowing window START date (dd-mmm)	15-nov
Enter cultivar change date (na if not in use)	na
Enter sowing window END date (dd-mmm)	10-dec
Must Sow	no
Enter amount of cumulative rainfall (mm)	10
Enter number of days to accumulate rainfall (days)	7
Enter amount of soil water (mm)	50
Sowing Parameters	
Enter cultivar :	Option
Enter 2nd Cultivar (na if not using a second cultivar)	na
Enter sowing density (plants/m2)	100
Enter sowing depth (mm)	30
Enter row spacing (mm)	250
Extra Parameters	
Enter Fertile Tiller Number (na for auto) :	na
Skip row :	solid
Name of tillage implement (na if not in use):	na

- **Locate** the common management functions on the lower panel of the APSIM interface that can be brought into the simulation by clicking **Management folder**, then **Manager (common tasks)** .

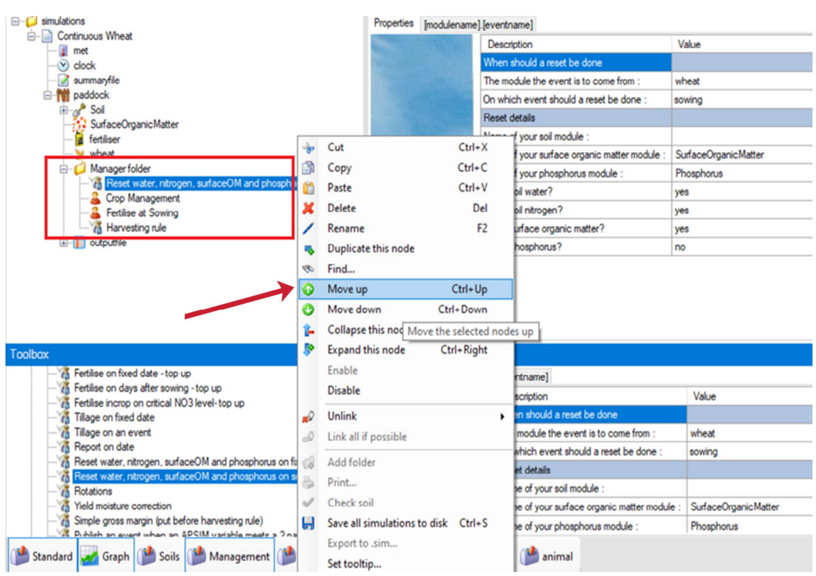


- **Drag** the two highlighted functions and bring them to the **paddock** in our simulation tree.
- **Go back** to the **paddock** to see these management functions and edit the details.



- **Care should be taken** to sequence the management actions.

The sequencing can be managed by right-clicking on a management tool and moving it up or down as needed. The sequence of events in the management folder is important and should be sequenced as shown in the picture below.

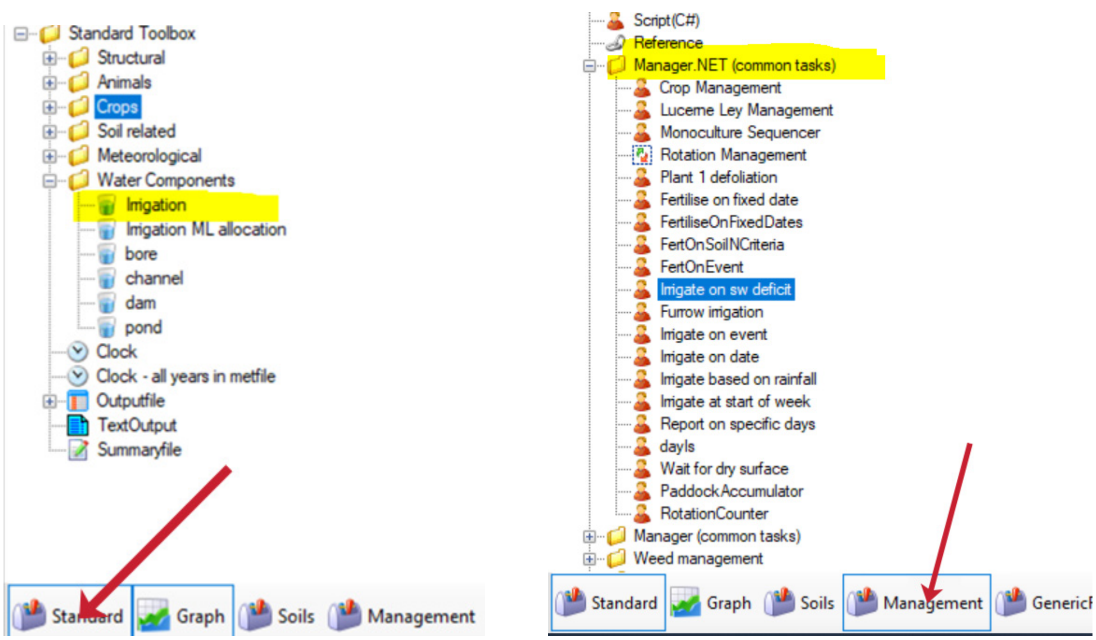


Now an irrigation module will be added to the **paddock** of **Flooding**.

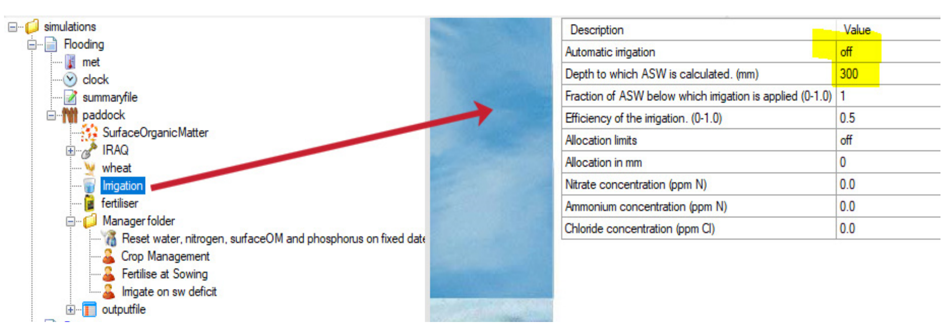
- **Find it** from the lower panel under (selecting **Standard**, then **Standard Toolbox**, then **Water Components**, then **Irrigation**).
- **Drag it** and place it in the **paddock**.

As mentioned earlier, these types of modules can have one or more management tools plugged in. The user will use a manager for irrigation on soil water deficit.

- **Note** that there are several types of irrigation managers located under the menu below the **Management folder**, under **Manager.NET (common tasks).** The one called **Irrigate on sw deficit** will be used.
- **Drag** **Irrigate on sw deficit** and place it under the **Manager folder** under the paddock of **Flooding**. See the screenshot below for details.
- **Customize** the **Irrigation** module as shown so that it mimics a flood irrigation mode.



- **Keep** the parameterization similar to the previous chapter for the **Irrigation** module.
- **Note** to keep **Automatic Irrigation** in **OFF** mode.
- **Keep** the irrigation efficiency as **1** (**100 per cent**) but later on, using the specific manager that comes under this module, it is possible to adequately parameterize the efficiency.
- **Click** the **Save** button.

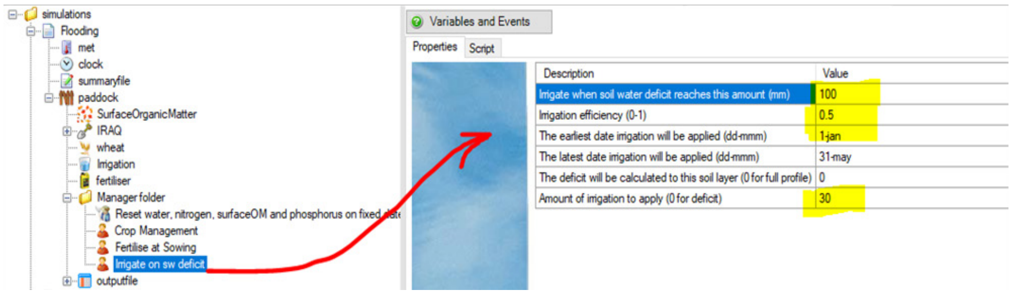


The next step is to parameterize the **Irrigate on sw_deficit** irrigation manager.

- **Parameterize** the **Irrigate on sw_deficit** manager.

Note that irrigation is provided between 1 January to 31 May if the soil moisture falls below a threshold. To mimic a flooding-based irrigation scheme, we have instructed APSIM that the irrigation efficiency is just 50 per cent and that the amount of water applied per irrigation is 30 mm.

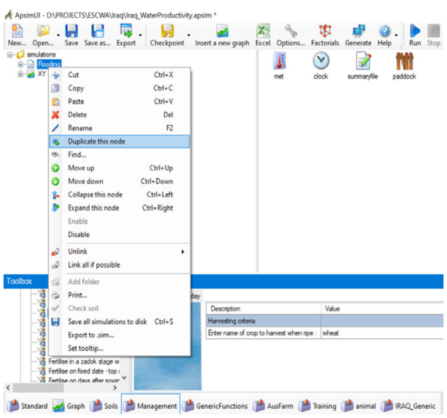
- **Click** the **Save** button.

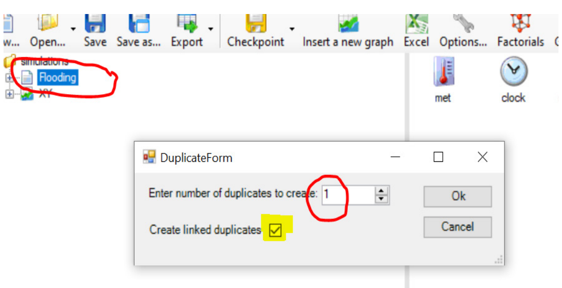


C. Creating the drip irrigation scenario

Adding scenarios is an easy process in APSIM. Once a standard simulation is established, the user can duplicate it and use it to create another scenario by changing specific elements and keeping other elements the same.

- **Collapse** the **Flooding** simulation tree.
- **Right-click** on the experiment **Flooding**.
- **Click duplicate this node.**





As soon as this is pressed, a pop-up window appears and asks how many duplicates are required whether they should be **linked**. This is a very critical step. If the user presses **linked**, all the duplicates will have all the variables linked (this means that a change made in one version will be reflected in the other versions). It is possible to **unlink** the selected portions later on to create specific scenarios. But, to start the process of creating scenarios, it is recommended that all the duplicates are **linked** initially when they are created.

- **Create** 1 duplicate scenario that is linked.

A copy of **Flooding** will be created as **Flooding1**. This is a default name.

- **Rename Flooding1** as **Drip**.

The plan is to create two scenarios as shown in table 5:

TABLE 5: Comparison of the two scenarios considered in the Iraq test case

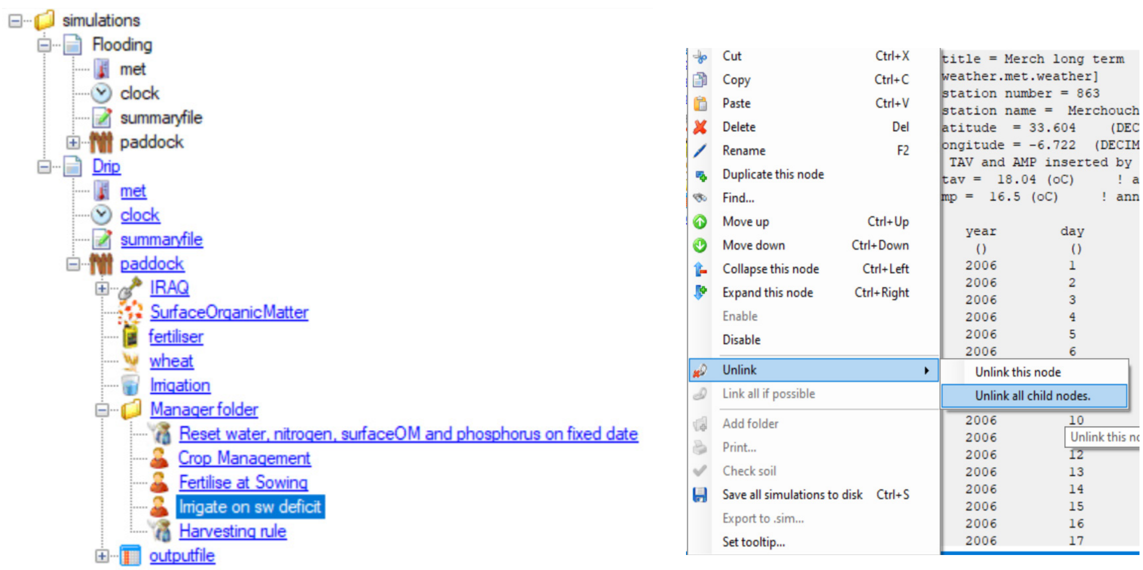
Scenario	Description
Flooding	Irrigated agriculture (Flooding-based) under RCP 8.5
Drip	Irrigated agriculture (Drip Irrigation-based) under RCP 8.5

You may, however, have noticed that this newly created duplicate scenario is blue in colour. The blue colour implies that these are linked. What we will do now is make them into different scenarios. At the moment, these scenarios have the same characteristics and are only different in their names.

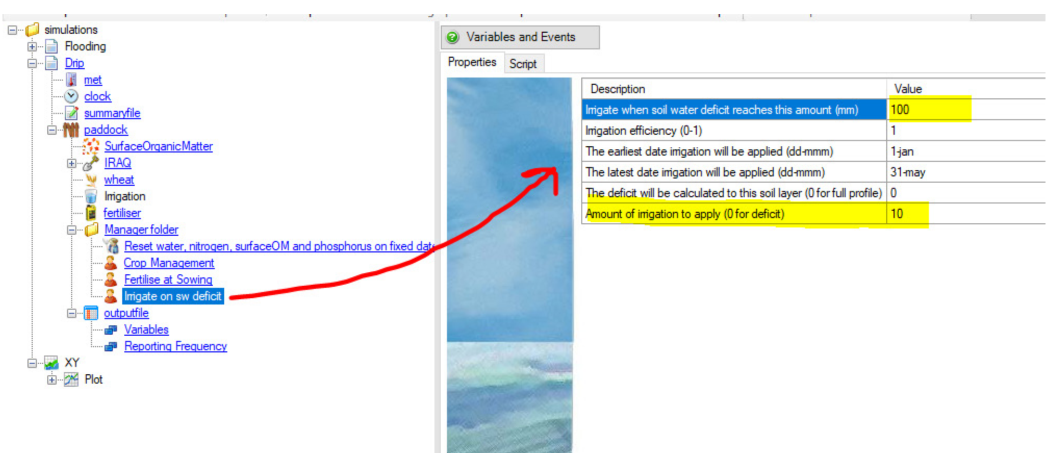
- **Expand** the simulation tree of scenario **Drip**.

As only irrigation components need to be changed in this scenario, do only the following:

- **Unlink** the following items (**Unlink all child nodes**).



- **Parameterize** the **Irrigate on sw_deficit** manager of the **Drip** experiment.



Now another scenario that conceptualizes drip irrigation has been created, but the outputs are not yet generated.

D. Setting up output variables and reporting frequencies

So far, the modelling environment and the necessary parameterizations have been set up. This lengthy and tedious process is now finalized. The following steps are to be followed to determine which variables to write out as outputs and the frequency of their reporting. This is a critical step, especially when we want to intercompare different simulations.

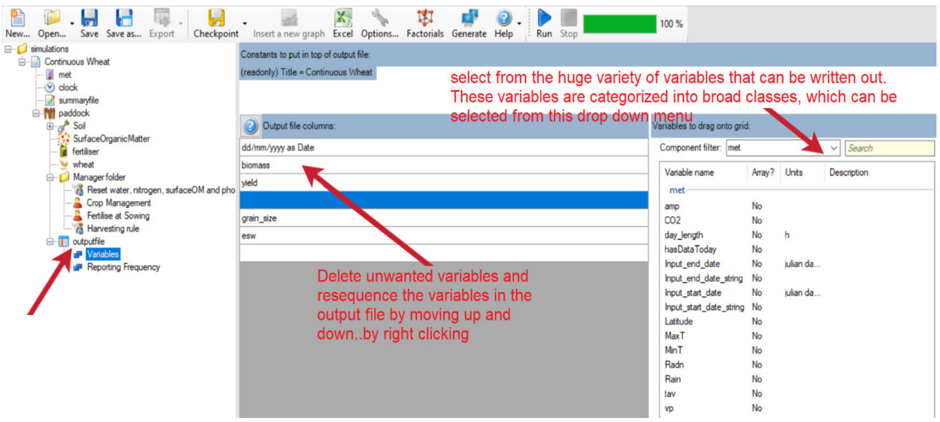
- **Click** **Variables** on the simulation window under the **outputfile** module.

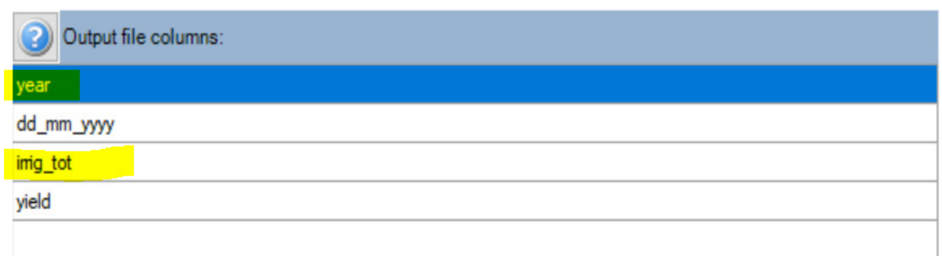
If closely observed, the output file exists for each of the experiments (Flooding and Drip). As they are linked, if the user makes a change in any one of them changes will be made in the other automatically.

- **Set up** the **outputfile** (review the previous chapter if there is any confusion). It should look like the two figures below, with the variables and frequency of reporting (**end_day**).

BOX 6: Scaling from point to region

APSIM is a point-scale model. This means it can only simulate one homogeneous unit at a given time. This is also known as lumped simulation. To make spatially explicit simulations, APSIM needs to simulate for each location separately and then analyse it spatially. This is only possible using high-performance computing platforms because the amount of computation on a point-based simulation itself is intensive.

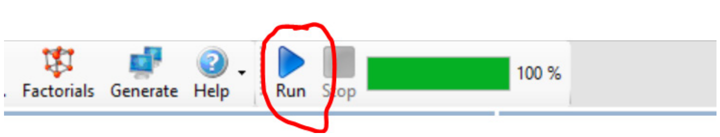




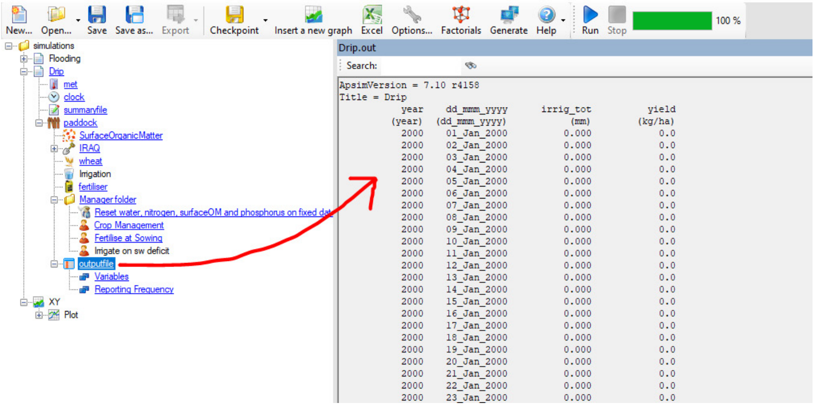
Because adequate setting up of the modelling environment has been done, the necessary parameterization has been provided and the output file has been customized, it is now time to run the two experiments as scenarios.

- **Pressing** the **ctrl** button, select the experiments **Flooding** and **Drip**, and **click** **Run**.

APSIM will run and once the simulation has loaded to 100 per cent, a buzzing sound can be heard. If there are errors, an error message will be shown and the user may review the error message and carry out the remedial actions.



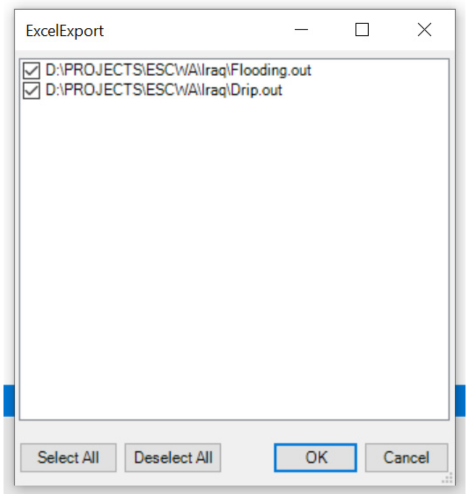
- **Click** on **outputfile** (not the subcomponents) to see the output file based on the set up of the output file, once the simulation has loaded to 100 per cent.



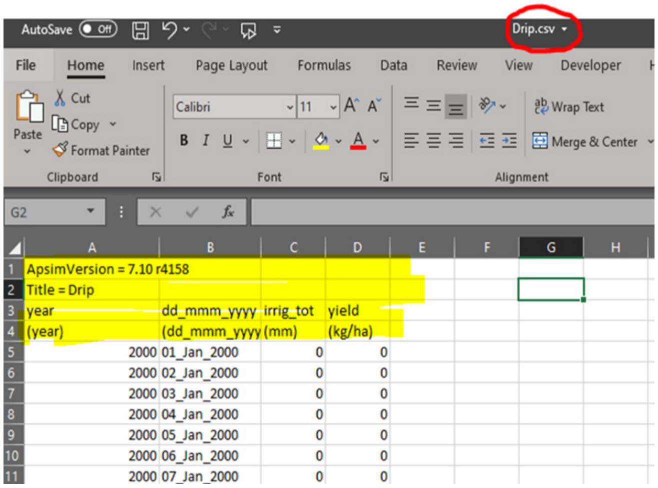
The user can now plot this data and analyse the results. In this exercise, we will export the simulated data as Excel files and do the analysis externally.

- **Collapse** the simulation trees of both the experiments.
- **Press** the **ctrl** button and select both simulation trees, then **click** the **Excel** icon on the main toolbar.

The following pop-up window will appear.

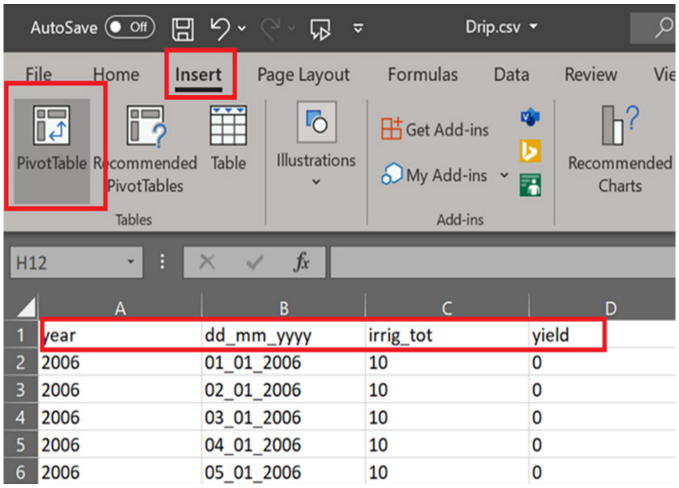


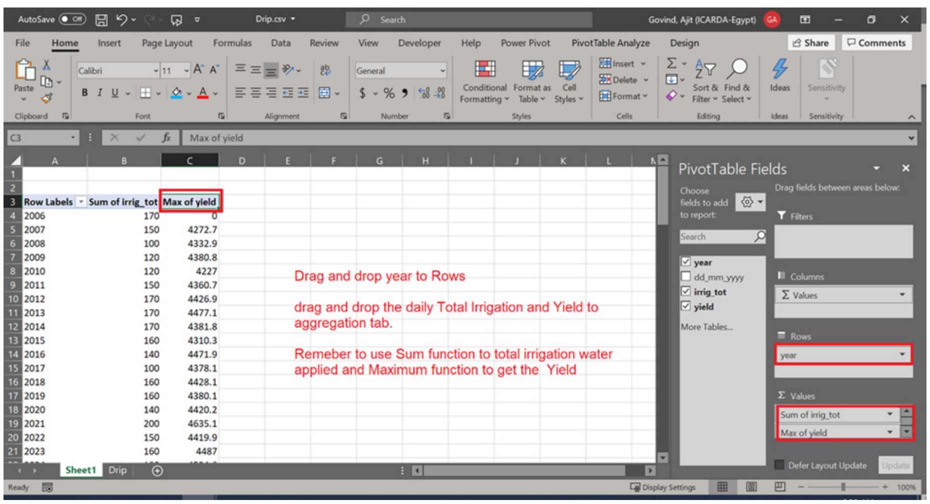
- **Click** **OK** to see Excel files of the two output files launched on your screen.



There are two files like this. One for Flooding and another for Drip. Note that these are on daily time steps. The pivot table function in Microsoft Excel should be used to aggregate this data in a suitable format for further analysis.

- **Delete** the rows that we don't need. They are highlighted in the picture above.
- **Select** all of the data and **click** the **Insert** button.
- Using the pivot table function, **develop** a summary table.





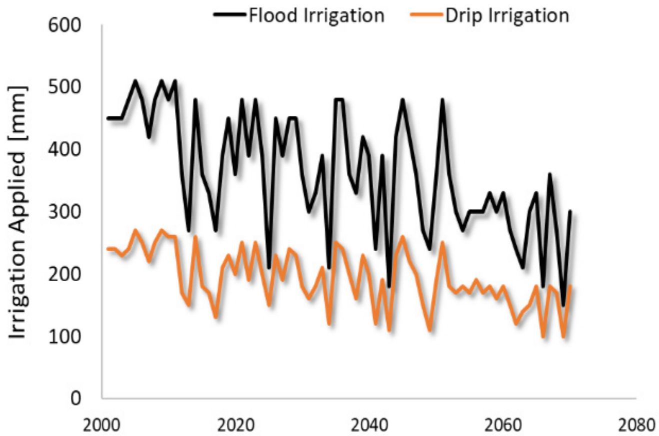
Repeat these actions with the Flooding file. Then, using the pivot tables, develop a consolidated table and do the further analysis.

TABLE 6: Consolidated table to be created using Pivot tables

Year	Flood irrigation			Drip irrigation		
	Total irrigation	Yield	WP	Total irrigation	Yield	WP
2000						
2001						

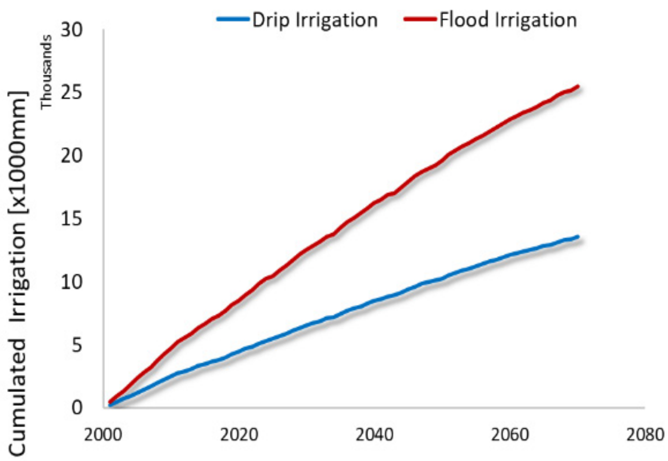
$$Water\ Productivity\ (WP) = \frac{Yield\ (kg/ha)}{Irrigation\ Applied\ (mm)}$$

Based on this tabulation, the following analysis can be made graphically in Excel.

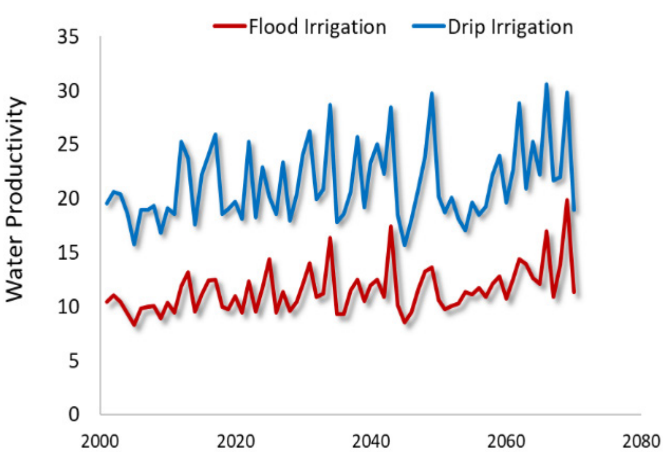


The flood irrigation technique consumes more water than drip irrigation every year between 2000 and 2100. This has a significant toll on the long-term sustainability of water resources.

The wider impact of this issue can be seen when the cumulated values of the irrigation water applied are analysed. The difference is as high as 15,000 mm/ha. Scale that to the region to understand the amount of water that could be saved based on this climate adaptation intervention.



It is clear that drip irrigation and judicious water use always enhances water productivity. Thus, this should be scaled up as an adaptation measure.



E. Summary and conclusions of this exercise

A simulation of the long-term yield and irrigation water use was performed in the irrigated agricultural context of Iraq under the influence of a changing climate using the RICCAR data under two scenarios of irrigation practices: (1) conventional flooding irrigation, where water is copiously applied, and (2) drip irrigation, where an adequate amount of water is applied. It was clear that the interannual yield dynamics do not significantly vary in either of the two scenarios. However, the irrigation water applied was significantly higher in the flooding system compared to the drip irrigation system to maintain the same level of yields in a changing climate. It was noted that flooding-based irrigation yields were slightly higher than drip irrigation-based systems. The amount of water consumed for irrigation increased in both cases as the years progressed because of changing climatic conditions. Because the yields were comparable, the water productivity of drip irrigation systems was significantly higher than flood-based irrigation systems. Although water productivities decreased with climate change, it was clear that it is essential to opt for climate adaptation measures, including using technologies such as drip irrigation, to make the system climate-smart. Thus, RICCAR-based crop modelling activities are useful for exploring such context-specific climate adaptation efforts by the stakeholders.

6. CLIMATE MITIGATION IN AGROECOSYSTEMS: CARBON SEQUESTRATION IN JORDAN VIA CROP DIVERSIFICATION

A. Problem statement

Soil is an invaluable natural resource that acts as the living medium where vegetation proliferates under the influence of climate (weather) and management. It is in the soil that the carbon from the atmosphere is assimilated by vegetation and is recycled into the biosphere in the long term. Thus, enhancing soil carbon through vegetation is an important aspect of climate mitigation action as it brings atmospheric carbon to the biosphere. Beyond mitigation, enhancing soil carbon can also be considered as an efficient climate adaptation intervention because soil carbon favours optimal plant growth and a healthy rhizosphere. Many studies show that enhanced soil organic carbon (SOC) in the soil favours resilience and soil health. Enhanced SOC facilitates the retention of soil moisture and nutrients because it acts as a chelating agent which can retain these molecules that favour plant growth. The macromolecules of SOC enhance the soil structure, positively favour the soil hydraulic properties and regulate the physicochemical properties of the soil such as pH and electrical conductivity (EC).

FIGURE 10: Fertile soil through better CO_2 sequestration

Source: ICARDA, "Carbon sequestration for better soil and food security", 8 September 2021. https://www.icarda.org/media/news/carbon-sequestration-better-soil-and-food-security.

The enhanced SOC also favours the proliferation of soil micro- (bacteria and fungi) and macro-organisms (earthworms) that will positively affect the rhizosphere, making it a self-sustaining system that can withstand shocks and quickly recover from shocks. Thus, soil with enhanced SOC will have lower chances of degradation in terms of physical conditions (structure, hardness, etc.) and chemical conditions (salinity, pH, etc.). Overall, SOC is vital for the long-term resilience of the soil, and maintaining adequate SOC in the soil is vital for ecological sustainability (whether in natural systems or agroecosystems). In agroecosystems, because of continued monocropping and repeated tillage and other management activities, the chances of SOC decline are quite high. This is especially true for a climate change context where the increased tillage and exposure of SOC to decomposition outweighs the SOC replenishment due to carbon recycled from the biomass (residue) of the crop grown. Continued monocropping is likely to bring a similar kind of residue to the soil year after the year, which may not favour the build-up of SOC. On the other hand, a more diversified crop rotation scheme is likely to bring a diverse range of SOC constituents into the soil. SOC diversity occurs when the SOC has a wide variety of C:N ratios. Different plant residues have different C:N ratios. The higher the C:N ratios, the more difficult decomposition of the soil becomes. This in turn helps SOC to accumulate. Legumes have a lower C:N ratio and decompose rapidly.

Assuming that you are now familiar with most of the functionalities in APSIM, this exercise will focus on simulating how soil organic matter might change under a diversified system of crop rotation with the effects of climate change in the Jordan valley situation (irrigated). Further to this, we will create more simplified (undiversified crop rotation) scenarios using this one as the template. Unlike the previous exercises, in this exercise, more than one crop will be included in the simulations for 100 years and the outputs will be analysed with an annual time step. This exercise is a bit advanced and thus, it is strongly recommended that the user has thoroughly practice the previous two exercises before embarking on this one. The three scenarios that are conceptualized in this exercise are shown in the figure below.

Crop Diversification with a crop rotation pattern that repeats only every 4 years from 2000-2100.

Year-1		Year-2		Year-3		Year-4	
Wheat	Soybean	Chickpea	Maize	Fababean	Maize	Barley	Soybean

Simple Cereal-Cereal sequence done continuously from 2000-2100.

Year-1		Year-2		Year-3		Year-4	
Wheat	Maize	Wheat	Maize	Wheat	Maize	Wheat	Maize

Simple Cereal-Legume sequence done continuously from 2000-2100.

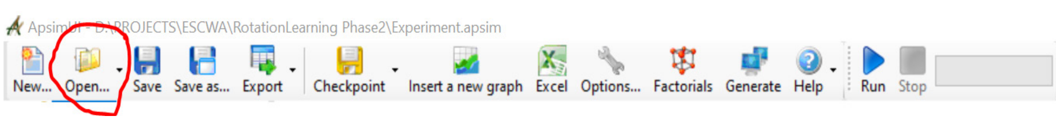
Year-1		Year-2		Year-3		Year-4	
Wheat	Soybean	Wheat	Soybean	Wheat	Soybean	Wheat	Soybean

B. Setting up the model and the necessary parameterizations

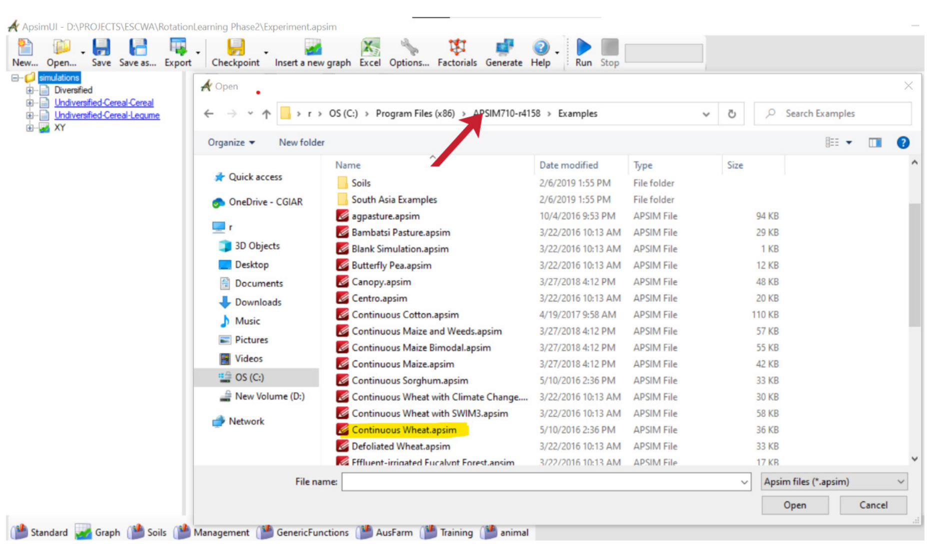
First, the APSIM interface is launched and an example simulation file already available in the APSIM database is selected. It will be used as a template simulation first and then the user will customize it for the specific needs of the current simulation rather than building from scratch.

- **Click** Open and browse for the APSIM example folder in the following file path.

C:\Program Files (x86)\APSIM710-r4158\Examples.



- **Open** the .apsim file called **Continuous Wheat.apsim.**

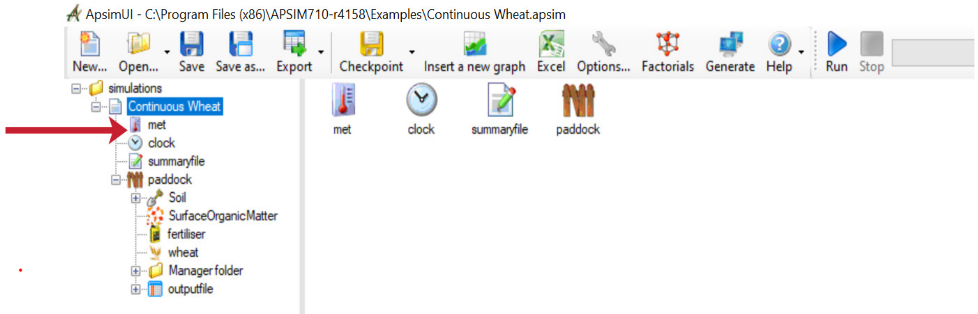


The user may already be familiar with the simulation tree and the components. If not, it is recommended that you revisit chapters 3 and 4 and familiarize yourself with the components. In this exercise, the first step involves two main alterations to the Continuous Wheat that was loaded as a template, and which will be customized for the needs of this exercise: (1) replace the meteorological file with the one relevant for our case study (Jordan) and (2) replace the soil profile.

- To replace the meteorological file, **click** the **met** icon in the simulation tree.

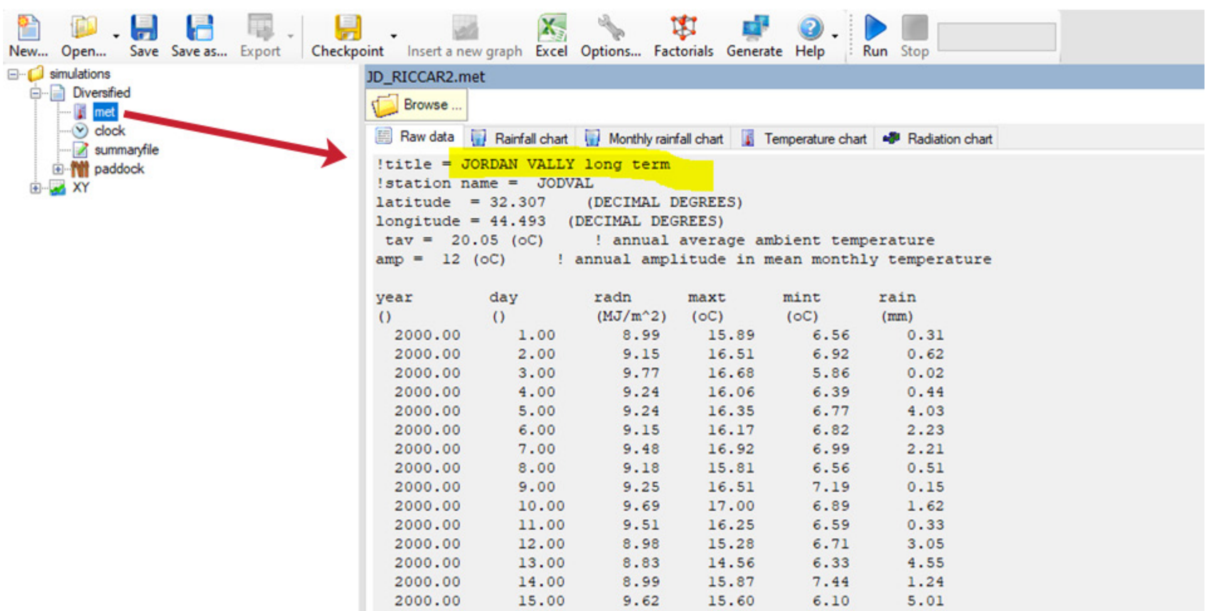
First of all, save this as a new simulation and give it a New File Name.

- **Save** this **Continuous Wheat** simulation as **Jordan_CropDiversification.apsim**.



The meteorological station for the example simulation will be shown as **Goondiwindi, Australia**. You may also notice that the dataset is for the period 1940 to 1989. Firstly, the user may replace this file with the meteorological file that was created for the site in Jordan (Dar Alaa) by browsing for it and opening it in the relevant location. In the input folder, the user should have should created a meteorological file for a location in Jordan valley from the RICCAR data, for the IPCC scenario RCP 8.5, prior to this exercise.

- **Load** the Jordan valley meteorological file.

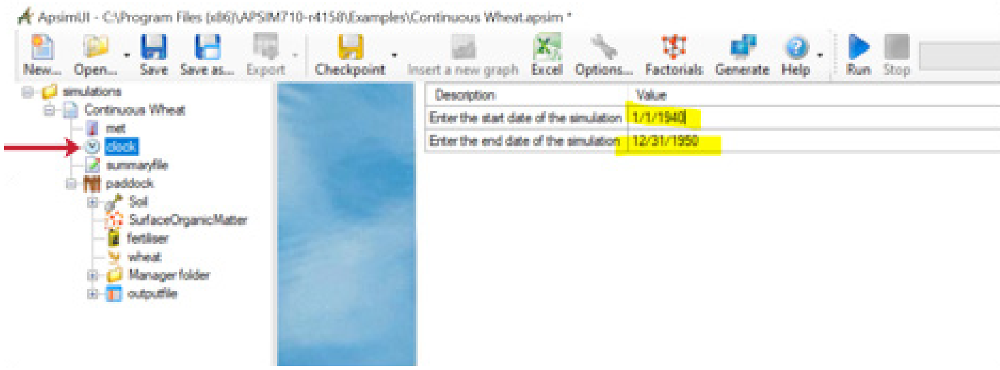


- **Rename** the existing numerical experiment as **Diversified**.

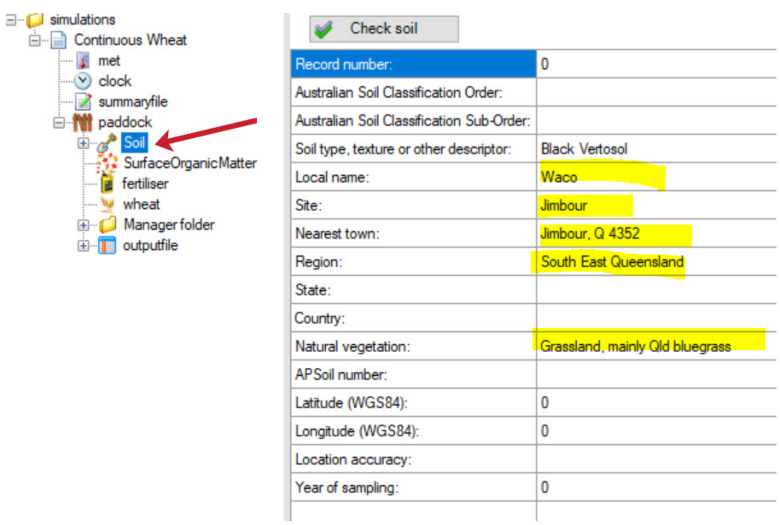
When the selected file is loaded, it can be seen that the name **Dar Alaa** appears, which is a field location in the Jordan valley. When scrolling down through the data, it is possible to see that the data ranges from 2000 to 2070. In this exercise, the simulation of the long-term effects of climate change (from 2006 to 2070) will be done without the specific influence of atmospheric CO_2 concentration as APSIM has not yet parameterized the plant physiological mechanisms of CO_2 fertilization for all the crops.

The next step is to adjust the simulation clock. In APSIM, although the extent of climate data is longer, it is possible to simulate for subset periods, for example, 2010-2015 from a temporal domain of 2000 to 2070. We will, however, simulate for the entire duration in this case.

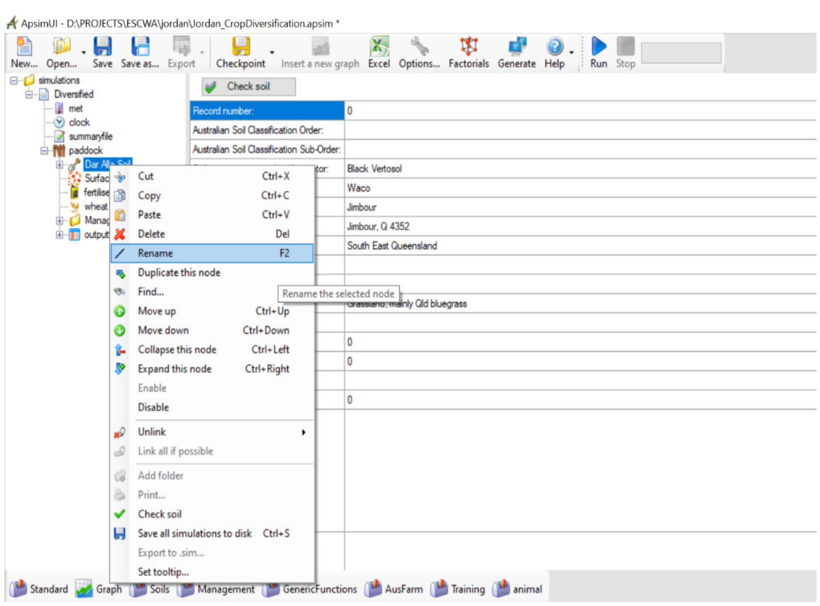
- **<u>Adjust</u>** the simulation clock, setting the **start date** to 1/1/2000 and the **end date** to 12/31/2070.



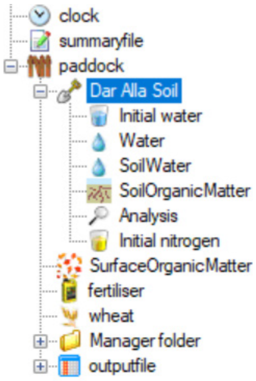
The next step is to parameterize various components of the paddock. The user may replace the soil profile with the one we want for this location. There are two solutions to parametrize soil profile in APSIM. For this exercise, the user will continue using the soil profile that came along with the Continuous Wheat simulation and parameterize it to suit the Dar Alla (Jordan) conditions.



- **<u>Keep</u>** the cursor on the soil and **<u>right-click</u>** to rename the soil (optional). It is possible to also edit the auxiliary information on the right panel (by replacing the highlighted text). After this, **<u>click</u>** **Save**.



- **Click** the **+** beside the soil (renamed now as **Dar Alla Soil**) to expand the list. Several modules can be seen for parameterization of the soil characteristics. It is necessary to parameterize each of these sections to suit the soil characteristics of the study site.



The parameterizations of these modules are quite similar to the procedures mentioned in chapter 2 and may be followed if needed to suit your site soil parameterization. The most important is the soil module Water where plant water relations are parameterized.

- **Click** the **Water** icon to see the parameterizations available for various crops.

You can see that this soil is a 3 m deep soil profile that has 11 layers. Here the user can edit the values of soil-plant water relations specific to each layer as a function of the crop they plan to simulate. Let's edit this soil profile for the current modelling needs.

- **Click** the **Manage crops** icon. We will delete some crops and add some new crops, as detailed below.

Manage crops

Depth (cm)	BD (g/cc)	AirDry (mm/mm)	LL15 (mm/mm)	DUL (mm/mm)	SAT (mm/mm)	KS (mm/day)	Wheat KL (/day)	Wheat XF (0-1)	soybean LL (mm/mm)	soybean PAWC 0.0	soybean KL (/day)	soybean XF (0-1)	Sorghum LL (mm/mm)
0-15	1.020	0.150	0.290	0.540	0.590		0.10	1.0		0.0			0.290
15-30	1.030	0.260	0.290	0.530	0.580		0.10	1.0		0.0			0.290
30-60	1.020	0.290	0.290	0.540	0.590		0.08	1.0		0.0			0.290
60-90	1.020	0.290	0.290	0.540	0.580		0.06	1.0		0.0			0.379
90-120	1.060	0.300	0.300	0.520	0.570		0.04	1.0		0.0			0.393
120-150	1.110	0.310	0.310	0.500	0.550		0.02	1.0		0.0			0.407
150-180	1.120	0.320	0.320	0.500	0.550		0.01	1.0		0.0			0.423
180-210	1.150	0.330	0.330	0.480	0.530		0.00	0.0		0.0			0.423
210-240	1.180	0.340	0.340	0.470	0.520		0.00	0.0		0.0			0.423
240-270	1.200	0.350	0.350	0.460	0.510		0.00	0.0		0.0			0.423
270-300	1.250	0.360	0.360	0.440	0.490		0.00	0.0		0.0			0.423

- **Delete** **Sorghum**, **Lucerne** and **Perennial Grass** and **click** **OK**.

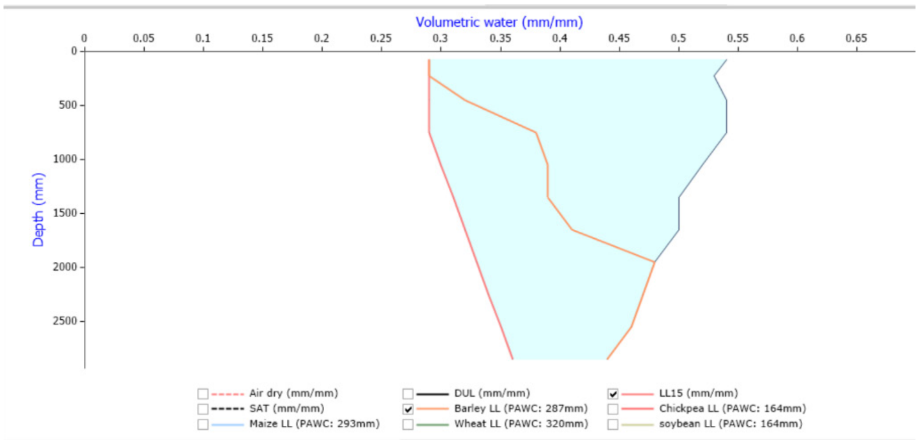
- **Add** the missing **crops soybean** and **fababean**. We should now have 6 crops in the soil for the plant-water relations parameterizations. When a crop is deleted, you can see that its parametrization columns are also deleted (except for the pink-coloured columns). When a crop (soybean in this case) is added, you may notice that a space is created for the crop. These columns need to be filled by the user for parameterizing the plant water relations.

Depth (cm)	BD (g/cc)	AirDry (mm/mm)	LL15 (mm/mm)	DUL (mm/mm)	SAT (mm/mm)	KS (mm/day)	L)	Wheat XF (0-1)	soybean LL (mm/mm)	soybean PAWC 163.5	soybean KL (/day)	soybean XF (0-1)	Sorghum LL (mm/mm)	Sorghum PAWC 334.1
0-15	1.020	0.150	0.290	0.540	0.590		0	1.0	0.290	37.5	0.10	1.0	0.290	37.5
15-30	1.030	0.260	0.290	0.530	0.580		0	1.0	0.290	36.0	0.10	1.0	0.290	36.0
30-60	1.020	0.290	0.290	0.540	0.590		8	1.0	0.360	54.0	0.08	1.0	0.290	75.0
60-90	1.020	0.290	0.290	0.540	0.580		6	1.0	0.430	33.0	0.06	1.0	0.379	48.3
90-120	1.060	0.300	0.300	0.520	0.570		4	1.0	0.510	3.0	0.04	1.0	0.393	38.0
120-150	1.110	0.310	0.310	0.500	0.550		2	1.0	0.500	0.0	0.02	1.0	0.407	28.1
150-180	1.120	0.320	0.320	0.500	0.550		1	1.0	0.500	0.0	0.01	1.0	0.423	23.3
180-210	1.150	0.330	0.330	0.480	0.530		0	0.0	0.480	0.0	0.00	0.0	0.423	17.3
210-240	1.180	0.340	0.340	0.470	0.520		0	0.0	0.470	0.0	0.00	0.0	0.423	14.3
240-270	1.200	0.350	0.350	0.460	0.510		0	0.0	0.460	0.0	0.00	0.0	0.423	11.3
270-300	1.250	0.360	0.360	0.440	0.490		0	0.0	0.440	0.0	0.00	0.0	0.423	5.3

- First, simply **copy** the values of a similar crop and fill it in. Later the user may modify it. Here we will copy and paste the values of **chickpea** for **soybean** and save it.

Care should be taken to click and paste on the first cell ONLY while pasting the copied text (in other words, do not highlight all the four columns and paste).

- **Repeat** this action for the other crops and **click** the **Save** button. The user may use the visualization mode to adequately see how various plants behave in terms of water availability to determine optimal parameterization. This is beyond the scope of this exercise and the user may explore this further to make the most appropriate parameterizations.

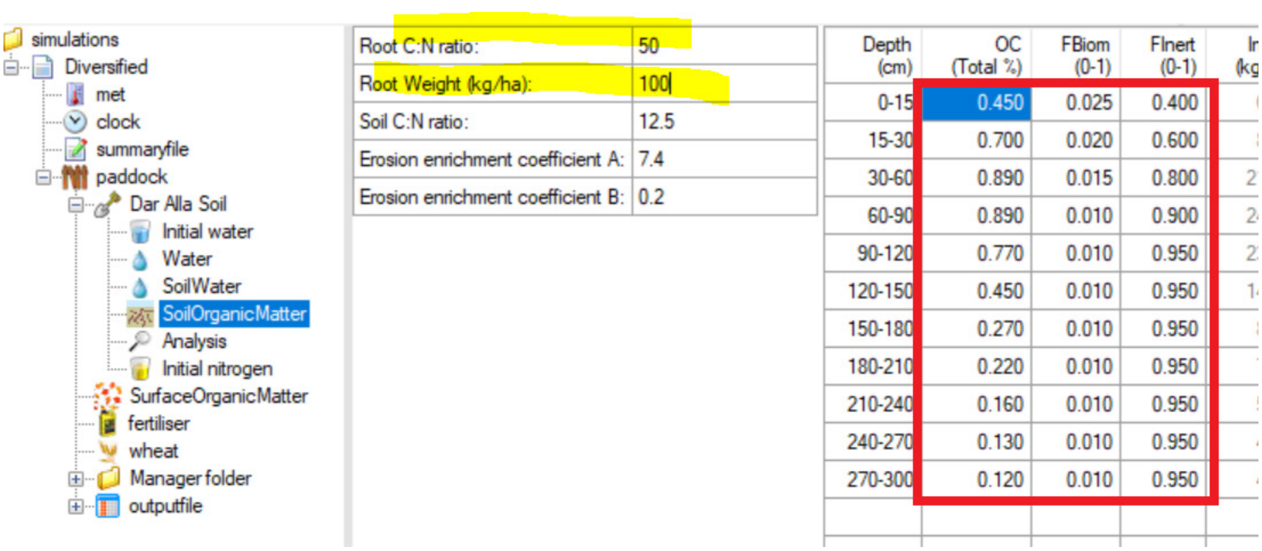


Likewise, the user can parameterize other aspects of the soil such as **Soil Water**, **Soil Organic Matter**, **Analysis and Initial Nitrogen** to better suit their site characteristics. Most of these parameterizations and their vertical soil distribution can be visualized graphically in the panel below. Such visualization is good for efficient parameterization of the soil characteristics.

- **Click Save**.

The next step is to parameterize the baseline **Soil Organic Matter** of the soil profile. This is a very important part of this exercise as the present chapter is focused on analysing the long-term change in SOM as influenced by a diversified cropping system.

- **Parameterize** the **Soil Organic Matter** component exactly as shown below.
- **Visualize** how the user-defined parameterization affects the **Soil Organic Matter** distribution in the soil by using the graphs below the parameterization panel.
- **Click Save**.



The next step is to move to other components of the **paddock**. In APSIM there are specific modules for various crop management topics such as the choice of **Surface Organic Matter**, **Crop**, **Fertilizer**, **Irrigation**, etc. Each of these modules needs to be listed under the paddock to be used in a simulation. Each of these modules can be given one or more specific management instructions, which are listed in the **Management folder**. For example, instructions can include explicitly adding crops and fertilizer.

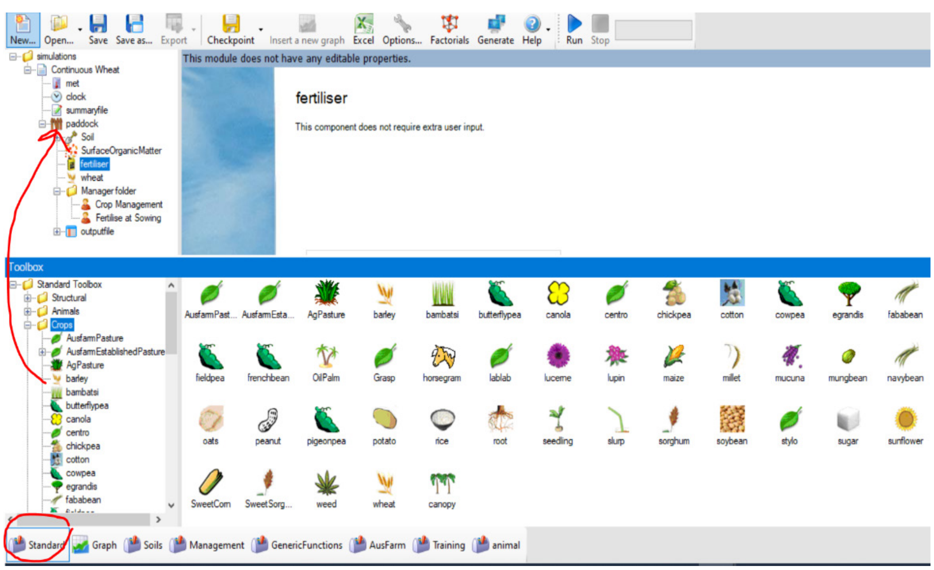
First, let's edit the **Surface Soil Organic Matter** module.

- **Change** the **C:N ratio of the initial residue** to **100** and the **Fraction of residue standing** to **0.5**.

Now we need to ensure that we have the right crop modules. We have seen in the initial description of the present chapter that we are going to have a diversified crop system involving several crops. To this end, we should have all the 6 crops listed in the crop rotation diagram: **Wheat**, **Maize**, **Barley**, **Soybean**, **Fababean** and **Chickpea**. In this simulation, the crop **Wheat** is already there.

As seen in the previous chapters, if the user wants to add or change the crop, it is possible to drag and drop the necessary crops from the panel below (selecting **Standard**, then **Standardoolbox**, then **Crops**) from the crops available in the APSIM environment.

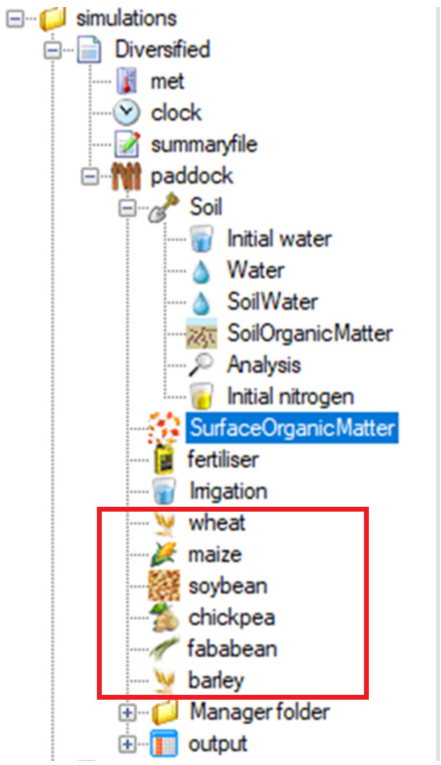
- Simply **drag and drop** the crops into the **paddock**. You should then have all 6 selected crops in the **paddock**.
- **Click** **Save**.



After this step, the paddock should look like the screenshot shown on the next page.

BOX 7: The Genotype x Environment x Management (GEM) approach in crop modelling

In addition to climate, soil and management, the cultivar type of a given crop has a significant influence on the nature of the end results. Thus, it is not always easy to make generalizations about the impact of soil and climate alone on a given crop. Climate-smart crop improvement plays a major role in climate adaptation in addition to agronomical interventions. For example, with conventional wheat varieties even under irrigated conditions, yield might decline under climate change due to the vernalization requirements of wheat. With the availability of low vernalization requiring heat tolerant varieties, farmers may be able to adapt adequately. Thus, simulating wheat crop under future climates without thinking about varietal differences may be insufficient to draw conclusions.



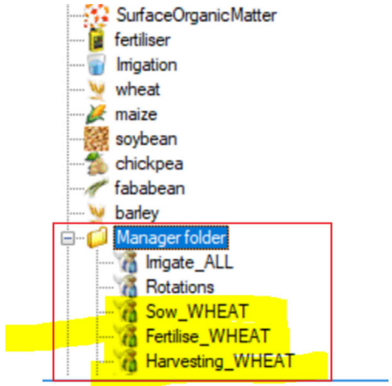
- **Ensure** that the **paddock** has the **fertilizer** module and the **Irrigation** module in addition to the 6 crop modules.

It is important to provide the necessary management instructions that will be plugged into these modules. Under the **Management Folder**, only two management actions can be seen: (1) **Crop Management** and (2) **Fertilize at Sowing**. These are crop-specific managers. In this case, they are currently specific to the wheat crop as wheat is already there. It is necessary to add a few more managers here. Please note that this exercise is a bit complicated in comparison to the previous one.

- **Add** two generic management actions (in other words, actions that are applicable to all the crops). We need to add 2 managers: **Rotations** and **Irrigate on sw deficit**. Both of these are available in the toolbox bar under the **Management folder**, in **Manager (common tasks).**
- **Drag and drop** both managers to the **Management folder** under the paddock.
- **Add** one non-generic manager called **Harvesting rule**. It is available in the toolbox bar under the **Management folder**, in **Manager (common tasks)**.

Now there should be 5 managers in the Manager folder: Irrigation, Rotation, Crop Management, Fertilize at Sowing and Harvesting rule. Among these, the first two are applicable to all the crops in the rotation sequence while the other three are crop-specific.

- **Rename** these 3 crop specific managers as shown below by right-clicking, selecting **Rename** and adding “wheat”, to indicate that they are for the wheat crop.



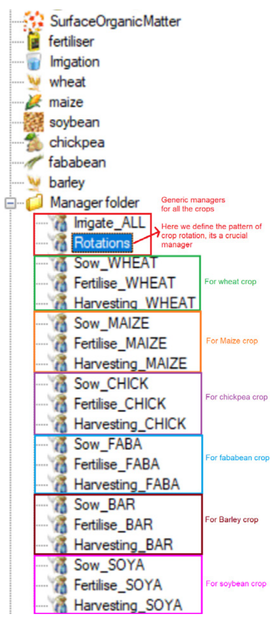
- **Click** Save.

The next step is a bit tedious and can easily go wrong. So, please be careful. Each of these three crop-specific managers needs to be replicated and renamed specifically for each of the six crops.

- **Create** a duplicate of a manager by simply dragging it and placing it in the **Manager folder** or right-clicking and creating a duplicate using the **duplicate this node** option. As soon as you do this, a duplicate will be instantly created with a default name.
- **Rename** this duplicate by right-clicking it and choosing the **Rename** option.
- **Repeat** this process for all 6 crops for all the three managers, such that a list of managers is created.

BOX 8: How to output a variable of a single layer or as the average of several layers?

In APSIM, the variables that are simulated for each soil layer (variables that are written in an "Array", appearing as "Array? YES") have to be explicitly denoted in the output file structure. Taking "ESW" as an example, if we put a square bracket "[]" soon after the variable, esw[], then the value that is written out will be the average of the entire soil profile. If not, values for each soil layer will be written out in the output file.



- **Click** Save.
- **Click** each of these managers and enter the parameters using the values displayed in table 7.

It is not practical to show the screenshot for each of the managers for each crop (as this would require 18 screenshots). Thus, data is provided in table 7 for the user to enter.

TABLE 7: Crop-specific parameterization for the different managers used in this exercise

	Wheat	Maize	Chickpea	Fababean	Barley	Soybean
Sowing criteria						
Sowing window start date	15 November	15 May	15 November	15 November	15 August	15 November
Sowing window end date	10 December	10 June	10 December	10 December	10 September	10 June
Must sow?	Yes	Yes	Yes	Yes	Yes	Yes
Amount of rainfall (mm)	10	0	5	2	5	0
NO. of days of rainfall	7	0	5	1	5	0
Min. allowable water (mm)	50	5	70	50	70	5
Name of the crop to sow	Wheat	Maize	Chickpea	Fababean	Barley	Soybean
Sowing density (plants/m2)	100	3	100	70	100	50
Sowing depth (mm)	30	50	30	30	30	30
Cultivar	Shatabdi	C79	Amethyst	Warda	Schooner	Davis
Crop growth class	Plant	Plant	Plant	Plant	Plant	Plant
Row spacing (mm)	250	1 000	250	250	250	500
Fertilizer application						
Which module should the event come from?	Wheat	Maize	Chickpea	Fababean	Barley	Soybean
On which event fertilizer be applied?	Sowing	Sowing	Sowing	Sowing	Sowing	Sowing
Module to apply fertilizer	Fertilizer	Fertilizer	Fertilizer	Fertilizer	Fertilizer	Fertilizer
Amount of fertilizer (Kg/ha)	150	100	40	40	100	30
Fertilizer type	Urea N	Urea N	Urea N	Urea N	Urea N	Urea N
Harvesting parameterization						
Name of the crop to harvest when ripe	Wheat	Maize	Chickpea	Fababean	Barley	Soybean

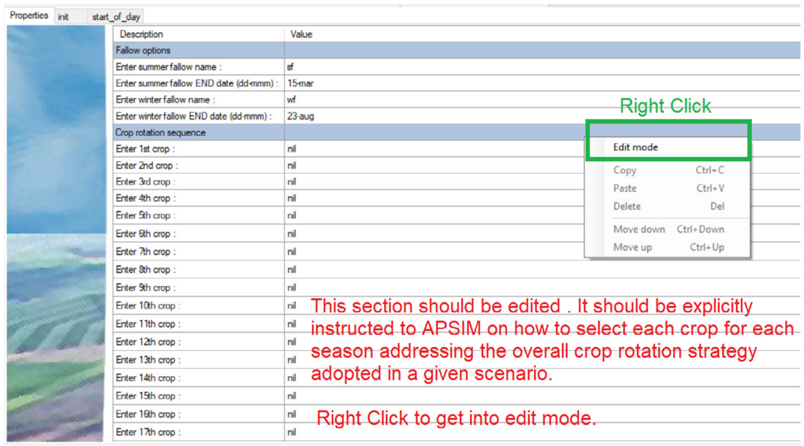
- **Click** **Save** after every step.

Now we will parameterize the two generic managers: **Irrigation** and **Rotation**.

- For the irrigation manager (**Irrigate on sw deficit**), simply **enter** the values shown in the screenshot below:

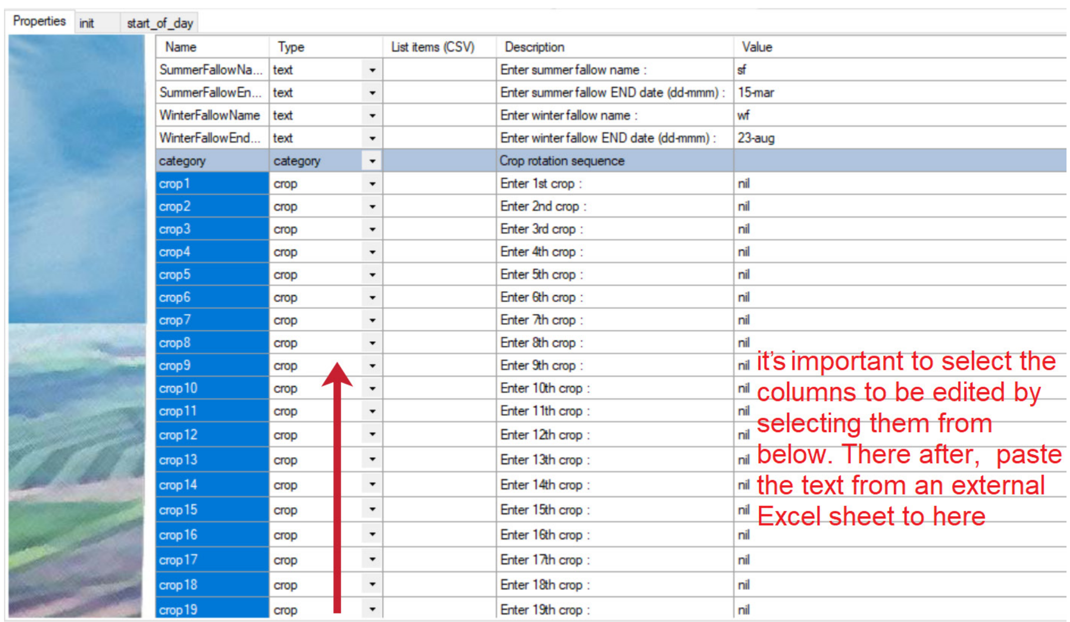
Description	Value
Irrigate when soil water deficit reaches this amount (mm)	200
Irrigation efficiency (0-1)	0.5
The earliest date irrigation will be applied (dd-mmm)	1-jan
The latest date irrigation will be applied (dd-mmm)	31-dec
Amount of irrigation to apply (0 for deficit)	20
Module to apply the irrigation	Irrigation

The next step is to set up the **Rotations manager,** which is a generic manager (in other words, a manager that is applicable for all the crops) for a **Diversified** scenario. Setting up this manager is a bit challenging as it requires extreme care. The **Rotation manager** tells APSIM which crops to choose from the 6 crops listed and defines the rotational sequence. This means it defines how the 200 crops (in other words, 2 crops per year over 100 years) will be sequenced.



- **<u>Open</u>** the **Rotation manager** and see its content.
- **<u>Edit</u>** it by right-clicking when placing the cursor anywhere on the manager and selecting **Edit mode**.

Because in this case, there are 200 crops to be simulated (2 crops per year over 100 years) and the crops are different for each season, it is important that APSIM is clearly instructed on the sequencing of the crops. The sequence can be developed eternally in Excel and can be pasted here.



In spreadsheets such as Microsoft Excel, it's easy to prepare long-time series that have a logical pattern. As an example, the following file was prepared in Microsoft Excel. This can be cut and pasted here using the procedure mentioned above. Below is an excerpt of a sequence that will be used for the **Diversified** scenario (see column N, highlighted in blue).

- **<u>Paste</u>** the sequence from the external spreadsheet into the **Rotation manager**.

BOX 9: Issues to consider: representing days in APSIM

In APSIM, care should be taken when entering the dates. They should be entered in dd-mmm format (for example, 07-apr, and not 7-Apr, 7-APR, or 07-APR).

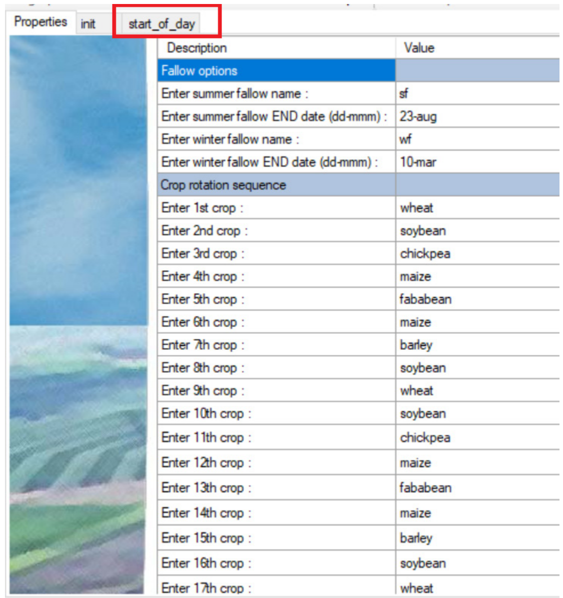
F	G	H	I	J	K	L	M	N	O	P	Q
		Crop1	crop	Enter 1st crop :		wheat	wheat	wheat	W		
		Crop2	crop	Enter 2nd crop :		soybean	maize	soybean	S		
		Crop3	crop	Enter 3rd crop :		wheat	wheat	chickpea	W		
		Crop4	crop	Enter 4th crop :		soybean	maize	maize	S		
		Crop5	crop	Enter 5th crop :		wheat	wheat	fababean	W		
		Crop6	crop	Enter 6th crop :		soybean	maize	maize	S		
		Crop7	crop	Enter 7th crop :		wheat	wheat	barley	W		
		Crop8	crop	Enter 8th crop :		soybean	maize	soybean	S		
		Crop9	crop	Enter 9th crop :		wheat	wheat	wheat	W		
		Crop10	crop	Enter 10th crop :		soybean	maize	soybean	S		
		Crop11	crop	Enter 11th crop :		wheat	wheat	chickpea	W		
		Crop12	crop	Enter 12th crop :		soybean	maize	maize	S		
		Crop13	crop	Enter 13th crop :		wheat	wheat	fababean	W		
		Crop14	crop	Enter 14th crop :		soybean	maize	maize	S		
		Crop15	crop	Enter 15th crop :		wheat	wheat	barley	W		
		Crop16	crop	Enter 16th crop :		soybean	maize	soybean	S		
		Crop17	crop	Enter 17th crop :		wheat	wheat	wheat	W		

After this sequence is pasted, the **Rotations** manager (in editing mode) should look like the screenshot below. Only crops 1 to 17 are visible in this window. In reality, there will be 200 crops but with the same sequence.

Name	Type	List items (CSV)	Description	Value
category	category		Fallow options	
SummerFallowNa...	text		Enter summer fallow name :	sf
SummerFallowEn...	text		Enter summer fallow END date (dd-mmm) :	23-aug
WinterFallowName	text		Enter winter fallow name :	wf
WinterFallowEnd...	text		Enter winter fallow END date (dd-mmm) :	10-mar
category	category		Crop rotation sequence	
Crop1	crop		Enter 1st crop :	wheat
Crop2	crop		Enter 2nd crop :	soybean
Crop3	crop		Enter 3rd crop :	chickpea
Crop4	crop		Enter 4th crop :	maize
Crop5	crop		Enter 5th crop :	fababean
Crop6	crop		Enter 6th crop :	maize
Crop7	crop		Enter 7th crop :	barley
Crop8	crop		Enter 8th crop :	soybean
Crop9	crop		Enter 9th crop :	wheat
Crop10	crop		Enter 10th crop :	soybean
Crop11	crop		Enter 11th crop :	chickpea
Crop12	crop		Enter 12th crop :	maize
Crop13	crop		Enter 13th crop :	fababean
Crop14	crop		Enter 14th crop :	maize
Crop15	crop		Enter 15th crop :	barley
Crop16	crop		Enter 16th crop :	soybean
Crop17	crop		Enter 17th crop :	wheat

In the **no editing** mode, the Rotation manager will look like shown in the next page. Note that **start_of_day** is highlighted. This is required for the next step.

- **Click Save**.

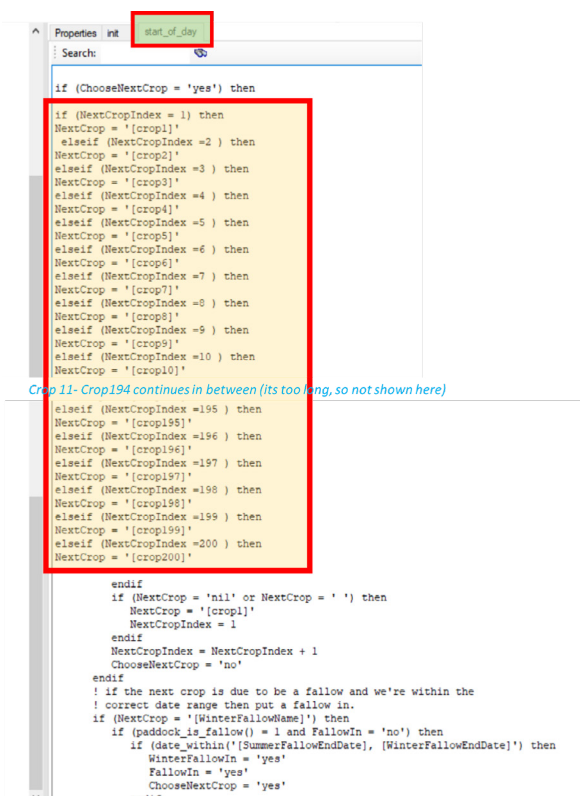


So far, only the sequencing of the crops has been provided to APSIM. But it is necessary to explicitly instruct APSIM on how to choose the crop one after the other. For this, it is necessary to edit a piece of code with which one can interact with the core kernel of APSIM. For this, it is necessary to do the following.

- **Click** the **start_of_day** item on the top right corner as shown in the previous screenshot. The user can see a set of codes there.

It is necessary to add a lengthy piece of code in the space highlighted in the yellow below. It has a similar pattern from Crop 1 to Crop 200. It can be written by hand, but as it is too long for 200 crops. It is hence recommended that this piece of code be developed externally and pasted here. In Appendix 3, a programme written in C language is provided that can generate this code.

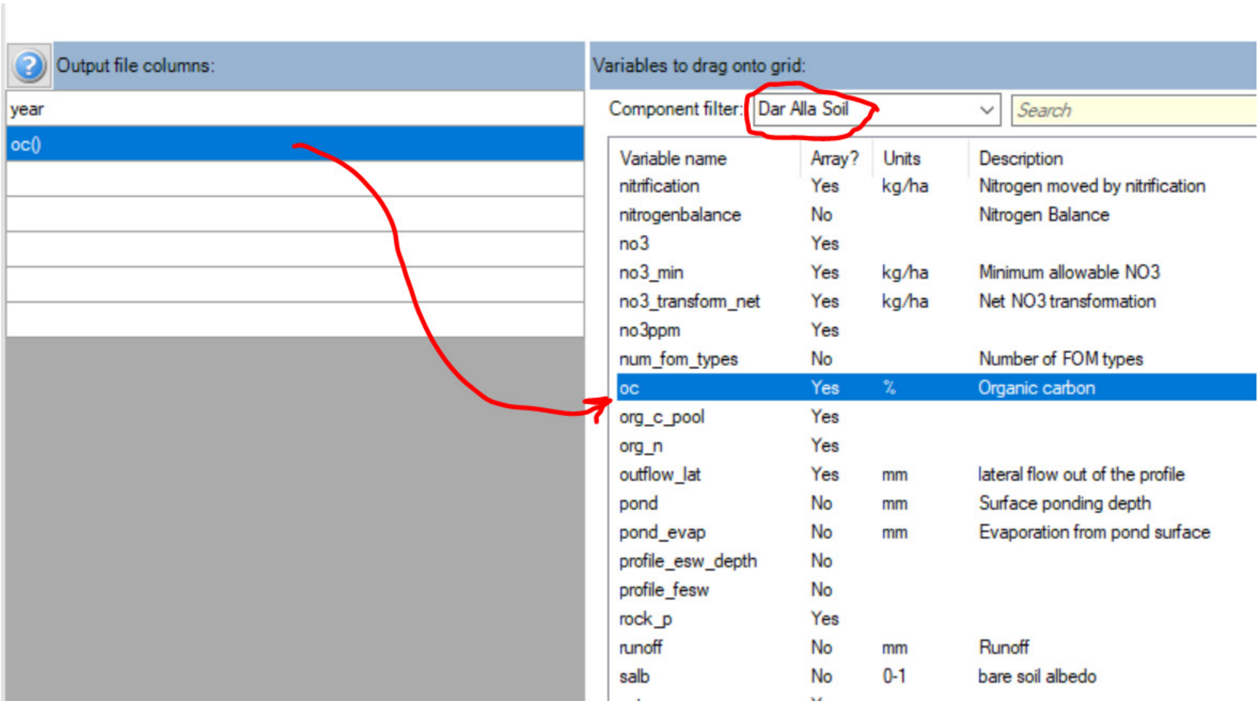
- Using this generated code, **edit** the code block in APSIM UI.
- **Click** **Save** and return to the **paddock**.



C. Setting up output variables and reporting frequencies

So far, the modelling environment and the necessary parameterizations have been set up. This lengthy and tedious process is now finalized. The following steps are to be followed to determine which variables to write out as outputs and the frequency of their reporting. This is a critical step, especially when we want to intercompare different simulations.

- On the simulation window, **click** **Variables** under the **outputfile** module.
- In this simulation, you may **delete** the **dd/mm/yy** as date variable and **replace** it with **Year**. Find **Year** under the **Clock** on the right panel.
- **Delete** **grain_size** and **ESW** variables.
- **Add** another variable called **oc** in %. This refers to SOC. It can be seen under **Dar Alla Soil**.



Parentheses should appear when **oc** is listed in the output file column, as seen on the screenshot above. These parentheses have significance. In the variable listing under the **Array** column, you will see that the **oc** variable is listed as **Yes**. This means that APSIM simulates the oc percentage for each soil layer. In the case of Dar Alla Soil, we have 11 soil layers. What is needed is an average value taken from the 11 soils of the soil profile. For this reason, we put parentheses in the output file columns. If it is written as **oc(3)**, It means APSIM will write out **oc** in the 3rd soil layer. Keep the reporting frequency as **harvesting**.

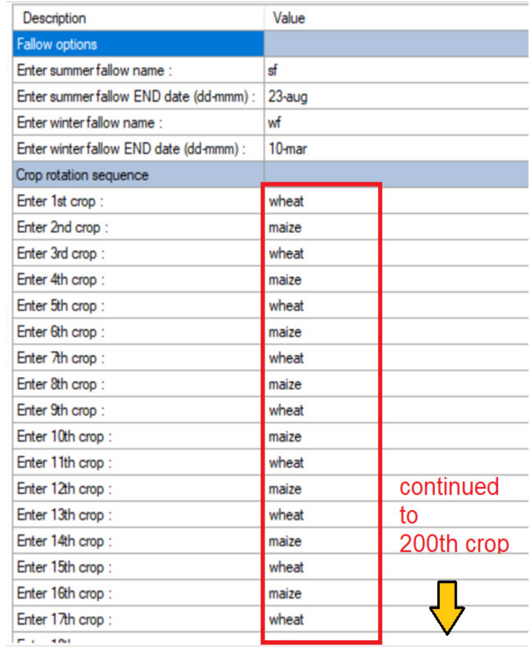
- After all these steps **click** **Save**.

Now the **Diversified** scenario is complete.

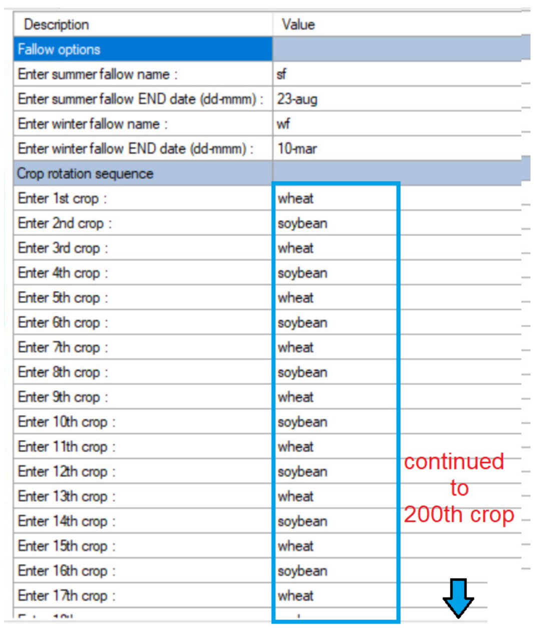
- **Collapse** the simulation tree of the entire **Diversified** scenario.

Now the user may create two replicas of this scenario and edit them to make different scenarios.

- **Replicate** the **Diversified** scenario twice (using the linked duplicates) modes. Refer to the previous chapters on how to do this.



Description	Value
Fallow options	
Enter summer fallow name :	sf
Enter summer fallow END date (dd-mmm) :	23-aug
Enter winter fallow name :	wf
Enter winter fallow END date (dd-mmm) :	10-mar
Crop rotation sequence	
Enter 1st crop :	wheat
Enter 2nd crop :	maize
Enter 3rd crop :	wheat
Enter 4th crop :	maize
Enter 5th crop :	wheat
Enter 6th crop :	maize
Enter 7th crop :	wheat
Enter 8th crop :	maize
Enter 9th crop :	wheat
Enter 10th crop :	maize
Enter 11th crop :	wheat
Enter 12th crop :	maize
Enter 13th crop :	wheat
Enter 14th crop :	maize
Enter 15th crop :	wheat
Enter 16th crop :	maize
Enter 17th crop :	wheat



Description	Value
Fallow options	
Enter summer fallow name :	sf
Enter summer fallow END date (dd-mmm) :	23-aug
Enter winter fallow name :	wf
Enter winter fallow END date (dd-mmm) :	10-mar
Crop rotation sequence	
Enter 1st crop :	wheat
Enter 2nd crop :	soybean
Enter 3rd crop :	wheat
Enter 4th crop :	soybean
Enter 5th crop :	wheat
Enter 6th crop :	soybean
Enter 7th crop :	wheat
Enter 8th crop :	soybean
Enter 9th crop :	wheat
Enter 10th crop :	soybean
Enter 11th crop :	wheat
Enter 12th crop :	soybean
Enter 13th crop :	wheat
Enter 14th crop :	soybean
Enter 15th crop :	wheat
Enter 16th crop :	soybean
Enter 17th crop :	wheat

- **Change** the default names of these two duplicates to **Undiversified-Cereal-Cereal** and **Undiversified-Cereal-Legume**.

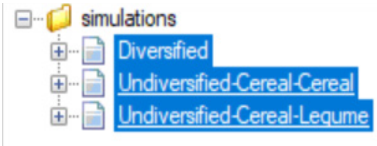
As we already know, these three scenarios are linked and do the same things (although the names are different for the time).

- **Unlink** the **Rotations manager** in the two duplicate **undiversified** scenarios. Then **customize** each as shown on the previous page.
- **Use** the Excel sheet that was prepared earlier to fill in the necessary rotation definitions.

There is no need to remove any crop managers even if they are not used. For example in the **Undiversified-Cereal-Cereal** (wheat-maize) rotation scenario, crops such as soybean, chickpea, fababean and barley are not relevant. However, it won't affect the simulations because, in the **Rotation manager**, we instruct APSIM on which crop modules to use each season.

Now that we have prepared all three scenarios accurately, it is time to run APSIM for all three scenarios simultaneously.

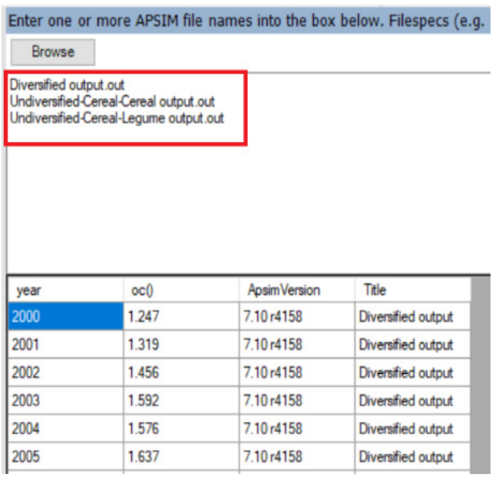
- **Collapse** all the simulation trees in the three scenarios. Then select all three scenarios using the **Shift** button and **click** **Run**.



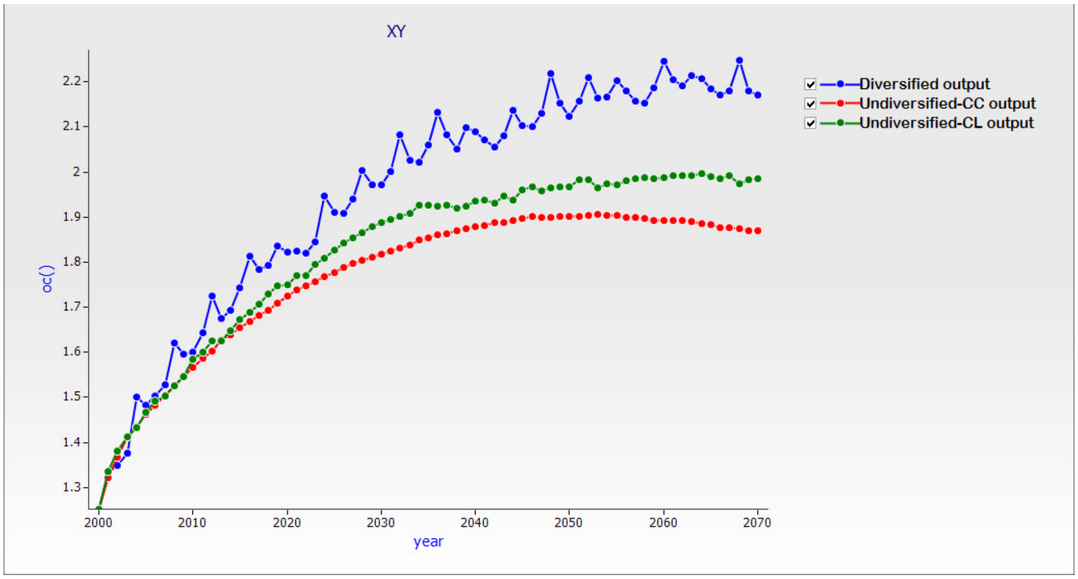
Once the simulations have loaded to 100 per cent, the user can click on **outputfile** (not the subcomponents) to see the output file based on the configurations that we designed during the simulation set-up phase.

The user can plot this data using the procedure set out in chapter 2.

- **Click** the **Graph** button from the bottom panel.
- **Select** **XY**. **Drag and drop** it under the **simulations** folder.
- **Click** the **+** of the **XY** graph icon, you can see two child icons **Plot** and **AspimFileReader**. Through this, you can browse for your three output files. You will then be able to see these loaded into the **Plot** icon.



- **Click** on the **X variables** to activate them (the background will turn pink) and **click** on the relevant year to list it in the pink area.
- **Click** on the **Y variable** to activate it (the background will turn pink) and **click** on yield so that it is listed in the Y variable box. Note that the X variable box will be white now.
- To visualize the graph, simply **click** on the **XY** icon.



D. Summary and conclusions of this exercise

A simulation of the long-term soil organic matter dynamics under the influence of a changing climate was carried out using the RICCAR data with various types of crop rotations. The investigation was done using three scenarios: (1) Undiversified crop rotation with a single cereal-legume system, (2) undiversified crop rotation with a single cereal-cereal system and (3) a fully diversified crop rotation with various crops considered in the rotation. While in all the scenarios the soil carbon initially increased and then slowly decreased with climate change, it was undoubtedly clear that a diversified crop rotation is indeed climate-smart and can enrich the soil carbon more than in an undiversified scenario. It was clear that wheat-legume rotation enhances soil carbon more than wheat-maize. Quantitatively, towards the end of the century, diversified cropping system will lead to a SOC level of around 2.2 per cent whereas the undiversified cropping system will have an average SOC level of around 1.8 per cent . The right step to climate smartness is hence to go for a more diversified crop rotation. RICCAR-based crop modelling activities are useful for exploring such adaptation/mitigation efforts.

7. SYNTHESIS AND CONCLUSIONS OF THIS TRAINING MANUAL

This training manual aimed to comprehensively train a non-expert user on how to use long-term location-specific climate data to drive a crop simulation model in order to understand the vulnerabilities under climate change. It also used a scenario-based approach to determine context-specific climate adaptation options. Comprehensive training material was developed for three solid test cases that are unique in terms of climate vulnerabilities, agroecosystem characteristics and climate adaptation interventions. Owing to its global popularity, the APSIM crop model was chosen to identify agricultural vulnerability under climate change and to identify the efficacy of the context-specific adaptation interventions. Starting with the characteristics of the RICCAR climate data at the outset, steps on how to develop input climate datasets using RICCAR in a format that the APSIM model requires were presented. Further to this, an elaborate discourse on how to create a soil profile or how to use an existing soil profile from the library of soil profiles and modify it to suit the modelling needs was provided. Furthermore, a walk-through of the APSIM UI was provided to familiarize the novice user with the main functionalities of the APSIM UI using an existing simulation example available in the APSIM interface software installation package. Here, an overview was provided on how to start a simulation, how to change the soil and management parameterizations, how to set up the output file and how to visualize the results. Following this, the simulation of crop responses to climate change was carried out using the RICCAR climate in three distinct contexts. Both conventional crop practices and "climate adaptation" practices were used as scenarios in these three cases. A step-by-step procedure was elaborated in the training material. The findings for the three contexts can be summarised as follows:

1. In the rainfed context in Morocco, the study focused on how wheat yields could change under climate change in a rainfed scenario, taking Merchouche as an example. The modelling showed that rainfall in Morocco is significantly reducing under climate change and that this has an impact on the interannual wheat yields under the business-as-usual scenario (RCP 8.5) from 2020 onwards. Supplementary irrigation was projected to help reduce this effect dramatically from 2050 onwards. Therefore, if this climate adaptation is applied adequately, it's possible to maintain the current wheat productivity until 2080 without significant effects.
2. In the irrigated context in the lower Mesopotamian plains of Iraq, although temperature dramatically increases, modelling showed that the rainfall doesn't change substantially with climate change. This is consistent with other studies (CEOBS, 2021). As the system is irrigated, yield reduction is not critically affected if irrigated agriculture continues according to the current practices of using water from the Euphrates-Tigris river system. This, however, implies that the quantum of applied irrigated water keeps on increasing which has a toll on the water resources. This also creates secondary problems such as salinization. Thus, it is important to enhance water productivity as an apt climate adaptation intervention. Technologies such as drip irrigation should be applied in irrigated systems replacing the conventional flooding system.
3. In the irrigated Jordan valley, the mechanism of enhancing SOC was explored as a plausible pathway to climate mitigation and is also a good climate adaptation measure. Besides enhancing plant water relations and creating a conducive microclimate for plant growth, enhancing SOC has a multitude of benefits. RICCAR-based modelling studies showed that diversified crop rotation enhances SOC substantially unlike undiversified crop rotation practices. Diversified crop rotation significantly increases SOM. Relatively undiversified crop rotation with wheat-soybean was better than wheat-maize.

In the three case studies, three context-specific climate adaptations were evaluated against the conventional practices using an ex-ante analysis approach. In the rainfed scenario in Morocco, modelling showed that the scaling up of supplementary irrigation methods is a plausible and influential climate adaptation strategy that can sustain yields under a changing climate. In the case of irrigated agriculture, however, it was concluded that the scaling of techniques to enhance water productivity is the primary climate adaptation intervention in countries such as Iraq, the Sudan and Egypt where water is available through surface water resources. In Jordan, we identified that diversification of the crop rotation can facilitate enhanced SOC. These analyses were primarily conducted using yield as an indicator. However, other indicators such as soil organic matter, irrigation water applied, the impact of crop diversification, alternative crops and cultivars all could be examined further.

It should be acknowledged that the purpose of this manual is simply to train the non-expert user on how to use APSIM to test all these hypotheses to arrive at logical conclusions. We therefore encourage the user to test other scenarios more creatively. The climate adaptation measures examined here are not the only forms of climate adaptation. It is recommended that the user tests several climate-smart adaptation interventions and choose those that have the maximum benefits.

It is also suggested that applying these adaptation interventions should be done in a bundled form (not just one adaptation at a time) and that this bundled approach should be used as a context-specific package of practices while scaling out these technologies to adapt to a changing climate. In analysing the climate data and seeing the interannual yield variabilities, we stress the urgent need for context-specific climate adaptation and scaling out these packages using the enabling environments provided by the national policies. This is important to sustain the agrifood systems in these MENA countries under a changing climate. Table 8 provides a synthesis of what we learned from the three exercises and how such results could be interpreted for operational actions by the stakeholders.

This training material simply opens the doors to the novice user to explore the other immense possibilities that can be tested using the APSIM model. Thus, to gain expertise in this, it is highly recommended that the user further explores other aspects of APSIM.

TABLE 8: A synthesis of the findings made in the three test cases using RICCAR-based APSIM modelling

	Case study and context	Findings from RICCAR-based modelling	Message to scientists	Message to small-holder farmers	Message to policy makers
Climate adaptation	Morocco roi: Rabat-Salé-Kénitra - Rainfed system	Annual rainfall in Morocco significantly reduces under climate change. This pattern is expected to have a great impact on wheat yield or on rainfed agriculture in general from the year 2050 onwards to the extent that wheat yields may decline by as much as 50 per cent from the current yield value (4.2t/ha may reduce to as little as 1.3t/ha). Supplementary irrigation helps reduce this effect dramatically. If this climate adaptation measure is applied correctly, it's possible to maintain the current wheat productivity until 2080 without significant effects.	• Develop agronomic research on planning and implementing supplementary irrigation. • Identify crop-specific supplementary irrigation needs and engage in capacity building in this area. • Also, identify deficit irrigation strategies to protect a crop in the event of adverse drought conditions.	• Select short duration crop varieties that can make use of the short rainy season. • Early identification of plant water needs should be based on discussions with extension agents. • Consider the consumptive water use for various crops based on the model outputs under the business-as-usual climate scenario.	• Develop early warning systems and agroclimatic weather services to help farmers do proper planning. • Invest in research and development on drought-tolerant varieties and market mechanisms for climate risks insurance. • Adopt soil and land-use planning practices. • Promote the capacity building of farmers and extension workers in the use of early warning systems and advisories on the application of supplementary/ deficit irrigation.
Climate adaptation	Iraq roi: Lower Mesopotamian plain - Irrigated system	In the LMP study location, modelling showed that the annual rainfall in Iraq doesn't change substantially with climate change (there is a slight increase in precipitation), but temperature dramatically increases. As the agricultural system is irrigated, yield reduction may not be evident as agriculture continues with water used from the Euphrates-Tigris river system. RICCAR-based analysis showed that the quantity of irrigation water increases with climate change. This means more water will be needed to have the same levels of food production. This has a great toll on the water resources of Iraq along with the rising population and also creates secondary problems such as salinization. Thus, it is important to enhance water productivity as a climate adaptation intervention. Technologies such as drip irrigation should be applied in irrigated systems. Modelling showed that drip irrigation enhances water productivity as much as 10 times compared to the conventional irrigation methods. This is a significant gain of yield for a given amount of water applied.	• Develop cost-effective and low energy consuming drip irrigation systems running on solar power. • Research alternative irrigation systems that enhance water productivity.	• Adopt drip irrigation facilities. • Avoid over-irrigation. • Adopt agronomic interventions (such as using the ICARDA mechanized raised bed planter*) to enhance water productivity by 30 per cent .	• Create enabling environments to foster water productivity as a theme of National Action/Adaptation Plans (NAPs). • Facilitate access to financing mechanisms and loans to adopt drip irrigation facilities. • Promote capacity building on water productivity under climate change. • Transboundary water sharing needs to be planned in advance (20 years in advance) based on the projected climate scenarios optimizing it with each country's sectorial water requirements.

	Case study and context	Findings from RICCAR-based modelling	Message to scientists	Message to small-holders farmers	Message to policy makers
Climate adaptation	Jordan roi: Jordan valley - Irrigated system	Enhancing SOC offers pathways to climate mitigation. It is also a good climate adaptation measure. Besides enhancing plant water relations and creating a conducive microclimate for plant growth, enhancing SOC has a multitude of benefits. RICCAR-based modelling studies showed that diversified crop rotation enhances SOC substantially unlike undiversified crop rotation practices. In the case of undiversified crop rotation, it was found that continuous wheat-soybean is better than continuous wheat-maize. But this greatly depends on the cultivars used in the rotation and the amount of residue left in the soil after each crop. Conservation tillage is the solution if undiversified crop rotation is followed. This study also has relevance for adaptation-mitigation co-benefits. This is because enhanced SOC while fostering climate mitigation also helps the system to adapt to a changing climate by enhancing water conservation in the soil. It also favours soil nutrient conservation in the long run.	• Identify the best crop sequence for each location that optimizes SOC along with yield and farm income. • Identify a crop sequence that enhances SOC but also soil nitrogen. • Identify methods to enhance SOC in rainfed contexts and in saline soils of MENA.	• Introduce legumes and maize in the crop rotation. • Adopt conservation agriculture occasionally. • Conduct occasional soil testing for nutrients and SOC with the help of extension agents.	• Include SOC as an important factor in NAPs. • Create carbon credits and carbon finance to encourage farmers. • Reduce taxes to farmers growing diversified crops. • Adopt policies on combating agricultural land degradation.

*The mechanized raised bed is an improved surface irrigation technique from ICARDA, which offers farmers a practical and more sustainable alternative to conventional irrigation systems. The technology has transformed irrigated wheat-based producing systems across Egypt, the Sudan and beyond, achieving significantly higher crop yields of 20-30 per cent while ensuring 25 per cent savings in irrigation water and reducing farming costs by about 20 per cent . For more information on this technique, see: ICARDA, "Mechanized raised bed technology for better wheat", n.d.
For more information on carbon credits, see: BBC, "The regenerative revolution in food", 22 October 2021.

APPENDIX 1

A code written in R-language to extract climate data as a time series from the RICCAR format

```
library(ncdf4) # package for netcdf manipulation
library(raster) # package for raster manipulation
library(rgdal) # package for geospatial analysis
library(ggplot2) # package for plotting
library(RColorBrewer)

outputFile <- "E:\\ICARDA\\APSIM\\IQ_escwa_TMAX85.txt"
#year loop to go through each NETCDF file
year <-seq(from=1999, to=2100, by=1)
for(j in seq_along(year)) {

 ###############################################################
 ##              PPT  RCP 45                        ##
 ###############################################################
 #
   # ncfile1 <- file.path(paste("E:\\ICARDA\\RICCAR_data\\PPT\\RCP4.5\\CNRM\\pr_MNA-44_CNRM-CERFACS-CNRM-CM5_
historicalandrcp45_r1i1p1_SMHI-RCA4_v1-bc-dbs-wfdei_day_19510101-21001231_",year[j],"_", year[j],".nc",sep=""))  #renaming
input netcdf file with year loop
   # ncfile2 <- file.path(paste("E:\\ICARDA\\RICCAR_data\\PPT\\RCP4.5\\EC-EARTH\\pr_MNA-44_ICHEC-EC-EARTH_
historicalandrcp45_r12i1p1_SMHI-RCA4_v1-bc-dbs-wfdei_day_19510101-21001231_",year[j],"_", year[j],".nc",sep=""))  #renaming
input netcdf file with year loop
   # ncfile3 <- file.path(paste("E:\\ICARDA\\RICCAR_data\\PPT\\RCP4.5\\GFDL\\pr_MNA-44_NOAA-GFDL-GFDL-ESM2M_
historicalandrcp45_r1i1p1_SMHI-RCA4_v1-bc-dbs-wfdei_day_19510101-21001231_",year[j],"_", year[j],".nc",sep=""))  #renaming
input netcdf file with year loop
   # nc_data1 <- nc_open(ncfile1)
   # nc_data2 <- nc_open(ncfile2)
   # nc_data3 <- nc_open(ncfile3)
   # lon <- ncvar_get(nc_data1, "lon")
   # lat <- ncvar_get(nc_data1, "lat", verbose = F)
   # if (year[j] %% 4== 0) dn=366 else dn=365
   # day=(1:dn)
   # pr.array1 <- ncvar_get(nc_data1, "pr")
   # pr.array2 <- ncvar_get(nc_data2, "pr")
   # pr.array3 <- ncvar_get(nc_data3, "pr")

 ###############################################################
 ##              PPT  RCP 85                        ##
 ###############################################################
 #
  # ncfile1 <- file.path(paste("E:\\ICARDA\\RICCAR_data\\PPT\\RCP8.5\\CNRM\\pr_MNA-44_CNRM-CERFACS-CNRM-CM5_
historicalandrcp85_r1i1p1_SMHI-RCA4_v1-bc-dbs-wfdei_day_19510101-21001231_",year[j],"_", year[j],".nc",sep=""))  #renaming
input netcdf file with year loop
  # ncfile2 <- file.path(paste("E:\\ICARDA\\RICCAR_data\\PPT\\RCP8.5\\EC-EARTH\\pr_MNA-44_ICHEC-EC-EARTH_
historicalandrcp85_r12i1p1_SMHI-RCA4_v1-bc-dbs-wfdei_day_19510101-21001231_",year[j],"_", year[j],".nc",sep=""))  #renaming
input netcdf file with year loop
  # ncfile3 <- file.path(paste("E:\\ICARDA\\RICCAR_data\\PPT\\RCP8.5\\GFDL\\pr_MNA-44_NOAA-GFDL-GFDL-ESM2M_
historicalandrcp85_r1i1p1_SMHI-RCA4_v1-bc-dbs-wfdei_day_19510101-21001231_",year[j],"_", year[j],".nc",sep=""))  #renaming
input netcdf file with year loop
  # nc_data1 <- nc_open(ncfile1)
  # nc_data2 <- nc_open(ncfile2)
  # nc_data3 <- nc_open(ncfile3)
  # lon <- ncvar_get(nc_data1, "lon")
  # lat <- ncvar_get(nc_data1, "lat", verbose = F)
  # if (year[j] %% 4== 0) dn=366 else dn=365
```

```
 # day=(1:dn)
 # pr.array1 <- ncvar_get(nc_data1, "pr")
 # pr.array2 <- ncvar_get(nc_data2, "pr")
 # pr.array3 <- ncvar_get(nc_data3, "pr")

 ###################################################################
 ##                    TASMIN  RCP 45                    ##
 ###################################################################
 #
 # ncfile1 <- file.path(paste("E:\\ICARDA\\RICCAR_data\\TMIN\\RCP4.5\\CNRM\\tasmin_MNA-44_CNRM-CERFACS-CNRM-CM5_
historicalandrcp45_r1i1p1_SMHI-RCA4_v1-bc-dbs-wfdei_day_19510101-21001231_",year[j],"_", year[j],".nc",sep=""))  #renaming
input netcdf file with year loop
 # ncfile2 <- file.path(paste("E:\\ICARDA\\RICCAR_data\\TMIN\\RCP4.5\\EC-EARTH\\tasmin_MNA-44_ICHEC-EC-EARTH_
historicalandrcp45_r12i1p1_SMHI-RCA4_v1-bc-dbs-wfdei_day_19510101-21001231_",year[j],"_", year[j],".nc",sep=""))  #renaming
input netcdf file with year loop
 # ncfile3 <- file.path(paste("E:\\ICARDA\\RICCAR_data\\TMIN\\RCP4.5\\GFDL\\tasmin_MNA-44_NOAA-GFDL-GFDL-ESM2M_
historicalandrcp45_r1i1p1_SMHI-RCA4_v1-bc-dbs-wfdei_day_19510101-21001231_",year[j],"_", year[j],".nc",sep=""))  #renaming
input netcdf file with year loop
 # nc_data1 <- nc_open(ncfile1)
 # nc_data2 <- nc_open(ncfile2)
 # nc_data3 <- nc_open(ncfile3)
 # lon <- ncvar_get(nc_data1, "lon")
 # lat <- ncvar_get(nc_data1, "lat", verbose = F)
 # if (year[j] %% 4== 0) dn=366 else dn=365
 # day=(1:dn)
 # pr.array1 <- ncvar_get(nc_data1, "tasmin")
 # pr.array2 <- ncvar_get(nc_data2, "tasmin")
 # pr.array3 <- ncvar_get(nc_data3, "tasmin")
 # #

 ###################################################################
 ##                    TASMIN  RCP 85                    ##
 ###################################################################
 #
 # ncfile1 <- file.path(paste("E:\\ICARDA\\RICCAR_data\\TMIN\\RCP8.5\\CNRM\\tasmin_MNA-44_CNRM-CERFACS-CNRM-CM5_
historicalandrcp85_r1i1p1_SMHI-RCA4_v1-bc-dbs-wfdei_day_19510101-21001231_",year[j],"_", year[j],".nc",sep=""))  #renaming
input netcdf file with year loop
 # ncfile2 <- file.path(paste("E:\\ICARDA\\RICCAR_data\\TMIN\\RCP8.5\\EC-EARTH\\tasmin_MNA-44_ICHEC-EC-EARTH_
historicalandrcp85_r12i1p1_SMHI-RCA4_v1-bc-dbs-wfdei_day_19510101-21001231_",year[j],"_", year[j],".nc",sep=""))  #renaming
input netcdf file with year loop
 # ncfile3 <- file.path(paste("E:\\ICARDA\\RICCAR_data\\TMIN\\RCP8.5\\GFDL\\tasmin_MNA-44_NOAA-GFDL-GFDL-ESM2M_
historicalandrcp85_r1i1p1_SMHI-RCA4_v1-bc-dbs-wfdei_day_19510101-21001231_",year[j],"_", year[j],".nc",sep=""))  #renaming
input netcdf file with year loop
 # nc_data1 <- nc_open(ncfile1)
 # nc_data2 <- nc_open(ncfile2)
 # nc_data3 <- nc_open(ncfile3)
 # lon <- ncvar_get(nc_data1, "lon")
 # lat <- ncvar_get(nc_data1, "lat", verbose = F)
 # if (year[j] %% 4== 0) dn=366 else dn=365
 # day=(1:dn)
 # pr.array1 <- ncvar_get(nc_data1, "tasmin")
 # pr.array2 <- ncvar_get(nc_data2, "tasmin")
 # pr.array3 <- ncvar_get(nc_data3, "tasmin")

 ###################################################################
 ##                    TASMAX  RCP 45                    ##
 ###################################################################

 #
```

```
  # ncfile1 <- file.path(paste("E:\\ICARDA\\RICCAR_data\\TMAX\\RCP4.5\\CNRM\\tasmax_MNA-44_CNRM-CERFACS-CNRM-CM5_historicalandrcp45_r1i1p1_SMHI-RCA4_v1-bc-dbs-wfdei_day_19510101-21001231_",year[j],"_", year[j],".nc",sep=""))
#renaming input netcdf file with year loop
  # ncfile2 <- file.path(paste("E:\\ICARDA\\RICCAR_data\\TMAX\\RCP4.5\\EC-EARTH\\tasmax_MNA-44_ICHEC-EC-EARTH_historicalandrcp45_r12i1p1_SMHI-RCA4_v1-bc-dbs-wfdei_day_19510101-21001231_",year[j],"_", year[j],".nc",sep=""))  #renaming input netcdf file with year loop
  # ncfile3 <- file.path(paste("E:\\ICARDA\\RICCAR_data\\TMAX\\RCP4.5\\GFDL\\tasmax_MNA-44_NOAA-GFDL-GFDL-ESM2M_historicalandrcp45_r1i1p1_SMHI-RCA4_v1-bc-dbs-wfdei_day_19510101-21001231_",year[j],"_", year[j],".nc",sep=""))  #renaming input netcdf file with year loop
  # nc_data1 <- nc_open(ncfile1)
  # nc_data2 <- nc_open(ncfile2)
  # nc_data3 <- nc_open(ncfile3)
  # lon <- ncvar_get(nc_data1, "lon")
  # lat <- ncvar_get(nc_data1, "lat", verbose = F)
  # if (year[j] %% 4== 0) dn=366 else dn=365
  # day=(1:dn)
  # pr.array1 <- ncvar_get(nc_data1, "tasmax")
  # pr.array2 <- ncvar_get(nc_data2, "tasmax")
  # pr.array3 <- ncvar_get(nc_data3, "tasmax")

  ###################################################################
  ##                    TASMAX  RCP 85                    ##
  ###################################################################
  #
  ncfile1 <- file.path(paste("E:\\ICARDA\\RICCAR_data\\TMAX\\RCP8.5\\CNRM\\tasmax_MNA-44_CNRM-CERFACS-CNRM-CM5_historicalandrcp85_r1i1p1_SMHI-RCA4_v1-bc-dbs-wfdei_day_19510101-21001231_",year[j],"_", year[j],".nc",sep=""))  #renaming input netcdf file with year loop
  ncfile2 <- file.path(paste("E:\\ICARDA\\RICCAR_data\\TMAX\\RCP8.5\\EC-EARTH\\tasmax_MNA-44_ICHEC-EC-EARTH_historicalandrcp85_r12i1p1_SMHI-RCA4_v1-bc-dbs-wfdei_day_19510101-21001231_",year[j],"_", year[j],".nc",sep=""))  #renaming input netcdf file with year loop
  ncfile3 <- file.path(paste("E:\\ICARDA\\RICCAR_data\\TMAX\\RCP8.5\\GFDL\\tasmax_MNA-44_NOAA-GFDL-GFDL-ESM2M_historicalandrcp85_r1i1p1_SMHI-RCA4_v1-bc-dbs-wfdei_day_19510101-21001231_",year[j],"_", year[j],".nc",sep=""))  #renaming input netcdf file with year loop
  nc_data1 <- nc_open(ncfile1)
  nc_data2 <- nc_open(ncfile2)
  nc_data3 <- nc_open(ncfile3)
  lon <- ncvar_get(nc_data1, "lon")
  lat <- ncvar_get(nc_data1, "lat", verbose = F)
  if (year[j] %% 4== 0) dn=366 else dn=365
  day=(1:dn)
  pr.array1 <- ncvar_get(nc_data1, "tasmax")
  pr.array2 <- ncvar_get(nc_data2, "tasmax")
  pr.array3 <- ncvar_get(nc_data3, "tasmax")

  ###################################################################
  ##                TAS 45                              ##
  ###################################################################
  #
  #   ncfile1 <- file.path(paste("E:\\ICARDA\\RICCAR_data\\TAS\\RCP4.5\\CNRM\\tas_MNA-44_CNRM-CERFACS-CNRM-CM5_historicalandrcp45_r1i1p1_SMHI-RCA4_v1-bc-dbs-wfdei_day_19510101-21001231_",year[j],"_", year[j],".nc",sep=""))  #renaming input netcdf file with year loop
  #   ncfile2 <- file.path(paste("E:\\ICARDA\\RICCAR_data\\TAS\\RCP4.5\\EC-EARTH\\tas_MNA-44_ICHEC-EC-EARTH_historicalandrcp45_r12i1p1_SMHI-RCA4_v1-bc-dbs-wfdei_day_19510101-21001231_",year[j],"_", year[j],".nc",sep=""))  #renaming input netcdf file with year loop
  #   ncfile3 <- file.path(paste("E:\\ICARDA\\RICCAR_data\\TAS\\RCP4.5\\GFDL\\tas_MNA-44_NOAA-GFDL-GFDL-ESM2M_historicalandrcp45_r1i1p1_SMHI-RCA4_v1-bc-dbs-wfdei_day_19510101-21001231_",year[j],"_", year[j],".nc",sep=""))  #renaming input netcdf file with year loop
  #   nc_data1 <- nc_open(ncfile1)
  #   nc_data2 <- nc_open(ncfile2)
```

```
#   nc_data3 <- nc_open(ncfile3)
#   lon <- ncvar_get(nc_data1, "lon")
#   lat <- ncvar_get(nc_data1, "lat", verbose = F)
#   if (year[j] %% 4== 0) dn=366 else dn=365
#   day=(1:dn)
#   pr.array1 <- ncvar_get(nc_data1, "tas")
#   pr.array2 <- ncvar_get(nc_data2, "tas")
#   pr.array3 <- ncvar_get(nc_data3, "tas")
#   outputfilepath_mn <- "E:\\ICARDA\\RICCAR_processing\\IRAQ\\0.43\\TAS45\\TAS_RCP45_AVG_"
#   outputfilepath_sd <- "E:\\ICARDA\\RICCAR_processing\\IRAQ\\0.43\\TAS45\\TAS_RCP45_SD_"

##################################################################
##                TAS 85                                ##
##################################################################
#
# ncfile1 <- file.path(paste("E:\\ICARDA\\RICCAR_data\\TAS\\RCP8.5\\CNRM\\tas_MNA-44_CNRM-CERFACS-CNRM-CM5_
historicalandrcp85_r1i1p1_SMHI-RCA4_v1-bc-dbs-wfdei_day_19510101-21001231_",year[j],"_", year[j],".nc",sep=""))  #renaming
input netcdf file with year loop
# ncfile2 <- file.path(paste("E:\\ICARDA\\RICCAR_data\\TAS\\RCP8.5\\EC-EARTH\\tas_MNA-44_ICHEC-EC-EARTH_
historicalandrcp85_r12i1p1_SMHI-RCA4_v1-bc-dbs-wfdei_day_19510101-21001231_",year[j],"_", year[j],".nc",sep=""))  #renaming
input netcdf file with year loop
# ncfile3 <- file.path(paste("E:\\ICARDA\\RICCAR_data\\TAS\\RCP8.5\\GFDL\\tas_MNA-44_NOAA-GFDL-GFDL-ESM2M_
historicalandrcp85_r1i1p1_SMHI-RCA4_v1-bc-dbs-wfdei_day_19510101-21001231_",year[j],"_", year[j],".nc",sep=""))  #renaming
input netcdf file with year loop
# nc_data1 <- nc_open(ncfile1)
# nc_data2 <- nc_open(ncfile2)
# nc_data3 <- nc_open(ncfile3)
# lon <- ncvar_get(nc_data1, "lon")
# lat <- ncvar_get(nc_data1, "lat", verbose = F)
# if (year[j] %% 4== 0) dn=366 else dn=365
# day=(1:dn)   #day loop within a single netcdf file
# pr.array1 <- ncvar_get(nc_data1, "tas")
# pr.array2 <- ncvar_get(nc_data2, "tas")
# pr.array3 <- ncvar_get(nc_data3, "tas")
# outputfilepath_mn <- "E:\\ICARDA\\IRAQ-ETBasin\\TAS85\\TAS_RCP45_AVG_"
# outputfilepath_sd <- "E:\\ICARDA\\RICCAR_processing\\IRAQ\\0.43\\TAS85\\TAS_RCP85_SD_"

##^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^

  for(i in seq_along(day)) {
  pr.slice1 <- pr.array1[, , i]
  pr.slice2 <- pr.array2[, , i]
  pr.slice3 <- pr.array3[, , i]

    conne1 <- file.path(paste(outputfilepath_mn,year[j], "_", day[i],".bin",sep=""))
  conne2 <- file.path(paste(outputfilepath_sd, year[j], "_", day[i],".bin",sep=""))

    r1 <- raster(t(pr.slice1), xmn=min(lon), xmx=max(lon), ymn=min(lat), ymx=max(lat), crs=CRS("+proj=longlat +ellps=WGS84
+datum=WGS84 +no_defs+ towgs84=0,0,0"))
  r2 <- raster(t(pr.slice2), xmn=min(lon), xmx=max(lon), ymn=min(lat), ymx=max(lat), crs=CRS("+proj=longlat +ellps=WGS84
+datum=WGS84 +no_defs+ towgs84=0,0,0"))
  r3 <- raster(t(pr.slice3), xmn=min(lon), xmx=max(lon), ymn=min(lat), ymx=max(lat), crs=CRS("+proj=longlat +ellps=WGS84
+datum=WGS84 +no_defs+ towgs84=0,0,0"))


  r1 <- flip(r1, direction='y')
  r2 <- flip(r2, direction='y')
  r3 <- flip(r3, direction='y')
```

```
    meanxx <- (r1+r2+r3)/3

    # For REGIONAL AOI DEFINITION
  ss <- extent(42.441635608457545,45.86715593581527,32.37278315907344,35.165326904202024)
 # writeRaster(meanxx, filename =conne1, datatype='FLT4S', format="raster",overwrite=TRUE)
  roundDigits <- 3

  # For LOCAL pixel extraction
 #alpha <- extract(meanxx, SpatialPoints(cbind(45.398, 31.593)))

 # For REGIONAL AOI extraction
  alpha <- mean(extract(meanxx, ss))
# alpha <- extract(meanxx, ss, fun = mean, na.rm = TRUE)

  write.table(alpha, outputFile, append=TRUE, row.names=FALSE,col.names=FALSE )

  }

  nc_close(nc_data1)
  nc_close(nc_data2)
  nc_close(nc_data3)

}
```

APPENDIX 2

Calculation of surface radiation using basic climate data

When no estimates of solar radiation are available to run the simulations, the only possibility is to model the solar radiation, as it is an essential input to run most of the crop simulation or hydrological models. The basic idea is to first simulate the extraterrestrial radiation above the atmosphere assuming that the sunspot cycles are not affecting the solar irradiance. The extraterrestrial radiation (Ra) for each day of the year and for different latitudes can be estimated from the solar constant, the solar declination and the time of the year, using the following formula:

$$R_a = \frac{24*60}{\pi} G_{sc} . d_r . \left[\omega . Sin(\varphi) . Sin(\delta) + Cos(\varphi) . Cos(\delta) . Sin(\omega)\right]$$

Ra extraterrestrial radiation (MJ m-2 day-1).
Gsc solar constant = 0.0820 (MJ m-2 min-1).
dr inverse relative distance Earth-Sun.

ω sunset hour angle (rad).
φ latitude (rad).
δ solar declination (rad).
J Julien day of the year.

The inverse relative Earth-Sun distance (dr) can be calculated as a function of the day of the year (J) as:

$$d_r = 1 + 0.033 . \ Cos \left[\frac{2\pi}{365} J\right]$$

The Solar declination angle (δ) can be calculated as a function of day of the year (J) as:

$$\delta = 0.409 . \ Sin \left[\frac{2\pi}{365} J - 1.39\right]$$

The sunset hour angle (ω) can be approximated as a function of declination angle and latitude of the location as:

$$\omega = \frac{\pi}{2} - Arctan \left[\frac{-Tan(\varphi) . Tan(\delta)}{\sqrt{\left[1 - [Tan(\varphi)]^2 [Tan(\varphi)]^2\right]}}\right]$$

All the angles are expressed in Radians (rad) and can be calculated in degrees as:

$$Radians = \frac{\pi}{180} Degrees$$

After calculating the extraterrestrial radiation, we calculate the surface incoming radiation following the method of Hargreaves and Samani (1982):

$$R_s = \left(k_{Rs} \left[T_{max} - \ T_{min}\right]^{0.5}\right) . R_a$$

APPENDIX 3

A code to generate the required instructions for modifying the APSIM Rotation Manager

This code may be compiled in any C compiler to generate a text file that contains the necessary code that can be replaced in the yellow highlighted area in the Rotation manager of chapter 5.

```
#include "stdio.h"
#include "stdlib.h"
main()
{
FILE *fout;
fout=fopen("E:\\ Rotation_Looper.txt","wt");
int year;
for(year=1; year<=200;year++) //year loop
{
fprintf(fout,"elseif (NextCropIndex =%d ) then\n", year);
fprintf(fout,"NextCrop = '[crop%d]'\n", year);
}
fclose(fout);
}
```

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ENDNOTES

1. For more information about RICCAR, see: United Nations Economic and Social Commission for Western Asia (ESCWA) et al. 2017. Arab Climate Change Assessment Report – Main Report. Beirut, E/ESCWA/SDPD/2017/RICCAR/Report.

2. For more details, see: Tomaszkiewicz, Marlene (2021). RICCAR Climate Modelling Updates: Mashreq Domain. ArabCOF – June 2021.

3. In computing, endianness is the order or sequence of bytes of a word of digital data in computer memory. Endianness is primarily expressed as big-endian (BE) or little-endian (LE). A big-endian system stores the most significant byte of a word at the smallest memory address and the least significant byte at the largest. A little-endian system, in contrast, stores the least-significant byte at the smallest address.

4. Supplementary irrigation is a simple but highly effective technology that allows farmers to plant and manage crops at the optimal time without having to wait for unpredictable rainfall.

Although several downscaled and bias-corrected climate datasets are available, their operational use is too challenging for non-expert users. To make the data meaningful, it must be used as inputs into crop models to identify and analyse context-specific climate-smart agriculture (CSA) solutions. This often presents technical challenges for the users. To overcome user challenges, and to support increased utilization of the data, a training manual on the use of the Regional Initiative for the Assessment of Climate Change Impacts on Water Resources and Socio-Economic Vulnerability in the Arab Region (RICCAR) data in a common crop simulation model is presented.

The main objective of the present training manual is to develop step-by-step instructional materials for agriculture extension agents on how to integrate and utilize long-term climate data in a typical and commonly used crop model such as the Agricultural Production Systems Simulator (APSIM) and identify a Context-Based Climate Adaptation Option (CBCAO), in three unique circumstances. Firstly, taking Morocco as an example, the manual demonstrates yield gap evolution under climate change in a rainfed agroecosystem and the relative effects of two Intergovernmental Panel on Climate Change (IPCC) scenarios,representative concentration pathways (RCPs) 8.5 and 4.5. Additionally, supplementary irrigation is applied as a key climate adaptation measure in a location suffering from increasing droughts to augment water supply in arid weather conditions. Secondly, taking Iraq as an example, the manual demonstrates changes in water productivity and yield dynamics in an arid but irrigated agroecosystem to show how judicious irrigation techniques, as opposed to conventional irrigation as a climate adaptation measure, can enhance water productivity while also maintaining and possibly maximizing yield. Thirdly, taking Jordan as an example of a semi-arid agroecosystem, the manual demonstrates crop diversification and defines optimum cropping patterns (selection of alternate resilient crops) as a key climate adaptation measure and assesses impacts on soil carbon sequestration.

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