WaPOR-Translator
Manual

Bringing WaPOR to a higher level

Ministry of Foreign Affairs of the Netherlands

Contents

1. Introduction

1.1 Background

Application of the Internet of Things (IoT) in agriculture is a possible game changer for food production and water savings. Currently, we witness how extreme weather, deteriorating soils and drying lands adversely impact crop production and rural development. Smart agriculture, digital agriculture and precision agriculture provide a new impetus to the sector, but only a limited group of growers has found access to this data and is implementing them. Nevertheless, in situ sensors (e.g. radiation, humidity, temperature, soil moisture) such as being advocated by Tahmo (tahmo.org) and remote sensors (satellites) do offer new ways to better understand the agribusiness.

The challenge is to bring this information into an integrated manner to farmers that need to make both (i) strategic and once-per-season decisions such as crop selection, soil treatment and cultivation practices, as well as (ii) daily decisions on irrigation, crop protection and fertilizer applications. Not only farmers require this information, also traders, insurance companies suppliers and agricultural credit providers need access to data for decision making, as well as Governments that can create positive business environments with incentives to stimulate certain developments (e.g.; subsidizing energy, stimulate conversion to drip irrigation, provision of fungi warnings, combatting land degradation etc.). In all semi-arid and arid countries, water conservation is a must for making cropping a sustainable business.

To better estimate agricultural change process and save simultaneously water resources in developing countries, the Food and Agricultural Organization of the United Nations (FAO) has with financial support from the Government of The Netherlands launched a data base platform focusing on food security and agricultural water management for Africa and Near East in June 2019. This data base is referred to as Water Productivity Open access Portal (WaPOR) and can be found at https://wapor.apps.fao.org/home/WAPOR_2/1. The main aim of WaPOR is to provide developing countries with a sensing system for crop water productivity i.e. the crop production per unit of water and foster in this manner the implementation of UN policies to pedal out hunger and save water in the agricultural sector. Crop water productivity is an expression for efficient use of natural resources. Sustainable Development Goal (SDG) 6.4 deals with increasing water use efficiency and many countries in Africa and Asia have a challenge on how to report on their current SDG 6.4 status. They all want to make the right choices to bring water productivity to a higher level, but how to achieve this if there is no measurement system in place ? While UN and other international organizations expect that increasing water productivity is the solution to combat the global water crisis, this is not going to happen if the stakeholders from the agri-sector have no access to essential basic information on crop growth, current consumptive use levels, weather conditions, the soil water balance and soil fertility – to mention a few.

WaPOR contains a number of standard spatial data layers based on 10 years of satellite data that are elementary to acquire fundamental insights in agricultural water management change processes. With a standard resolution of 250 m, and for all the countries receiving aid from the Directorate of International Cooperation (DGIS) of the Kingdom of The Netherlands having a spatial resolution of 100 m, this is an unprecedented level of detailed information for the African continent and the Near East. In addition, the time interval is 10 days only. Hence, there is data at hand lapsing from 1 January 2009 to current (i.e. December 2019) that comprises 11 annual growing with discrete time intervals of 36 decades for every year. Such data is valuable to study problems such as famine, droughts, land degradation, water over-exploitation and the remedial actions required to stop these trends. But also to survey land areas that appeared resistant to external factors and have been able to produce more food. The power of spatial data is that successful areas can be spotted, so remote sensing is not only for useful for early warning of disasters; It can also help to survey and monitor bright spots with successful investments of Governments and farmers, and sometimes together as Public-Private-Partnerships.

WaPOR is meant to provide elementary information on crop production and water consumption. It is the current suburb database for agricultural water management practices, both for small holders and commercial farms. Governments, UN organizations, NGO's, commodity traders, packers, exporters, consultants, processing plants, insurance companies, manufacturers and agricultural credit banks get a chance to improve their services and become more effective and efficient. On paper, they can utilize WaPOR for their own specific field of application. According to formal project documents, WaPOR is intended to produce "An action framework to provide relevant and specific information on water and biomass status for stakeholders at different scales - from the policy level to the farm level - to develop workable solutions to sustainably increase agricultural land and water productivity". Thus WaPOR is by design dedicated to facilitate all these stakeholders. There are however additional efforts required to make this happen.

After the WAPOR database is posted on line in June 2019 (the beta version was released from 2017 onwards), it appeared that the data sets are partially understood by the academic community and to a lesser extent by the other potential users. In the period of big data, chances are dynamic, and many of the stakeholders from the agricultural sector do not keep the pace on following these data changes. The WaPOR data base has created interests in the remote sensing community with scientists working in that sector for a longer period. It appears that only a few grasp the power of the data. To enhance the uptake of the database, it is believed that the data components should be re-processed such as the creation of accumulated values for a growing season. Or a trend across the last 10 years. The amendment of WaPOR data with extra data on soil, topography and climatology creates also many more opportunities. Processed data makes the uptake of WaPOR data easier as it provides more direct data components of interests of a larger society.

MetaMeta Research has therefore created a piece of software that translates the basic data sets found on the WaPOR website into data components that are more appealing for a larger society. This tool is referred to as the WaPOR-Translator, or shortly Translator. The synergy with a dictionary was made as this new tool converts basic data that are not fully understood (analogy to a foreign language) into information that is easier to digest by a larger audience (analogy to a native language), see Figure 1. The Translator includes other open-access data sets and establishes combinations with the default WaPOR data. The result is that the number of data components increase from say 15 to approximately 60, and that the nature of the data is becoming more appealing and easier to adopt for various applications.

(၁၉-၆-၂၀၁၉) ရက်နေ့မှ (၃၀-၆-၂၀၁၉) ရက်နေ့အထိ မြန်မာနိုင်ငံသို့ လာရောက်မည်ဖြစ်ပါသဖြင့်. မန္တလေးအပြည်ပြည်ဆိုင်ရာလေဆိပ်မှ ဆိုက်ရောက်ဗီဇာ (On Arrival Visa) ရရှိရေးကို စီစဉ်ဆောင်ရွက်ပေးနိုင်ပါရန် ရည်ညွှန်းပါစာဖြင့် ရန်ကုန်မြို့ရှိ FAO ဌာနေကိုယ်စားလှယ်ရုံးမှ မေတ္တာရပ်ခံလာပါသည်။ ၂။ အဆိုပါပုဂ္ဂိုလ်သည် ဆည်မြောင်းနှင့်ရေအသုံးချမှုစီမံခန့်ခွဲရေးဦးစီးဌာန နှင့် FAO တို့ ပူးပေါင်းဆောင်ရွက်နေသည့် "Water accounting and auditing training" အတွက် သင်တန်းပို့ချရန် သင်တန်းနည်းပြအဖြစ် ဆောင်ရွက်ရန်အတွက် မြန်မာနိုင်ငံသို့ လာရောက်ခြင်းဖြစ်ပါသည်။	*We will provide you with an on arrival visa so that you can enter our country and represent FAO upon the training regarding water accounting and auditing for a better appreciation of the renewable water resources and how we should make this analysis in a matter that assists our policy makers*

Figure 1: Example of two sources of information (in this case languages) with different adoption levels that will have impact on understanding and utilization

This report is a manual of the Translator and explains which types of additional data components are generated by the Translator. The physical-mathematical background is provided, including references to some essential handbooks or publications. Several hints and suggestions of applications are provided, albeit this document should not be considered as a handbook for WaPOR applications.

The Translator produces different data levels (see also Figure 2) in full synergy with earth observation data products provided by the international space agencies:

- Level 1 automatically reads and collects the original data available from various open access websites (WaPOR and other open-access data bases)

- Level 2 reveals a number of intermediate bio-physical, soil-physical and atmospheric parameters that are of interest for advanced users, and are needed for the generation of Level 3 data
- Level 3 encloses data layers for different fields of application, such as food security, water productivity, irrigation management and climate smart agriculture. More fields of applications can be added later

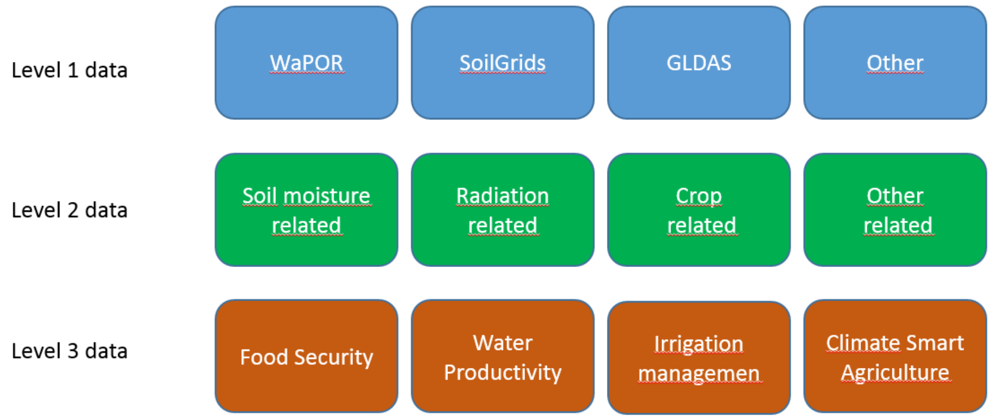


Figure 2: Flow chart of WaPOR Translator schematization

The primary goal of WaPOR is to help users on their water productivity management decision making process. The Governmental users can be working at the Ministries of Agriculture, but also at the Ministries or Departments of Irrigation, Water Resources or Natural Resources, depending on the organization per country and other administrative boundaries. The Government of The Netherlands has introduced a formal policy to increase Water Productivity (WP) by 25% in their aid projects. This policy is also applicable to their trust funds of the World Bank and Asian Development Bank. For answering questions on trends of WP with time, it is deemed to have an analytical tool at hand. The Translator helps the processing of dedicated data that supports swift WP analysis, like what are the variations across a watershed and is WP increasing in time or not. How long does it take before 25% increase is achieved ? Is the WP change related to weather (i.e. naturally) or because of intended interventions (i.e. anthropologically) ?

Any trend in WP has to be related to a trend of biomass production in the numerator and a trend of consumptive use (i.e. ET) in the denominator. So these dynamics during and between cropping seasons need to be reviewed, and software should be available to facilitate this analysis for the millions of pixels present in the WaPOR database. So the first step is to isolate all the pixels with agricultural land use. For increasing WP, it is imperative to understand the causing factors for changes in biomass production and crop ET. This requires additional analysis of rainfall, soil moisture, LAI development, length of cropping season, soil organic matter, slope of the cropped land and many more parameters. The manual downloading of all these data layers and performing spatial analysis in a GIS environment is very laborsome, and will discourage potential WaPOR users to go through these lengthy and tedious procedures. The Translator assists in a vivid and standardized data analysis. It is a stimulus for potential users to start exploring the power of WaPOR.

One bottleneck is the lack of crop type information on WaPOR. While the Translator will distinguish different cropping seasons, it does not have the capacity to assess the type of crop. Instead, it is possible to upload existing crop maps that have been created by the user or a GIS consultant. The advantage is that crop yield can be computed (otherwise it is accumulated biomass production for a given season being the basis for crop yield assessments). Crop type information is also greatly welcome for protections against fungi, insects and typical diseases.

The objective of the Translator is thus to generate a number of additional data layers that adds value to the existing basic data products (level 1) and facilitates quick analysis of trends across a country (or during the last 11 years) and some of the underlying reasons of these trends. The Translator helps Governments on making longer term policies of food production. Also to identify regions that require more technical assistance than other regions due to for instance a larger vulnerability to droughts, extreme low efficiency of natural resource etc. NGO's, Small and Medium Enterprises and consultants might have specific interests in helping farmers in achieving "more crop per drop" or to advise Irrigation Departments on canal management operations on weekly crop water requirements. Banks can use WaPOR data for ranking the priority of irrigation rehabilitation projects. Commodity traders can benefit from standardized decadal crop production information for the entire African continent. Insurance companies can assess independently the production gap due to weather anomalies. While these are all logical and good examples, it requires additional efforts to present the enhanced datasets into some key graphs and indicators. The Translator is not preparing standardized tables and monitoring reports. In fact that is the next step where the sector themselves should have a much stronger role. But the Translator will create appealing data sets and images that should be sufficient to trigger Governments, private sector and NGO's.

1.2 Python code

A python code has been created that reads the WaPOR and auxiliary geographical open-access data in an automated manner. This code is publicly available at the international standard repository for software development GitHub (https://github.com/TimHessels). Two codes are required for the execution of WaPOR:

- WaPOR API
- WaPOR Translator

The folder WaPOR API provides a python code that automatically downloads a larger set of data from the FAO WaPOR server. This is very important if for instance crop production and water productivity analysis need to be done in time steps of 10 days, but across a long period (e.g. 11 years). Especially for multiple years, manual downloading becomes a tedious activity. WaPOR API facilitates an automated downloading process of the Level 1 data. It is possible to define the number of years that the user wants to download. For the computation of historic soil moisture measurements, however, it is required to include the year 2018 in the data set (this is a special case where data from 2018 is used to assess the net radiation for the period prior to 2018). The earliest year for which WaPOR data is available is 2009.

The Translator tool is made on a 64-bits Windows 10 computer using Python 3.7. Your computer should have enough RAM (minimum of 16 Gb working memory) for the processing of larger areas. For smaller areas, it is sufficient to work with a 8 Gb RAM working memory. A stable broad band internet connection is required. A minimum internet of 80 mb/sec is preferred in order to keep the downloading time reasonable. The data collection part with the WaPOR API can take one hour up to two days depending on the internet speed. It is evident that the size of the area has also a great impact on the downloading. For an area of 100 km x 100 km (i.e. 1,000,000 pixels), one year of data lasts approximately 30 minutes of downloading using an internet connection with 80 mb/second. The execution of WaPOR Translator takes not more than 10 to 30 minutes. Hence, the collection of Level-1 data is by far the most time consuming. Experiences have learned that the downloading is mainly limited by the surface albedo from MODIS and the 3 hourly GLDAS climatic data. Large MODIS tiles need to be downloaded first before the area of interest can be clipped. The collection of GLDAS climate data is a tedious process because the basic climate data is available 3 hourly. The Translator has now an option to select monthly climate data, and replaces the true surface albedo by a look-up table. This reduces the download time by more than a factor 300.

The folder WaPOR Translator on the Github account contains the latest version of the Python code to process the Level 2 and Level 3 data. The code is updated regularly as to accommodate suggestions and user experiences. The date of uploading can be reviewed. There is also a Manual with the description on how to install the Python freeware on your computer (https://github.com/TimHessels/WaporTranslator#chapter8). The downloading of Python software including all the modules required to operate the WaPOR Translator are specified and described.

There a number of Translator model variables that are user specific and need to be defined a priori. These variable are for instance related to the number of years to be analyzed. Or the type of crop in case of monocrops or a crop layer prepared as part of an ongoing project. The WaPOR Translator creates crop yield maps if the user provide existing crop maps and defines the harvest index and soil moisture content of the harvestable product in the .json file. It is possible to define the type of crop for each of the 3 seasons discerned, or what the type of perennial crop is, in case the latter is applicable. If they are not provided and uploaded, crop yield will not be computed.

Other information to be defined is the duration or number of decades that a certain pixel should be recognized as irrigated before it is being flagged as “irrigated crop” for the entire growing season (a season has rainfed and irrigated crops; no hydbrid of this classification). More of these variables are specified in Table 1. The user should inspect these variables and modify if so required. The model setting has to be specified in a .JSON file. A JSON file is a file that stores simple data structures and objects in JavaScript Object Notation (JSON) format, which is a standard data interchange format. It is primarily used for transmitting data between a web application and a server. JSON files are lightweight, text-based, human-readable, and can be edited using a simple NotePad editor. This file is meant for specifying all variables and organize all choices. Users of the Translator should not edit the Python script.

While python is not user-friendly, it is extremely powerful in the determination of complex raster-based operations. Because of its freeware status and the requirement for strong analytical software that can deal fast with the numerous mathematical operators, Python is currently the best possible software package to process WaPOR related data.

Table 1: Specification of model variables for the WaPOR Translator in the .JSON file that is called upon by the main Python code

Model variable	Purpose	Range
Period of analysis	Defining start and end of period of interests	1 to 9 years
Surface albedo	Download large and time consuming MODIS files or use a look-up table that does not require any downloading efforts	MODIS or TABLE
Solar radiation	Decision on downloading MSG-based solar radiation data from KNMI (ClimateSAF) or Meteo Portugal (LandSAF)	KNMI or LANDSAF
Meteorological data	Choice between daily values (derived from 3 hourly time steps) and monthly values	Daily or monthly
Champion percentage	Target percentile for detecting the group of champion farmers	80 to 99.5 %
Phenology Threshold	No. of consecutive decades with incremental Transpiration fluxes	3 to 15
Phenology Slope	Minimum value of the maximum positive slope (mm/d)	1 to 7
Crop type	Relating type of crops to be provided by separated raster or shape files to harvest index and moisture content. For every type of season it is feasible to ascribe a certain type of crop	Harvest index and moisture of fresh product for each type of crop

Irrigation decades threshold	Classifying a pixel as being rainfed or irrigated on the basis of irrigation duration	1 to 36

2. Data Components

2.1 Level 1 products

WaPOR 1.0 and 1.1 were prototypes of the data base that were released during 2017 and 2018, with the main task to explore first the WaPOR data series and check the quality of the data components by a selected group of users. After consultations and conducting quality checks (http://www.fao.org/3/ca4895en/CA4895EN.pdf), the WaPOR 2.0 data was formally released during June 2019 as part of the World Day on Combatting Desertification and Drought. The Translator described in this report is utilizing version 2.0 of the WaPOR data only. It is encouraged to exploit the 100 m data because the spatial resolution of 1 ha fields in Africa is more realistic than the default 250 m spatial resolution (6.25 ha). Table 2 shows the WaPOR input data being used for the Translator.

The agricultural land use is taken from the European Space Agency Climate Change Initiative (ESA) high resolution (20 m) land use product (https://www.esa-landcover-cci.org). The legend of this data set includes 10 generic classes: "trees cover areas", "shrubs cover areas", "grassland", "cropland", "vegetation aquatic or regularly flooded", "lichen and mosses / sparse vegetation", "bare areas", "built up areas", "snow and/or ice" and "open water. Pixels with the legend classes (i) grassland and (ii) cropland are being used as a mask for the processing of pixels with agricultural land. WaPOR contains also an own land use map that is based on the Copernicus land use data base. The original pixel size of Copernicus is 100 m (https://land.copernicus.eu/global/products/lc). The WaPOR land use map is updated every year, being a great contribution for monitoring changes. The Translator integrates these two land use data bases to a dynamic 100 m x 100 m grid of cropland and agricultural land. In the Level 2 product series, these agricultural pixels are further split into rainfed and irrigated crops, along with their duration of each cropping cycle. Pixels with 100 m that are non-agricultural, will not be processed further in the WaPOR Translator.

The SoilGrids data base from ISRIC World Soil Information affiliated with Wageningen University has been explored to derive a number of extra key parameters being relevant for the determination of soil physical properties, i.e. the fractions of sand, silt and clay, and bulk density (www.soilgrids.org). Soil organic carbon content is also taken from this SoilGrids data base to help the quantification of soil fertility and sequestration of atmospheric carbon. Terrain information is needed in addition for explaining the variability of crop production detected in WaPOR. Terrain information is also required for the preparation of Agro-Ecological Zones (AEZ). The terrain characteristics used for this purpose are slope and elevation. They are derived from the Jet Propulsion Laboratory (JPL) – based Shuttle Radar Topography Mission (SRTM), see https://www2.jpl.nasa.gov/srtm/. The SRTM data comes at 90 m, and is resampled to a 100 m grid. Information on slope and soil organic matter can in future versions of the Translator also be used to determine soil erosibility.

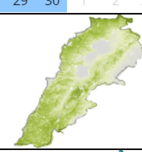
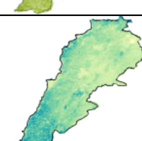
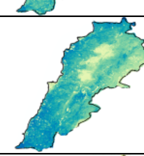
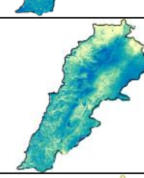
The next layer of data is climate related. The air temperature, air humidity and wind speed are taken from the Global Land Data Assimilation System (GLDAS), https://ldas.gsfc.nasa.gov/gldas. According to NASA, the goal of GLDAS is to ingest satellite- and ground-based observational data products, using advanced land surface modeling and data assimilation techniques, in order to generate optimal fields of land surface states and fluxes. The software drives multiple, offline (not coupled to the atmosphere) land surface models, integrates a huge quantity of observation based data, executes globally at high resolutions (2.5-degrees to 1 km), and is capable of producing results in near-real time. A vegetation-based tiling approach is used to simulate sub-grid scale variability, with a 1-km global vegetation dataset as its basis. Observation-based precipitation and downward radiation products and the best available analyses from atmospheric data assimilation systems are employed to force the models. The high-quality, global land surface fields provided by GLDAS support several current and proposed weather and climate prediction, water resources applications, and water cycle investigations. The output data comprises climatic data since 1948. It is also feasible to collect the model outputs of different type of Land Surface

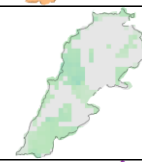
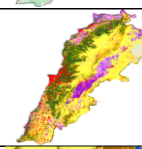
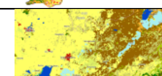
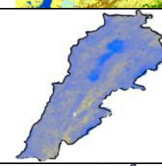
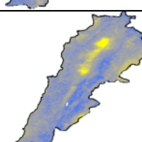
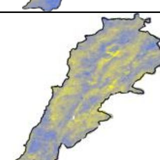
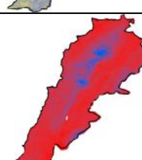
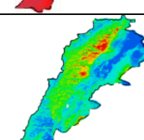
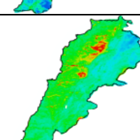
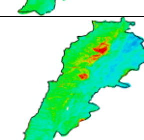
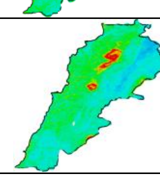
Models (Noah, CLM, VIC, Mosaic, and Catchment), such as soil moisture, runoff, percolation and other components of the soil water balance.

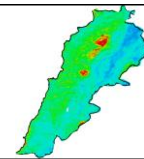
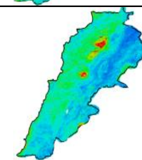
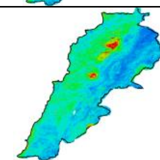
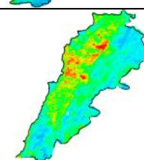
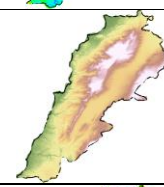
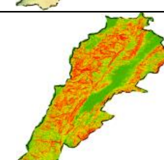
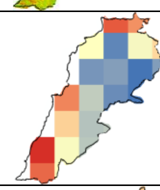
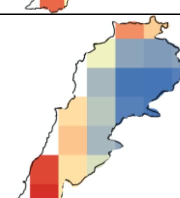
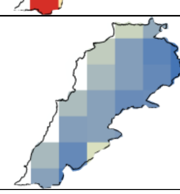
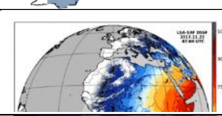
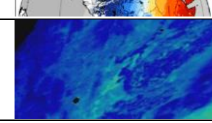
We have more trust in measurements of solar radiation data acquired from geo-stationary satellites than radiation from GLDAS model based on atmospheric circulation simulations. The Meteosat Second Generation (MSG) satellite covers Africa, MENA and Europe. The solar radiation data from LandSAF (https://landsaf.ipma.pt/en/) has the best quality and can be imported into WaPOR Translator. Another data source is the solar radiation data being made available through the Climate Explorer of the Royal Netherlands Meteorological Institute (KNMI) which is also based on MSG measurements, but with a slightly different algorithm. Unfortunately, KNMI and Meteo Portugal are not providing MSG-based solar radiation data earlier than 2016 (LandSAF program of Meteo Portugal) and 2017 (ClimSAF program of KNMI) respectively. An alternative solution has been built into the Translator to assess solar radiation and net radiation for the period prior to 2016 exploring the longer time series of reference ET_0. The consequence is that for any older period of analysis, the year 2018 has to be included in the time series. Otherwise soil moisture of the root zone cannot be computed.

The surface albedo is required for the computation of net radiation, being an important input into the computation of soil moisture of the root zone (see later). The surface albedo is taken from the MODIS website because it is updated automatically and regularly (every 16 days). MODIS generates the albedo products (MCD43A) at a 500-m resolution. The MCD43A3 provides black-sky albedo (directional hemispherical reflectance) and white-sky albedo (bihemispherical reflectance) data at local solar noon for MODIS bands 1 through 7 (https://lpdaac.usgs.gov/products/mcd43a3v006/).

Table 2: Specification of the input data being used in the WaPOR Translator

Data Component	Source	Example
Number of days in period (Decadal)	WaPOR 2.0	
Net Primary Production (NPP) in g/m^2 – Decadal (100m)	WaPOR 2.0	
Actual Evapotranspiration and Interception (ET) in mm – Decadal (100m)	WaPOR 2.0	
Transpiration (T) in mm – Decadal (100m)	WaPOR 2.0	
Evaporation (E) in mm – Decadal (100m)	WaPOR 2.0	
Interception (I) in mm – Decadal (100m)	WaPOR 2.0	

Reference Evapotranspiration (ET0) in mm – Decadal (250m)	WaPOR 2.0	
Precipitation (P) in mm – Decadal (250m)	WaPOR 2.0 (based on CHIRPS)	
Land use Land Cover - Annual (100m) (updated to 2018)	WaPOR 2.0 (based on Copernicus)	
Land use Land Cover	CCI Sentinel	
Sand fraction in % for 30 cm depth (250m)	SoilGrids	
Clay fraction in % for 30 cm depth (250m)	SoilGrids	
Silt fraction in % for 30 cm depth (250m)	SoilGrids	
Bulk density in kg/m^2 for 30 cm depth (250m)	SoilGrids	
Soil Organic Carbon in g/kg for 0 cm depth (250m)	SoilGrids	
Soil Organic Carbon in g/kg for 5 cm depth (250m)	SoilGrids	
Soil Organic Carbon in g/kg for 15 cm depth (250m)	SoilGrids	
Soil Organic Carbon in g/kg for 30 cm depth (250m)	SoilGrids	

Soil Organic Carbon in g/kg for 60 cm depth (250m)	SoilGrids	
Soil Organic Carbon in g/kg for 100 cm depth (250m)	SoilGrids	
Soil Organic Carbon in g/kg for 200 cm depth (250m)	SoilGrids	
Soil pH x 10 in H_2O for 0 cm depth (250m)	SoilGrids	
DEM SRTM (90m)	JPL - NASA	
DEM Slope (90m) (GIS-tool Slope using SRTM)	JPL - NASA	
Air Temperature in K – (25km)	GLDAS - NASA	
Air Humidity in kg/kg – (25km)	GLDAS - NASA	
Wind Speed in m/s –(25km)	GLDAS - NASA	
Shortwave Solar Radiation $K^{\downarrow}$ (1 to 3 km)	LandSAF - Meteo Portugal	
Surface Albedo α (1000 m)	MODIS - USGS	

Harvest Index	Appendix 1 to this report	
Moisture value harvestable product	Appendix 1 to this report	
Mono culture Crop type (optional)	Manual	
Mono culture C3 or C4 Crop type (optional)	Manual	

2.2 Level 2 products

The level 2 products are a culmination of a single or more multiple level 1 WaPOR data. Well-accepted and internationally published mathematical relationships in environmental physics and remote sensing are used to derive data layers that provide useful information to interpret the land and water productivities detected. Level 2 data comprises vegetation, soil moisture and soil parameters that are often used as input data in models of the Soil-Vegetation-Atmosphere continuum or in regional scale distributed hydrological models. Level 2 data can also be of interest for building new customized applications that are currently not being considered in Level 3. Level 3 provides different application possibilities, and more flexibility is feasible if there are more Level 2 data. Hence, the user can always build new Level 3 type of applications using Level 1 and Level 2 data products. In fact, the philosophy behind WaPOR is to build as many as possible Level 3 data layers.

Figure 3: Different types of applications in agricultural water management that can be built on WaPOR type of spatial data

2.2.1 Crop parameters

The 100 m spatial resolution of Leaf Area Index (LAI) is computed from an exponential expression of the ratio between actual transpiration (T) and reference ET_0. This relationship is taken from Choudhury (1994) who was inspired by the work of Al-Kaisi et al. (1989). The original coefficient of -0.59 has been modified into -0.55 for acquiring slightly larger LAI values. This is a great solution to acquire 100 m LAI data, that is consistent with the ET and biomass production data. Namely, the original NDVI or LAI data to compute essential Level 1 data components are not provided on WaPOR. By deriving LAI from ET this problem is tackled. The equation for every parameter is provided in Table 3.

The equation for root depth is based on LAI data and has been determined by the MetaMeta WaPOR project team on publications on data pairs between LAI and root depth. A second order polynomial equation has been determined (see Table 3). Because the effective depth for the computation of the soil water balance is smaller than the maximum depth of certain hair roots, an effectivity factor of 0.85 has been added to the equation. The fractional vegetation cover Vc is an exponential function of LAI

(Choudhury, 1994) and this equation is widely supported in many international remote sensing publications. Different empirical coefficients exist in the international literature on Vc(LAI) relationships that vary with the leaf angle distribution function, which is theoretically defined to be equal to 0.5 for randomly distributed leaves. For erectophile leaves, the coefficient is lower than 0.5 and for planophile crops it outght to be more than 0.5. The mean value is 0.67 with a standard deviation of 0.16 for 18 different crops (Ross, 1975). We have adopted a mean value of -0.65 for acquiring proper ranges of fractional vegetation cover Vc from LAI values.

The standard FAO solution for crop coefficients (Kc) is based on dry soil conditions and a variable canopy development. The minimum Kc value for emerging crops has a fixed ratio (0.2) of the reference ET_0 (see Allen et al., 1998). Following Johnson and Trout (2012) and many others, the water unlimited crop transpiration component is mainly a function of fractional vegetation cover Vc. The larger the cover with green leaves, the more T occurs, and this is rather independent of the type of crop. Something similar was found already by Azzali et al 30 years ago for row crops in Argentina (Azzali et al., 1990). Note that the crop coefficient applies to pristine growing conditions, so there is no stress from water, diseases, nutrients, salinity or other unfavorable growing conditions. Such kind of upper limit of ET is referred to as ET crop or shortly ETc (FAO) or potential ETp. The basic equation for Kc is based on Vc, but the result is verified for the sake of consistency between ETa, ETp and ET0. This is achieved by comparing ETa against ETp, where ETp presents Kc x ET0. In cases that ETa > ETp, the value of K_c is updated sothat it is no longer governed by Vc only.

2.2.2 Radiation and energy balance

The net radiation Rn is a key parameter of the surface energy balance and the main source of energy to make exchanges of turbulent fluxes between land and atmosphere feasible: momentum flux (τ), sensible heat flux (H) and latent heat flux (LE). Another part of the energy is conducted into the soil, known as soil heat flux (G):

Rn = G + H + LE

Net radiation consists of a shortwave radiation component caused by solar radiation, and a longwave component controlled by thermal emissions. Both are natural processes. The incoming solar radiation (i.e. emission of sunlight) and surface albedo determine the net shortwave radiation. For longwave radiation, FAO has developed an empirical relationship that depends on the prevailing air temperature and a net emissivity value reflecting the differences between apparent emissivity of the atmosphere and land (see Table 3).

For WaPOR, we only consider 24 h total fluxes of the energy balance. Because heat up and cooling down of the soil is in equilibrium, the 24 h component of G is negligible small. The partitioning of Rn into H or LE is described by means of the Evaporative Fraction (EF), which for 24 h periods can be simplified into:

EF = LE/Rn

For wet land surfaces, EF is usually 0.8 or more, while for dry land surfaces, LE/Rn is 0.2 or less. In the case of the latter, most net radiation is used for warming of the air layer above the land surface and then H is 0.8 x Rn. Evaporation thus cools the air. While LE is the latent heat flux expressed in energy terms (W/m^2), ET is a rate expressed as a water flow (mm/d). In general, ET=LE/28.4 applies.

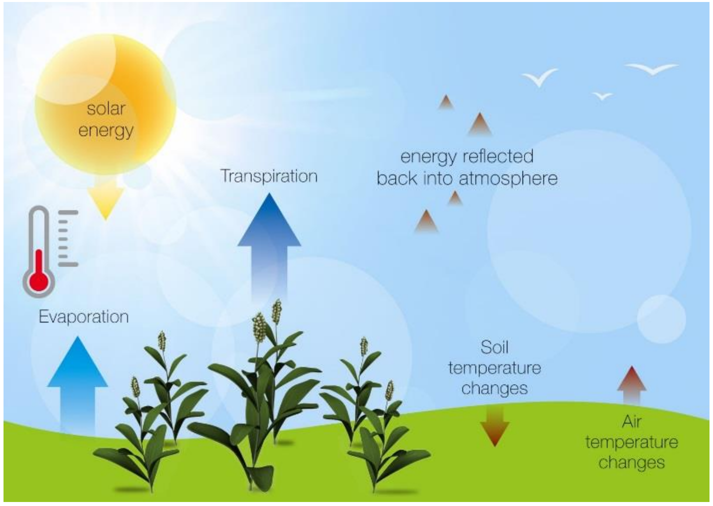


Figure 4: Main principles of the surface energy balance

Because EF reflects evaporative cooling and land wetness, Bastiaanssen et al. (1997) and Scott et al. (2003) showed that EF can be used to estimate the water in the root zone that is available for ET processes. Hence, the partitioning of Rn into either H or LE can be used to look into the root zone. This subsoil moisture is far more interesting than using any microwave based solution that estimates soil moisture in the upper skin (Bastiaanssen et al., 1994; de Jeu et al, 2011). While for thermal images the vegetation is used as an indicator of water stress, vegetation forms an obstacle that scatters and attenuates microwave signals (van de Griend and Owe, 1994).

The EF scales the soil moisture between 0 and 1, and the maximum value of soil moisture occurs when the porous soils are filled with water, i.e. saturation (θ_{sat}). This maximum value for soil moisture θ_{sat} can be derived from SoilGrids data layers. Table 2 provides a number of “home cooked” pedo-transfer functions that provide a coherent data set for soil water and irrigation management. The soil water holding capacities are very realistic, and a large capacity can retain more water resources. Soils with more water in the pores help crops to survive periods of droughts and for assessing the capacity to apply deficit irrigation practices. Key parameters for soil water retention are θ_{sat}, θ_{fc} and θ_{wp}, and they are all estimated in the Translator, where θ_{sat}, θ_{fc} and θ_{wp} represent maximum, field capacity (suction -200 cm or -20 cbar) and wilting point (suction – 16000 cm or -16 bar). An additional soil moisture parameter that is very practical for irrigation scheduling is the critical soil moisture value below which the easily available water is depleted and crop water stress is triggered, i.e. θ_{crit}. An average p-fraction of 0.35 is taken from the FAO 56 tables that is valid for many crops.

2.2.3 Soil water balance

Level 1 products rainfall (P) and actual evapotransiration ETI (or ETa) are the two most important terms of the soil water balance. When ET is not specified further, it is should be the actual ET flux (like P also represents the actual rainfall). Their difference P-ET is carrying essential information on the net supply (ET>P) or net drainage (P>ET) of a given pixel for a certain period. Positive values of P-ET reflect the amount of total drainage water and surface runoff that will go ultimately into a stream or river. So spatially integrating P-ET for a sub-basin or basin will provide a first estimate of streamflow. In case that P – ET is negative, it is obvious that there is another source of water in addition to rainfall. For cropland this is a gentle method to detect whether a pixel is irrigated, and also to make estimates on the total amount of applied water. For non-cropland, ET exceeding P occurs for inundation areas or groundwater dependent ecosystems. Exploitation of discrete P-ET information per pixel gets even more value of also storage changes are included. Table 3 includes a correction term for soil water storage, which improves the estimates of stream flow or applied water on the basis of P-ET data. The storage term is based on the temporal changes of soil water content stored in the root zone. This can be estimated from the differences in soil moisture, and this is another example where soil moisture of the root zone is needed for.

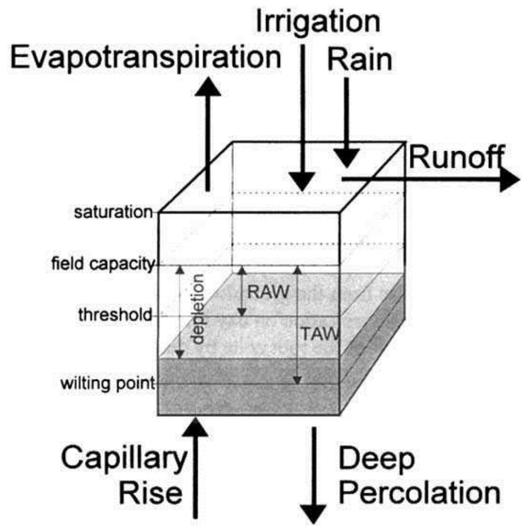


Figure 5: Soil water balance of an irrigated crop (source: FAO)

Deep percolation occurs only when the soil moisture exceeds its field capacity value. Field capacity typically occurs one or two days after a rainfall or irrigation event, when excess water is drained out, and the soil matrix has sufficient suction to retain the remaining water. We assume that all excess water is drained out in the same period of 10 days. The surface runoff is computed with the Soil Conservation Equation (SCS) but with some essential refinements for dynamic storage capacity in the top soil (Schaake et al., 1996). If more water is infiltrated into the top soil, overland flow will be reduced. So runoff should be a function of the storage capacity of the top soil. This is the same as the total volume of pores being filled with air. This storage capacity in the SCS equation for the estimation of surface runoff is in the Translator made a function of (i) topsoil moisture deficit, (ii) LAI to reflect the presence of vegetation and roots that crack the soil and (iii) sand fraction that usually enhances the infiltration capacity. The topsoil properties from SoilGrid should be used, rather than the subsoil properties. This fast surface runoff is a crucial parameter for downstream flood analysis. The last parameter in this list of soil water balance parameters is the water storage at 80% depletion. This is a water buffer that first needs to be depleted before it is very certain that irrigation must occur. The value of 80% is rather high, and reflects the moderate accuracy of crop depth without crop type information. In this case, the buffer acts like a safety factor for the estimation of irrigation process. We will see later that it is extremely important to know for every decade whether a pixel receives irrigation water, and the role of the buffer is detrimental.

Table 3: Specification of the analytical relationships between parameters, starting with Level 1 data sets

Data component	Unit	Equation	Data in equation
Leaf Area Index (LAI)	m^2/m^2	$\mathrm{LAI} = \frac{\ln(1 - \frac{\mathrm{T}}{\mathrm{ET0}})}{-0.55}$	*T = Transpiration* *ET0 = Reference Evapotranspiration*
Root depth (Zr)	cm	$\mathrm{Zr} = 0.85 * 100 * \mathrm{MAX}(0, -0.0326 * LAI^2 + 0.4755 * LAi - 0.0411)$	*LAI = Leaf Area Index*

Fractional vegetation cover (Vc)	-	$Vc = 1 - e^{-0.65*LAI}$	*LAI = Leaf Area Index*
Crop coefficient (Kc)	-	$Kc = 0.95\,Vc + 0.2$	*Vc = Fractional Vegetation Cover*
Net radiation	W/m^2	$= (1-\alpha) * K\downarrow + \left(0.34 - 0.14\sqrt{e}\right) * \left(1.35\frac{n}{N} - 0.35\right) * (5.67 * 10^{-8}) * (273.15 + Tair)^4$	*α = Surface albedo* *K↓= Shortwave solar radiation* *e = Actual vapor pressure* *LSE = n/N is relative sunshine hours* *Tair = Air Temperature*
10 year mean Net Radiation	W/m^2	$= Rn(y) * \frac{ET0_{10yr}}{ET0(y)}$	*Rn(y) = Net radiation of given year* *$ET0_{10yr}$ = ET0 averaged for 10 years* *ET0(y) = ET0 of given year*
Evaporative fraction		$= \frac{ET * 28.4}{Rn}$	*(1)ET = Actual Evapotranspiration and Interception* *(Rn = Net Radiation*
10 year mean Evaporative Fraction		$= \frac{(ET_{10yr} * 28.4)}{Rn_{10yr}}$	*ET_{10yr} = ET for 10 years* *Rn_{10yr} = 10 year mean Rn*
Silt Fraction	-	$= 0.7\,Fclay^2 + 0.3 * Fclay$	*F_{clay} = Clay Fraction*
θ_{sat} Subsoil	cm^3/cm^3	$= 0.831 - 0.282 * BD + 0.027 * F_{clay} + 0.019 * Fsilt$	*BD = Bulk Density* *F_{clay} = Clay Fraction* *F_{silt} = Silt Fraction*
θ_{FC} Subsoil	cm^3/cm^3	$= -2.2 * \theta sat^2 + 2.92 * \theta sat - 0.59$	*θsat = Saturated soil water content subsoil*
θ_{WP} Subsoil	cm^3/cm^3	$= 3.058 * \theta sat^{4.523}$	*θsat = Saturated soil water content subsoil*
Soil Water Holding Capacity	mm/m	$= (\theta fc - \theta wp) * 1000$	*θfc = Soil water content at field capacity subsoil* *θwp = Soil water content at wilting point subsoil*
Θ subsoil	cm^3/cm^3	$= \theta sat * e^{\frac{(EF-1)}{0.421}}$	*θ_{sat} = Saturated soil water content subsoil* *(2)EF = Evaporative Fraction*
10 year mean θ subsoil	cm^3/cm^3	$= \theta sat * e^{\left(\frac{EF_{10r}-1}{0.421}\right)}$	*θsat = Saturated soil water content subsoil* *EF_{10yr} = 10 year mean EF*
Θ critical	cm^3/cm^3	$= \theta wp + (\theta fc - \theta wp) * (0.65 + 0.04 * (5 - ETpot))$	*θwp = Soil water content at wilting point subsoil* *θfc = Soil water content at field capacity subsoil* *ETpot = Potential ET rate*
Soil Water Storage Change ΔS	mm/decade	$= Zr * 10 * (\theta_{end} - \theta_{start})$	*Zr = Root Depth* *SM_{end} = Soil Moisture at end period* *SM_{start} = Soil Moisture at start period*
Net Supply (+), Net Drainage (-)	mm/decade	$= (ET - P) + \Delta S$	*ET = Actual Evapotranspiration and Interception* *P = Precipitation* *ΔS = Soil Water Storage Change*
Deep percolation q↓	mm/decade	if $\theta >$ θfc then $(\theta - \theta fc) * Zr * 10$	*Θ = actual soil moisture*

			Θ = soil moisture at field capacity *Zr = depth of root zone*
Storage coefficient for surface runoff SRp	mm/decade	$= 4 * (\mathrm{Fsand} * \mathrm{LAI}) * (\theta\mathrm{sat} - \theta)$	*Fsand = Sand Fraction* *LAI = Leaf Area Index* *θsat = Saturated soil water content topsoil* *θ = Soil water content*
Surface runoff Rp	mm/decade	$= \frac{((\mathrm{P} - \mathrm{I}))^2}{((\mathrm{P} - \mathrm{I}) + \mathrm{SRp})}$	*P = Precipitation* *I = Interception* *SRp = Storage Coefficient for Surface Runoff*
Available water for 80% depletion	mm	$= 0.8 * (\theta\mathrm{FC} - 0.12) * 10 * \mathrm{Zr}$	*θ = Soil moisture* *θwp = Soil moisture at wilting point* *Zr = Root depth*
Potential ET (ETpot)	mm/decade	$= \mathrm{Kc} * \mathrm{ET0}$	*Kc=crop coefficient* *ET0= reference ET*
Crop Water Requirement (CWR)	mm/decade	$= \mathrm{MAX}\,(\mathrm{ET}, \mathrm{ET}_{\mathrm{pot}})$	*ET = actual ET* *ETpot = potential ET*
Crop Coefficient update		$= \frac{\mathrm{CWR}}{\mathrm{ET0}}$	*CWR = Crop Water Requirement* *ET0 = Reference ET*

2.2.4 Cropping seasons

WaPOR is currently the leading spatial data base for Africa with an agricultural focus. Unfortunately, WaPOR does not include crop information, hence the Translator aims at estimating as a bare minimum to detect cropping seasons. The analysis of cropping seasons is done only for pixels that are labelled as being agricultural land. As explained in previous sections, cropland is taken from the annual updates of the Land Cover Classification (LCC) in conjunction with the Sentinel data on pastures and cropland. The Translator distinguishes five different cropping seasons in an annual cycle:

- Single crop
- Double crop
- Triple crop
- Perennial crop
- Pasture

In addition, a crop can be rainfed or irrigated, hence there are currently 10 possible combinations of seasons and source of water. Such kind of preliminary determination of crop phenology is required to assess the accumulation of crop production for a given season, and this can be accomplished without knowledge on crop type or cropping systems. The phenology defines the boundaries of the growing season for every pixel separately. A cropping system refers to the type and sequence of crops grown and practices used for growing them. It encompasses all cropping sequences practiced over space and time. While we have the space and time components, we cannot refer to it as cropping system because do not know the crop type.

The pixel dependent assessment of cropping cycles has a great advantage over the usage of classical cropping calendars. Due to weather, seasons namely vary from year to year, and by making it variable by pixel and by year, effects from late or early planting are included. During periods of droughts or cold (e.g. night-frost) and under other weather anomalies, farmers may have sound reasons to shift the cultivation period, or change the type of crop (e.g. barley instead of wheat).

The dynamics of crop transpiration form the basis for classifying cropland into one of the 5 cropping seasons described above. Namely, a developing crop exhibits an increase in crop transpiration due to canopy development and favorable radiation and temperatures regimes. Crops are cultivated during periods of favorable weather conditions (sufficient solar radiation and minimum air temperatures) for having sufficient carbon assimilation sothat the crop grows fast. Besides evaporative cooling and carbon intake, crop transpiration or sap-flow is required for uptake of water and the transport of nutrients and salts in solution. Hence, there must be a certain sap-flow in the crop for development and production. This is a sound basis for distinguishing crop phenologies and detect growth cycles.

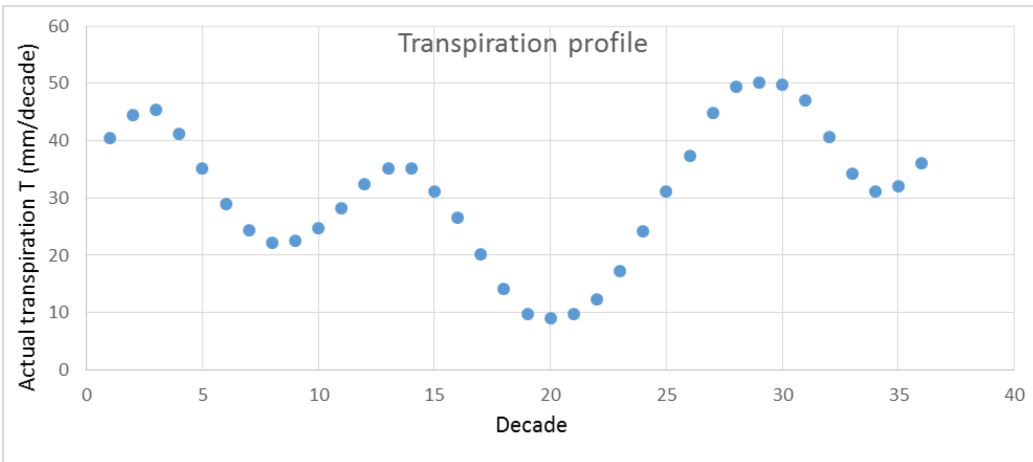


Figure 6: Annual cycle of crop transpiration after applying a moving window of 5 decades. Three different growing seasons can be distinguished on this example from Mwea irrigation scheme in Kenya

The automated classification of every pixel into 1 of the 5 seasons is based on the time profile of Transpiration T (see Figure 6). To remove noise from the T(t) transpiration dynamics, all decadal T values are first exposed to a moving average of 5 decades. This creates a rather smooth behavior in time. Next periods with a positive T(t) slope are detected, and such period of vegetative growth commences from the change in slope sign (from negative to positive). There should be a minimum period of positive slope that reflects the elongation and leaf development of 30 days. But in other crops, this might be longer. This minimum value of positive slope must be defined in the .json file described before. The first season could emerge from a previous calendar year, and the Translator is programmed in a way that it looks backward into the previous year to detect the start of season. The start of a new season is usually associated with a sudden increase of T with a steep slope for at least 3 consecutive periods during the vegetative phase with the maximum slope $\delta T/\delta t$ >20 mm/decade or 2 mm/d. The latter values are adjustable. The maximum slope is included to exclude false growth from for instance surrounding trees or weed development. If for an elongated period the slope is negative, then the end of the cropping season is detected. Furthermore, a constraint with the accumulated $\sum T$ for a single season exceeding 150 mm is built in. If all these criteria are met, then one cycle with a Day of Year (DOY) specifying the start and a DOY for the end is established. The minimum period is 90 days; crops can simply not grow faster. The slope analysis of T(t) is done for agricultural land use pixels only.

In case that a season has a total amount $\sum T$ exceeding 400 mm, while simultaneously the maximum slope T(t) is gentle (< 4 mm/decade), a pixel will be labeled as being a perennial crop. Typical perennial crops are sugarcane, tropical fruit trees (banana, citrus) and other tree crops (walnuts, apples). All cropland that has no status of perennial crop, should be designated with a single season. It is checked whether 2nd and 3rd season can be detected on the same pixel. Three cropping cycles in a calendar year is not very common, but does occur under favorable weather conditions. The Translator allows to modify the T(t) settings, and by doing so guide the separation into proper cropping seasons.

With the boundaries of emergence and harvest being identified, the possibility arises to discern crop development stages. The period between planting / sowing and emergence depends on thermal degree days and can thus be back computed from our inflection point of $\delta T/\delta t$. The maturity is obtained on the plateau when the maximum decadal T values are reached. The late season starts when $\delta T/\delta t$ is negative.

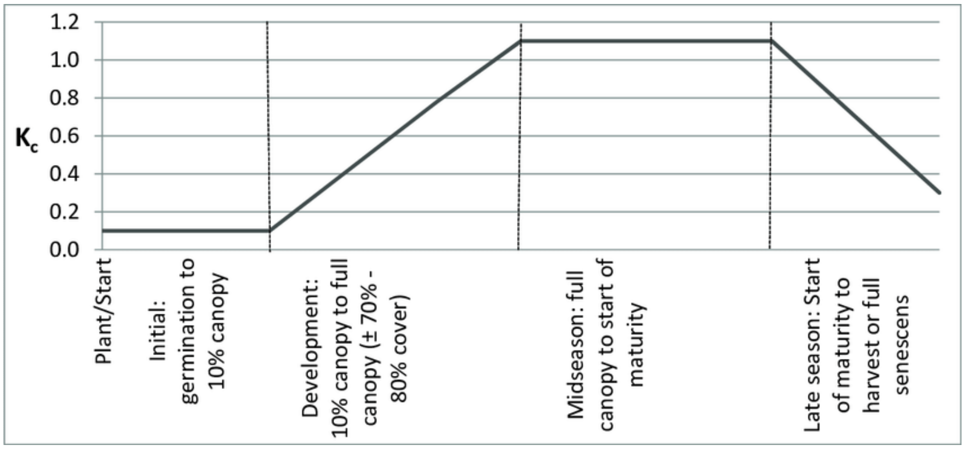


Figure 7: Different crop growth development stages (Allen et al., 1998)

The Translator thus discerns cropping seasons and the phenology for every pixel uniquely. Neither the type of crop (e.g. wheat), nor the crop class (e.g. cereals) is determined. The bio-physical properties such as ∑T, growing degree days, maximum LAI, ∑bio and crop development stages of Figure 7 can now be quantified as co-variates, which together with statistical information on crop occurrences in certain administrative areas should help to prepare a first algorithm for classifying crop types. This aspect is not included in the current version of the Translator because first the cropping seasons require more validation.

3. Level 3 products

3.1 General

Level-3 data supports specific analysis of certain directions within the context of agricultural water management. These directions were introduced before in Figure 2 such as Food Security, Climate Smart Agriculture etc. The main aim is to empower specific user groups with customized information to evaluate a project, making strategic decisions on longer term policy, monitor natural resources efficiencies or check the 25% increase in water productivity strategy. For instance, securing the national food production and import of commodities is a common denominator in general policy making. How much food is produced ? What are the differences in total food and feed production between Provinces ? How relate WaPOR data to statistical data, and can we now improve our understanding ? Which areas are more susceptible to climate change ? Ministries of Water Resources and Irrigation, have a focus on conserving water in the agricultural sector. Federal Governments need to make water allocation plans for transboundary rivers that share water between National States. How much irrigation water is really required and do we have this amount of water in our rivers for a safe withdrawal ? Are scarce irrigation water resources equitably distributed ? Is there a difference between head and tail end water flows of the main canals ?

These type of questions, can be answered with support of WaPOR data if we can establish the link between data provision and information requirements. The information requirements are hardly investigated. With the facilitation of WaPOR level 3 data, at least the data provision side of the equation has made progress. The next step would be to reach out to the potential information users, and this needs to be accomplished under WaPOR phase 2 that is planned for post 2020.

Figure 8: Commercial farming that could utilize WaPOR data if they get certain agronomic reports on crop health with a regular interval. Currently they do not know WaPOR exists

Not only the Government needs supporting data, also international NGO's such as Nature Conservation, Wetlands International, World Concern International and local NGO's being active in achieving a better world require proper information. While the average farm size in sub-Saharan Africa is 2.4 hectares, there are many commercial farmers and plantation growers that possess more land area. For instance sugarcane plantations occupy often a larger area of land (hundreds of hectare). The same applies for citrus, pineapple, banana and mango plantations. These commercial growers pack and export themselves and have land in various countries. These commercial farmers with larger fields can all potentially use WaPOR data, provided that the data is presented to them in a format that they understand or is created by them. They will not download NPP or BWP data from the FAO website.

One strong vantage point of spatial data is the capacity to study the crop production of a given season vs. the production of the champion farmer for the same season and the same agro-ecological zone. The yield gap is a very important parameter in crop production (e.g. Sadras et al. 2015). The yield gap due to current on-farm practices can be estimated for any region for which a proper target value can be presented. Another example for commercial farmers is having access to the trend line of biomass production for the last 10 year. Such trend line provides strategic value of the economic returns on investment: is crop production really increasing due to more advanced farm inputs, or is it going down due to for instance soil fertility and land degradation.

Smallholder farming is at the edge of being detectable by the spatial resolution of WaPOR. The picture of Figure 9 shows a field size of 0.1 hectare or smaller. Intercropping is a common phenomenon. In such case, the pixel size of 100 m will represent a mixture of different fields and different crops. There is an edge effect with neighboring fields, so effectively the plot size needs to be larger for utilizing the 100 m crop information. A practical rule of thumb is that fields needs to encompass 5 x 5 pixels. If we disregard all the edge pixels, then 3 x 3 pure pixels can be used to infer the information wanted. An area of 5 x 5 pixels at 100 and 250 m resolution is 25 ha and 156 ha respectively. A realistic description of farming practices is thus only feasible for commercial plantations and dairy farms in the Middle East. Also for areas with mono-cropping systems such as the wheat-rice, maize-rice and cotton systems.

Figure 9: Example of a small holder farm in Africa with mixed crops

A different way to present the capabilities of WaPOR is the organization by spatial aggregation level:

- Field scale: - describe best practices on crop development, soil moisture management and water conservation, detect stunted crop development, provide tailor made agricultural extension services, advice on irrigation practices; it works for 25 ha single fields or regions with mono-cropping systems

- Provincial scale: - define target values on water productivity, assess vulnerability to drought, plan rainfed and irrigated land, make water allocation plans for irrigation systems, monitor groundwater abstractions

- National scale: - assess deteriorating soil and land degradation, planning of food security, import, export and storage of commodities, provide proper education, improve crop and water statistics, introduce climate smart agriculture, SDG reporting to UN

3.2 Food Security

3.2.1 Agro-ecological zones

When dealing with food security, it is imperative to answer questions like (i) can we expect this year the same production as the average production from the last 10 years ? (ii) what are the gaps in food production and what might be the bio-physical factors causing the lack of production (planting date, rainfall anomaly, soil fertility), (iii) what is the impact of climate change on crop production, (iv) what is the relationship between natural disasters (droughts and floods) and crop production. These essential questions can be answered if the crop cycle is broken down into smaller periods of 10 days, and assess simultaneously the spatial variability of crop production in a certain regions. i.e. agro-ecological zones. The AEZ classes are used for benchmarking land and water productivity values. So the comparison between crop productions spatially and across the last 10 years is done only within the same AEZ.

The previous sections have explained that different crop seasons can be discerned along with the dates of crop emergence and dates of crop harvest. While the mapping of crop types and cropping systems are in it's infancy, Agro-Ecological Zones (AEZ) can be identified. The AEZ classes in the Translator are based on a pragmatic combination of six available building blocks (see Table 4):

- crop season
- irrigated or rainfed
- soil type
- elevation of terrain
- slope of terrain
- climate

A standard codification is used for each AEZ class. The filename of a certain AEZ class has a specific meaning that follows the specifications set out in Table 4: Digit1=season (1..4); Digit2=irrigated/non irrigated (1..2); Digit3=soil type (1..3); Digit4=elevation (1..3), Digit5=slope (1..2) and Digit6=climate (1..3). A simplified methodology was developed to limit the number of possible Agro-Ecological Zones to 4 x 2 x 3 x 3 x 2 x 3 = 432 combinations. Because triple crop seasons are rare, they are part of double season.

Table 4: Building blocks for the Agro-Ecological Zonation

Class	Crop season	Irrigated-rainfed system	Soil type	Elevation	Slope	Climate
1	Single	Irrigated	Clay	Lowland (< 500 m AMSL)	Flat (<2%)	Arid ($ET_0/P>2$)
2	Double & Triple	Rainfed	Loam	Intermediate	Steep (>2 %)	Average
3	Perennial		Sand	Highland (>1500 m AMSL)		Humid ($ET_0/P<0.5$)
4	Pasture					

The difference between rainfed and irrigated pixels is estimated using an accumulation of ∑(P – ET) since the day of emergence. Irrigation is not expected and unusual as long as P > ET. But during periods of drought, ∑(P – ET) will become negative. This is known as the rainfall deficit period (e.g. Wang-Erlandson et al. 2018). A negative ∑(P – ET) value does not necessarily imply that irrigation takes place, because crop ET can also take soil moisture from stock. This occurs typically during periods of drought where soil moisture gets depleted. There is however a situation that negative ∑(P – ET) values cannot be longer explained by water withdrawn from the buffer in the root zone of the crop. In that case, the pixel must be irrigated for that particular decade. The buffer in the root zone that can supply extra water is computed in WaPOR translator as 80% of the available water between field capacity and an arbitrary soil moisture value, tentatively fixed at 0.12 cm³/cm³. Hence, for every period of 10 days it is inspected whether ∑(P – ET) is lower than the buffer of 80% of available water, and if so, the pixel is classified as being irrigated. The great implication of this approach is that every pixel is checked on the irrigation status on a decade by decade basis. An example is demonstrated in Figure 10 and the graphs reviews one irrigation system (not a single pixel). AEZ-mapping does not require decade values of irrigated land. To simplify this process, a pixel is labelled as being irrigated if for more than 1 months per year it is identified as being irrigated.

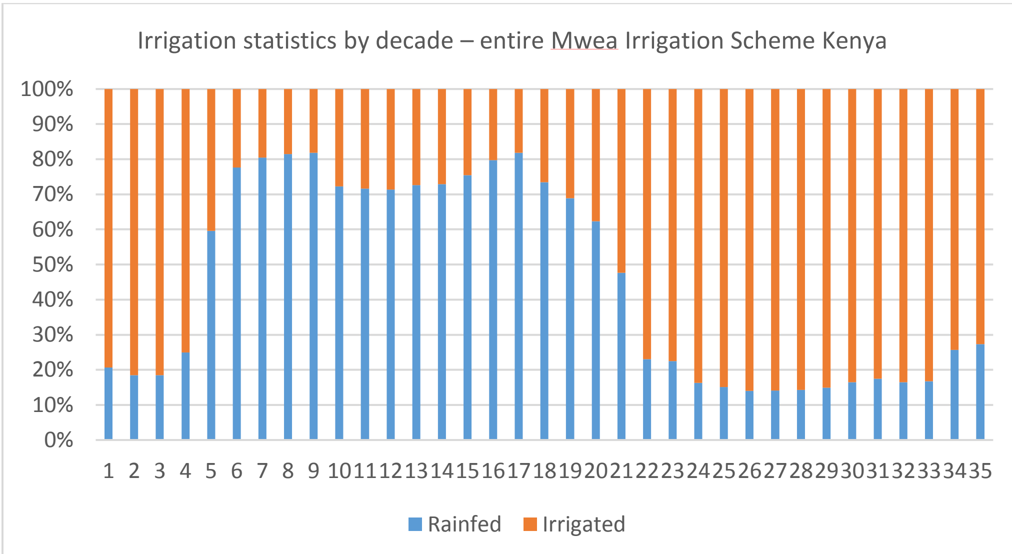


Figure 10: Decadal assessment of the percentage of land (all pixels enclosed in the boundaries of the irrigation scheme) that is irrigated. Clearly decade 7 to 19 is the rainfall season with only a small fraction of the pixels receiving irrigation water

The soil type is based on the classical texture triangle displayed in Figure 11. This is based on the soil texture triangle of NRCS-USDA (Natural Resources Conservation Service Soils of United States Department of Agriculture) (https://www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/survey/?cid=nrcs142p2_054167). Because of the availability of percent silt, percent clay and percent sand from SoilGrids, it is feasible to determine the exact type of soil. In total, 12 soil classes are distinguished.

For AEZ classes, the soil types are clumped to only 3 types: clay, loam and sand (see Table 5). It is referred to as clay if percent clay >35%. For soils <35%, it is either loam (percent sand < 55%) or sand (percent sand >55%).

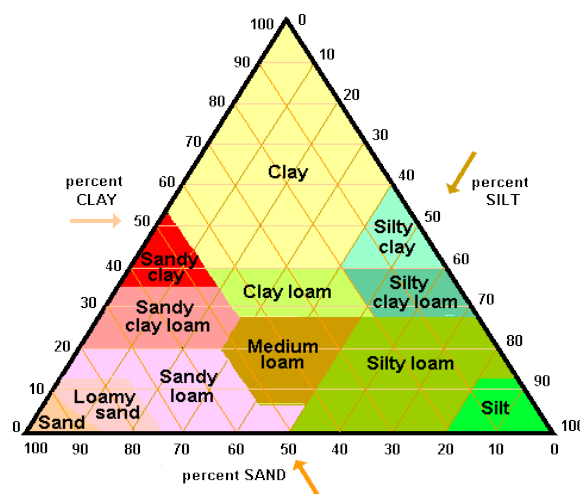


Figure 11: Soil textural triangle of USDA

Table 5: Relationship between texture building blocks and soil type according to USDA

Soil Type	Clay (%)	Silt (%)	Sand (%)
Sand	(silt + 1.5 * clay) <15		
Loamy sand	((silt + 1.5 * clay) >=15 & ((silt + 2 * clay) <30)		
Sandy loam	(clay >=7) & (clay <20) & (sand >52) & ((silt + 2* clay) >=30)		
Loam	>=7 & <27	>=28 & <50	<=52
Silty loam	>=12 & <27	>=50	
Silt	<12	>=80	
Sandy clay loam	>=20 & <35	<28	>45
Clay loam	>=27 & <40		>20 & <=45
Silty clay loam	>=27 & <40		<=20
Sandy clay	>=35		>45
Silty clay	>=40	>=40	
Clay	>=40	<40	<=45

The elevation data is acquired from the SRTM 1-Arc Second Global data set. Three elevation classes were distinguished. Lowlands are all areas < 500 M AMSL. Highlands are defined as >1500 m AMSL and the intermediate elevation layer is situated in between. The slope of the terrain is also based on SRTM and is divided into <2% (flat) and > 2% (steep). Steep terrain is more common for grasslands and small scale rainfed agriculture. Most irrigation systems and commercial farms are located on flat terrain where flood irrigation (borders, furrows) is common and the risk of erosion is reduced. Flat land occurs often in delta's and plains that are exposed to floods. They often have an alluvial type of soil. The final factor in the AEZ classification is the climatology. While the role of climate on crop production can be made very complicated (e.g. different periods of rainfall, temperature and ET_0), we have simplified climatic systems into classes of aridity:

Aridity = ET_0 / P

So the effect of cloud cover, temperature and air humidity is culminated into an expression of reference evapotranspiration ET_0 following the standardized FAO Penman Monteith equation (Allen et al., 1998). It should be noted that researchers from Wageningen University and Royal Netherlands Meteorological Institute (KNMI) argue that the Penman-Monteith equation systematically over-estimates advection in dry climates, and that the absolute value of ET_0 computed by the standard FAO-PM method becomes under these conditions highly uncertain (De Bruin et al., 2016). The Translator includes therefore also their alternative expression for ET_0 of well watered grass for infinitely large surfaces. The current version of ET_0 in the aridity index is based on Penman-Monteith, but this could be replaced if more research confirms that de Bruin – Holtslag method seems better. The 3 climatic classes discerned exists of arid ($ET_0/P>2.0$) and humid ($ET_0/P<0.5$). The class intermediate lies in between.

3.2.2 Food and feed production

Crop photosynthesis uses light to convert carbon and water into oxygen and carbon-hydrates. Atmospheric carbon is acquired through the stomates of crop and this intake of carbon is known as the Gross Primary Production (GPP). Part of the carbon flux intake is respired as maintenance respiration which leaves a pool of net carbon behind in the crop for generating crop organs, or Net Primary Production (NPP), see Figure 12. NPP data is approximated by remote sensing algorithms in WaPOR using the concept of Light Use Efficiency. NPP is a standard key component of the Level 1 data series. The carbon assimilates are partitioned into leaf, root, stem and other organs. The conversion of carbon into carbon-hydrates on the basis of molecular weights is 30/12 or 2.5. In other words, one kilogram of net carbon C intake would be equal to 2.5 kilogram of CH_2O. The crop dry matter content contains also Nitrogen and other substances (e.g. Mg and Cu). Consequently, the conversion of C into crop dry matter is not exactly 2.5. WaPOR is using a factor of 2.22, which creates a key conversion of NPP into biomass production (biomass production or dry matter production are identical) as follows:

Bio = NPP / 0.45

The biomass production is the incremental dry matter produced in a given decade. It is the extra dry matter weight of the crop due to intake of carbon and solutes from soil moisture. Decadal biomass production needs to be accumulated for assessing the accumulated biomass production for the season, The final crop yield depends namely on the accumulated biomass production for the season. The harvest index and the moisture content of the harvested product are the conversion factors that are crop dependent (and must for this reason be specified in the .json file). This is encouraged for conducting special studies such as for the mono-cropping systems of Wonji (sugarcane, Ethiopia) and Mwea (rice, Kenya).

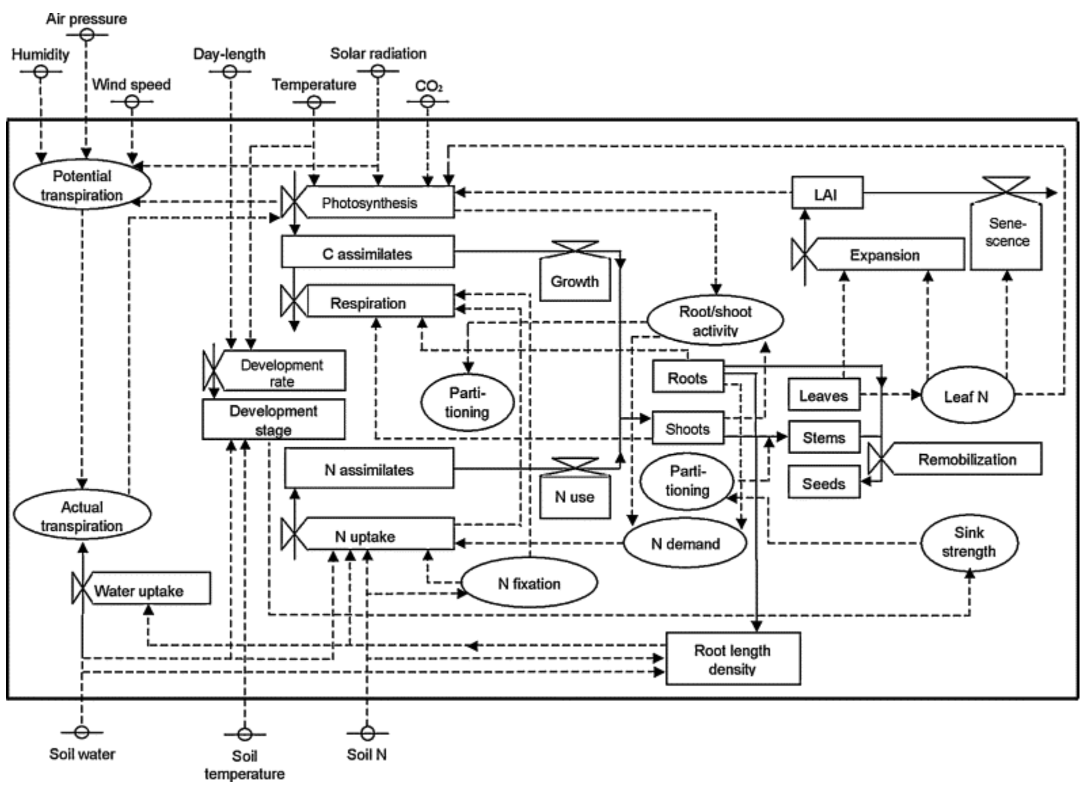


Figure 12: Major processes of carbon intake and water uptake on carbon assimilation, growth and the partitioning into crop organs (source: Danubia crop growth model, Lenz-Wiedemann et al., 2010)

The relationship between accumulated biomass production and crop yield is basically linear (crop stress may have some impact on the harvest index but we ignore this aspect for simplicity). The relative values for accumulated biomass production are then a proxy for the relative range of crop yield. The latter observation is key for starting to compare the spatial and temporal variability of crop yield: relative values of accumulated biomass production can be taken as surrogates for relative crop yield. Yield gaps can thus be based on gaps of biomass production. Ranking of Y/ET is similar to ranking of Bio/ET. Especially when the spatial and temporal analysis are conducted within given AEZ zones, valuable information can be retrieved.

The Translator uses the temporal variability of biomass production to explain why crop yield (or accumulated biomass production) is low or high. It is interesting to compare the time profile of decadal biomass production Bio(t) against the time profile of the actual biomass production of the pixel with the Target_Biomass_Production. The group of pixels with the highest accumulated biomass production for the season should be identified first. The Translator will do that on the basis of the frequency distribution of all pixel with ∑bio values within the same AEZ class. The target biomass production is selected as the 95% percentile or the 5% highest value on the frequency distribution. The percentile can be user adjusted.

The time profile will show during which decade crop production starts to deviate from its optimum value. An example of a time profile of accumulated biomass is depicted in Figure 13. The target value of ∑bio was approximately 9000 kg/ha. This is the green line in the left panel of Figure 13. The blue line represents the average crop, but it could be any pixel being located in the same AEZ class. The gap in crop production arises mainly in a fortnight between 1 and 16 July. This is clearly on the right panel where the deviations bio95 minus bio50 are plotted. This seems to be the crucial period. The root cause is not understood from such kind of analysis, and needs an agronomic interpretation: Is it because of problems during flowering period, an emerging fungi or something else that is causing the accumulated difference ? Yet, it is clear something went right at the champion farm, and something went wrong on most other farms. If we do the proper data analysis, both quantified differences in crop production, as well as periods of deviation can be detected. This is very valuable information for agronomists to assist them in their problem analysis, and where farmers and their advisor can improve their decision making process.

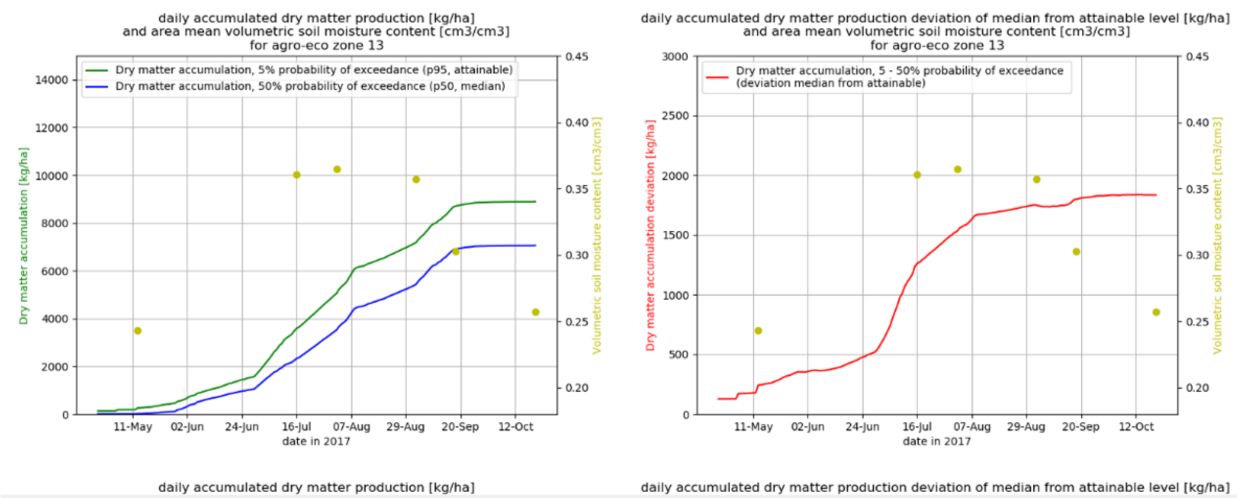


Figure 13: Example of accumulation of biomass production in Almaty (Kazakhstan). The left hand panel shows the average (bio50) and the target values (bio95). The right hand panel shows the accumulation of the deviations bio95 – bio50

In general terms, the lack of nutrients and water are considered as being the major constrains of food production in Africa (Rabbinge, 2001). To better understand the impact of water shortage on food production, the Production_Gap_Soil_Moisture is generated. So the Translator says how much crop production is lost due to insufficient water resources. If there is a gap in production, but it cannot be ascribed to water, then the causing factors should be sought in lack of nutrients, diseases or soil treatment. If the gap due to insufficient soil moisture is substantial (e.g. >30%), the introducing of irrigation systems could be considered (providing the necessary water resources are available). Soil moisture stress is therefore provided for better appraising the magnitude of the problem.

Table 6: Specification of the Translator folder structure of data components feeding into "Food Security"

Folder name	Unit	Purpose
Accumulated_Biomass_Production _Season	Kg/ha/season	Surrogate for crop yield; fix target value for each AEZ class; compare against 10 year average value; benchmarking production
Actual biomass production	Kg/ha/day	Breakdown of crop production in discrete time steps of 10 days
AEZ	No.	Division of agricultural land into zones with similar growing potential
Grassland	No.	Separation between grassland (1=grassland) and crop land; basis for distinguishing between feed and food production
Irrigation	No.	Identification of pixels being irrigated on a decade-by-decade basis; essential for water allocation and water management options
Irrigation maps yearly		Identification of pixels being irrigated for longer than 3 months
Mean Biomass_ Production	Kg/ha/day	Overall potential of the soil and climate system to produce a certain average crop production; is used for the reference production in a given area and early detection of anomalies in production
Production_Gap_Soil_Moisture	Kg/ha/day	Deficit crop production due to soil water stress on a decadal basis
Production_Gap_Spatial	Kg/ha/day	Lack of crop production as compared to what is attainable in the same period and same AEZ on a decadal basis
Production_Gap-Temporal	Kg/ha/day	Relate produce in current decade to what is normal on basis of 10 year average. Basis for assessing fluctuations in annual food security
Soil_Moisture_Stress	-	Fraction of water limited / water unlimited crop production. This is a relative indicator; others have an absolute character
Yield	Kg/ha/season	The fresh crop yield being harvested based on the accumulated biomass production per season and an auxiliary input file specifying the type of crop
Yield_Fresh_Grass	Kg/ha/season	The fresh feed yield being harvested based on the accumulated biomass production per season

For every decade, the 10 year average value for a number of key parameters is computed (i.e. biomass production, ET, ET0, P). This can be used as a reference value for every 10 day intervals of the growing season. What do we normally produce in this period ? For short duration crops (< 100 days) it is essential to timely detect that production is below or above average level. And when inspecting this for a longer period, it become feasible to start making predictions of the percentage deviation from the longer term average food production (because 17% lower ∑bio value is a good approximation of 17% lower crop yield). If in an early stage of crop production it can be said that the final crop production is systematically lower as compared to the 10 year mean – and this is occurring for many pixels in a given region - then it is obvious that food supply is less secure. Governments may react by timely import food from the international market. Prices of commodities have a strong inverse relationship with the total produce (Torbati, 2017), hence information on reduced food production is not only relevant for the Government, it is also very important for the economic returns of farmers. While these facts are known for some time, the new element is that these deviations from the longer term can be analyzed based on much more data, and data that is geographically discrete.

While the list of explanatory factors for low and high production is long, certain typical explanations on stunted crop production can be quantified with the Translator:

- Impact of soil moisture deficiency on crop production

- Impact of poor germination due to dry top soil
- Impact of reduced number of sunshine hours
- Impact of frost due to early planting
- Impact of heat waves
- Impact of extreme drying power of air
- Impact of low soil organic matter content
- Impact of soil erosion due to overland flow and washing of nutrients
- Impact of limited soil water holding capacity
- Impact of fungi based on weather conditions

The Translator creates automatically a number of folders in the category Food Security (see Table 6). Because of the above explained relationship with crop yield, the far most important folder is the accumulated biomass production for the season. The Translator detects the duration of the first, second and third crop growing cycle for every pixel. The accumulation of biomass or dry matter production is based on these periods. For every of the 3 seasons detected, a selected number of accumulated values will be provided: bio, ET, T, ET_0 and P. The reporting to commodity growers, weather based insurances or crop protection early warning is beyond the scope of the present manual, and the format for reporting needs to be prepared in close consultation of the end-users.

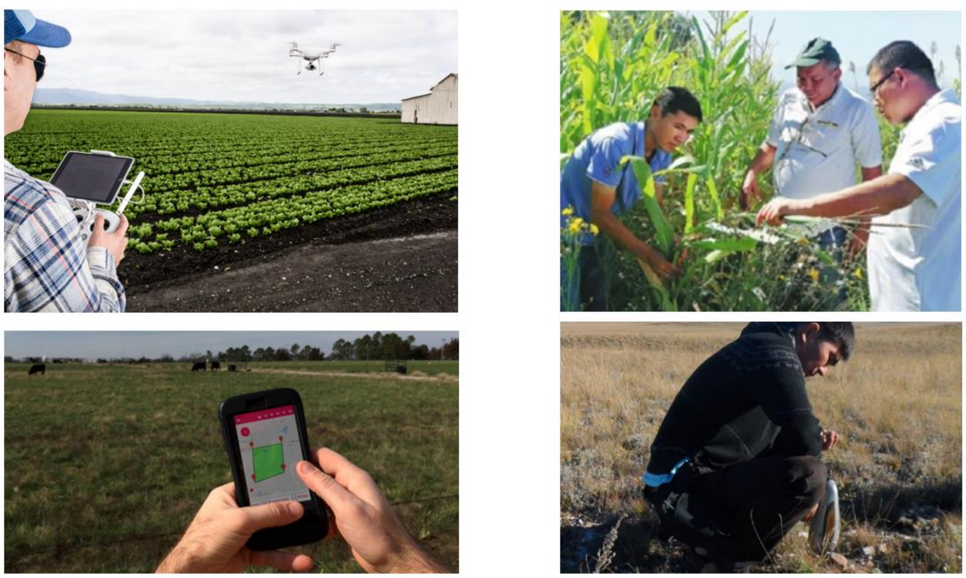


Figure 14: Visiting champion farms for detecting reasons for a very favorable crop production

Examples of good applications of WaPOR data for Food Security:

- Compute total crop production for given areas of interest (e.g. province, district, irrigation scheme)
- Deviations from the longer term mean crop production would imply a higher food security risk and adjustment of market prices. Tension can rise under extreme anomalies of food insecurity and famine
- Crop yield forecasting one month before harvest and timely import of foreign commodities – if so required
- Quantify yield gap by comparing actual and target crop production per AEZ zone
- Detect periods and crop phenology that have contributed to decline in crop production
- Assess relationship between soil type, soil fertility, soil water holding capacities and crop production for surveying regional differences in food production potential
- Determine relationship between weather conditions (rain, sunshine hours, temperature, humidity) and crop production for appraising vulnerability to climate change
- Assess gap due to water availability only and evaluate needs for water harvesting and irrigation solutions to combat production constraints
- Assess the need to manage existing irrigation systems better to produce more food
- Arrange transport and storage of food and feed between Provinces and States
- Selection of productive land suitable for farm profits
- Examine temporal trends in crop production for timely detecting land degradation
- Study impact of land reforms, land consolidation and commercial land lease on food security
- Survey blocks of land on commercial farms that under-perform due to variety, age of perennial crop etc.
- Evaluate objectives and impact of donor projects
- Detect stunted crop development in fields of 25 ha or more
- more

3.3 Water Productivity

The ultimate goal of WaPOR is to provide multiple years of Water Productivity (WP) data for specific areas in Africa and Near East. Such type of database does currently not exist, and WaPOR should receive recognition for being the first initiative in this particular field of interest. Biomass Water Productivity (BWP) is the crop production (i.e. total dry matter) per unit of water consumed (i.e. ET). The difference between WP and BWP is that WP refers to crop yield and BWP refers to total dry matter production (i.e. total biomass production). The interesting phenomena is that the relative ranges of WP and BWP are similar (but the absolute values are not). The denominator is the same for both, so that has no impact on the relative ranges of WP and BWP values. As explained in previous sections, WP is per definition a fraction of BWP and this fraction is governed by the harvest index (H_i) and the moisture content of the fresh yield (θ_c):

$$WP = BWP \frac{Hi}{(1-\theta c)}$$

While BWP can be computed for every pixel being identified as a cropped surface, WP can be determined only for pixels where the crop type is known. The latter is not straightforward due to technical challenges to prepare crop maps for Africa. The relative patterns of BWP and WP are however similar because H_i and θ_c are fairly constant for a certain crop variety cultivated in a given region. Globally, the range of H_i for a particular crop can vary significantly due to crop breeding programs and the ability of farmers to adjust on-farm practices. Under local circumstances, however, the impact of crop varieties on H_i and θ_c is minor. The relative values of BWP can therefore be considered as a surrogate of relative values of WP. BWP is for practical reasons therefore much wider applicable.

One of the first issues in regional scale analysis is the benchmarking of BWP against what is attainable. The value of BWP depends on crop production (∑bio) and consumptive use (∑ET). The Translator computes these ranges of every pixel from WaPOR. Specific reasons of ∑bio variability need to be sought. For instance drip irrigation usually creates higher ∑bio values than what is plausible for rainfed crops. The same can be said for consumptive use (ET). Irrigation scheduling, irrigation type, plant spacing, infiltration characteristics, mulching and soil treatments among others affect ∑ET. Hence large ranges of ∑bio and ∑ET occur.

A methodology to normalize for the differences in ∑bio and ∑ET values – and start comparing them - is the Water Productivity Score (WPS). WPS is a score between 1 and 10 that tells the farmer, water manager, NGO specialist or the policy maker immediately about the level of WP satisfaction (Bastiaanssen and Steduto, 2017). The score is evaluated per class of ∑bio with a class increment Δ∑bio being 1000 kg/ha. This are the so called vertical columns of crop production ∑bio; Each column represents a different production potential, and for each column the range of ∑ET is evaluated. Hence a commercial farmer with a high land productivity (∑bio) is having a range of ∑ET being different from a household garden with low land productivity. The BWP or ∑bio/∑ET is assessed for every column or vertical between a minimum and maximum BWP value. The minimum BWP is receiving a score of 1 and the maximum BWP a score of 10. A commercial grower can also get a WPS of 1, even when production is satisfactory (but the related consumptive use is outrages).

Vice versa, a farmer on poor hillslopes with low yield potential can be very efficient with water and can get a WPS of 10. In this manner, every type of farming ecosystem will be evaluated against its own environmental context. The smallholder is perhaps using treadle pumps and drip kits for bringing a low amount of water on exactly the proper place and gets a reasonable productivity on return, despite soil conditions are poor. Such farmer should be rewarded and rank high on the WPS grade scale. Over against that, a commercial farmer on laser-level land of a size that is suitable for mechanical treatment by tractors and is using despite these boundary conditions more water than needed, should be evaluated with a low WPS grade.

Tot hier

Reasons for low and high water productivity can be rather diverging. A palette of options exist to push WPS into the right direction. It should be clear that each package should be tailored towards the agro-ecological zone conditions described above. Further to simple and advanced interventions, the package of options of improvement deals with increasing production and another package with the reduction of consumptive use. What works best for certain environments is hard to say on beforehand. The detection of the champion farmer on the image is a great possibility to find the main causes of high WP by visiting and interviewing that farm, preferably located in different agro-ecological zones. Figure 12 demonstrates the champion farmers with highest BWP in Gezira, Sudan for 5 different years of analysis (2014to 2018). The list of best practices that causes BWP to rise should emerge from field interviews. This list of recommendations should then be disseminated to other farmers that are practicing in the same agro-ecological zone. Hence, agricultural extension agencies and consultants can do their job much more effectively if they use WaPOR data for determining best practices under local conditions.

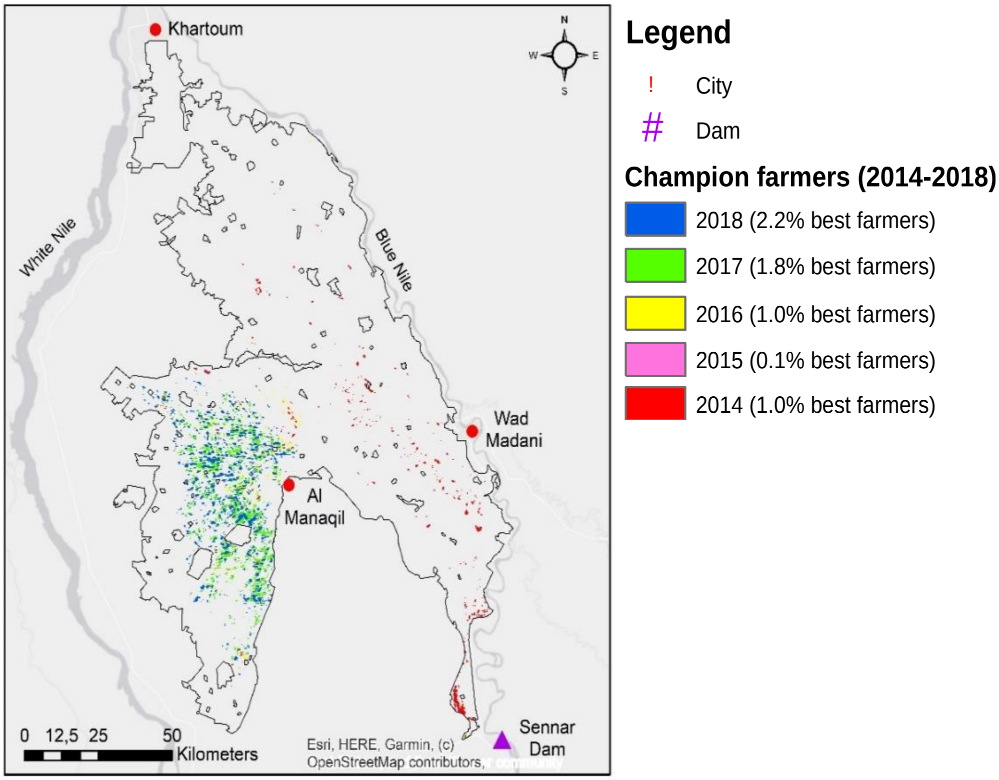


Figure 14: Detection of the champion farmers in Gezira Scheme(source: MetaMeta)

Package to increase crop production

- Proper fertilizer application
- Organic fertilizers for increasing soil fertility
- Crop protection (biological & chemical) against diseases
- Mechanical or chemical weed control
- Optimized planting date
- Optimized plant and row spacing
- Drought tolerant crops and varieties
- Zero tillage
- Breaking hard pans
- Wind breaks
- Avoidance of night frost
- more

Package to decrease consumptive use

- Shift to low ET crops
- Straw and mechanic mulching to reduce soil evaporation
- Varieties with high LAI that reduces soil evaporation
- Greenhouse crop cultivations
- Deficit irrigation practices
- Partial root zone drying
- Uniform and reliable water supply
- Flat furrow and borders to prevent water ponding
- Micro-irrigation to reduce soil evaporation
- Alternate wetting and drying rice crops
- Drainage to reduce soil evaporation and soil salinization
- Drainage to prevent anaerobic conditions
- more

The additional data layers produced by the Translator to support WP and WPS analysis are specified in Table 7. The standard data sets are provided per decade, but in addition several data components are expressed as accumulated values of the (variable) growing season. The trends between different years is also provided, being an interesting option for quickly reviewing which areas are gradually becoming more productive per unit of water, and which areas have a negative trend – for whatever reason. Figure x shows for example that BWP in Tadla (Morocco) is going down for both irrigated and rainfed crops. The below average rainfall is the main reason for this phenomenon. The irrigated crops are also affected due to low water levels in the reservoirs.

Climate has a crucial role in both ∑bio, Y, ∑ET and BWP, and these relationships are not univocal. Climate in WaPOR is expressed as a reference ET_0 and precipitation P. Note that P per definition includes rainfall and snowfall. The sensitivity of BWP to weather is essential for explaining deviations from the longer term mean BWP values. If for instance ET is decreasing and ET_0 does the same, then it is obvious that clouds, temperature and air humidity are plausible factors for lower ET. But clouds will also affect ∑bio, and this may compensate BWP (e.g. Zwart et al., 2010). Success in increased WP values can under such circumstance not be claimed by good on farm practice or large scale investments. The role of weather anomalies on BWP needs therefore always be investigated as a first step of the process.

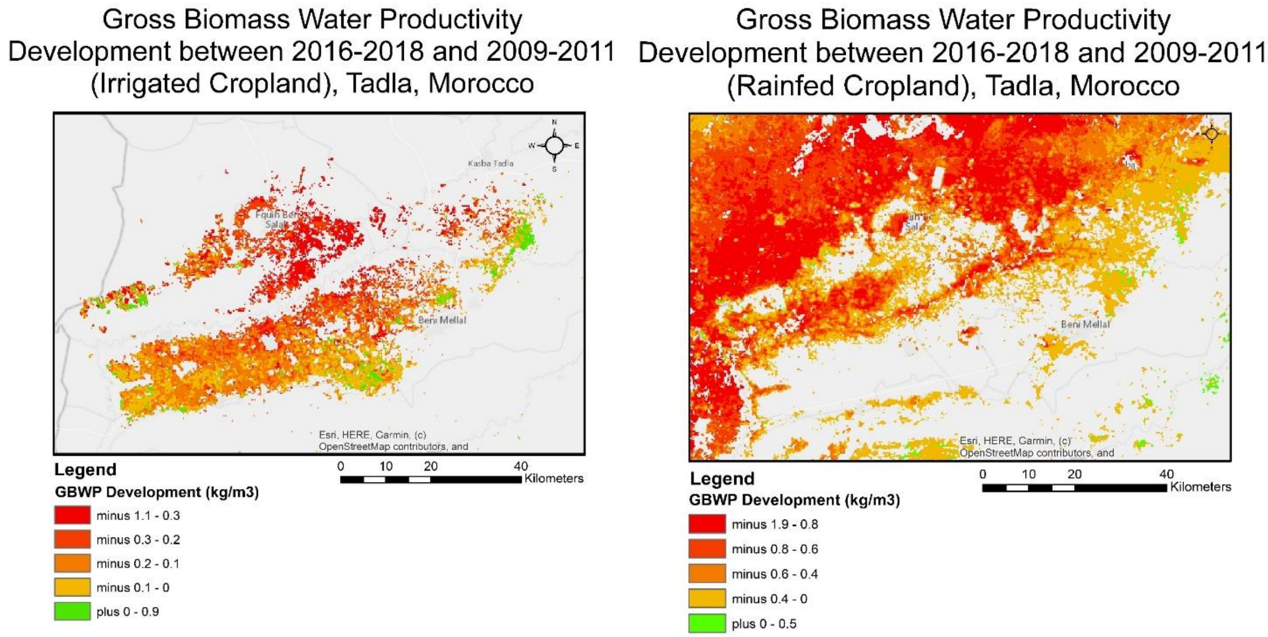
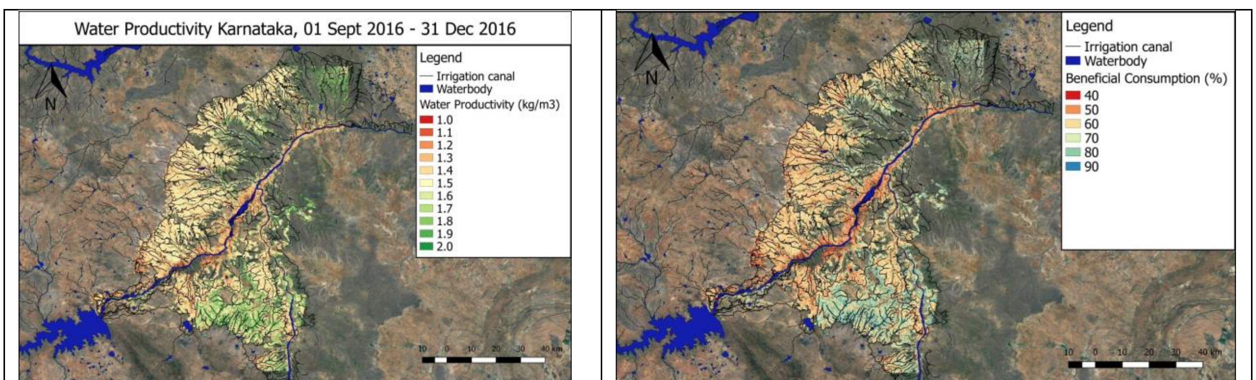


Figure 15: Temporal changes of BWP for irrigated and rainfed cropping systems in Tadla region, Morocco

The T in ET is directly related to beneficial consumption of water because T evaporates into the atmosphere through stomates that will take in carbon C from the atmosphere. It is a truly exchange process where water vapor H20 is exchanged for C. A pixel with high values of T and low values of E is preferred because it sequesters atmospheric carbon and enhance food security. Earlier studies have demonstrated strong relationships between T/ET vs. WP see Figure 16. T/ET can be managed by selecting crops with fast canopy development and high LAI values (e.g. corn). Micro-irrigation is also a substantial contributor to high T/ET values.



Crop water productivity (Y/ET)	Beneficial fraction (T/ET)

Figure 16: Impact of beneficial T expressed as a fraction of ET (T/ET) on the water productivity of Tungabhadra, Karnataka (India). It appears obvious that a T/ET ratio > 0.8 ensures a WP > 1.7 kg/m3 in flooded rice systems

The AquaCrop water use efficiency is an essential bio-physical property $\sum bio/(\sum T/\sum ET_0)$ that is model specific but essential for understanding the analytical relationship between crop production and normalized Transpiration rates ($\sum T/\sum ET_0$). The AquaCrop model parameter is generated from WaPOR to satisfy the users of the AquaCrop model (Steduto et al., 2006; 2016) that aim at studying on-farm incentives to increase water productivity (e.g. Berhane and Kefale, 2018). AquaCrop water use efficiency can also be considered as a check of the realism of the WaPOR data. The AquaCrop guideline value lies between 15 to 20 gr/m^2 for C3 crops and 30 to 40 gr/m^2 for C4 crops. C4 crops have a lower internal CO_2 concentration which implies that they always have a higher C intake flux as compared to C3 crops, simply because δC/δz of C4 crops is always more or less double as compared to C3 crops. Most crops are C3, except for sugarcane, corn and oilseeds that are C4. Hence this particular data layer produced by the Translater should reveal values between 15 to 40 gr/m^2. There are several papers on the calibration of normalized water productivity in AquaCrop, and this is great material for consistency checks of WaPOR data. While the AquaCrop values for water productivity are normalized against ET_0 and also for atmospheric CO_2 concentration, T-efficiency is a simpler ratio $\sum bio/\sum T$ that has been promoted since the early work of Tanner and Sinclair et al. (1983), see for instance Vadez et al. (2014). The principles of transpiration efficiency are similar as for AquaCrop, namely that carbon fluxes C and water vapor fluxes H_20 are bio-physically connected. It is a nice consistency check on WaPOR data.

Table 7: Specification of the folder structure of data components feeding into "Water Productivity"

Folder name	Unit	Purpose
Accumulated_ET	mm/season	Total consumptive use for producing a certain crop. It is the total value for the season
Accumulated_ET_Trend	mm/season/yr	Indicating per pixel the increase or decrease in consumptive use; very relevant for water conservation projects
Accumulated_ET0	mm/season	Total climatic evaporative demand for a growing season; can be used to assess role of weather variability on ET
Accumulated_ET0_Trend	mm/season/yr	Indicating per pixel the increase of decrease of climatic ET
Accumulated_P	mm/season	Total rainfall in a season; assessing possibility of rainfed agriculture; impact of rainfall on crop production
Accumulated_P_Trend	mm/season/yr	Indicating changes of rainfall
Accumulated_T	mm/season	Total consumptive use for a season that is beneficial
Accumulated_T_Trend	mm/season/yr	Indicating changes in beneficial crop water consumption
AquaCrop_Water_Use_Efficiency	gr/m^2	Making key parameters in AquaCrop and Wapor compatible
T_Efficiency	kg/m^3	Bio-physical property for checking realism of WaPOR data
GBWP_Decade	kg/m^3	Breakdown of GBWP into smaller time increment for understanding when gap in BWP arises
GBWP_Gap	kg/m^3	Gap between attainable and actual BWP; indication of possible real water savings
GBWP_Improvement_Requirement	kg/m^3	??
GBWP_Season	kg/m^3	Total GBWP for a season; intermediate parameter
GBWP_Target	kg/m^3	BWP of the 5% champion farmers; can be used as maximum attainable value in a certain agro-ecological zone
Normalized_GBWP_Max_Per_TBP	kg/m^3	Max GBWP per column or silo of Δbio
Normalized_GBWP_Min_Per_TBP	kg/m^3	Min GBWP per column or silo of Δbio
Water_Productivity	kg/m^3	Crop yield per unit of water consumed; can only be acquired if crop type is known
Water_Productivity_Score	kg/m^3	Grading system of WP between 1 and 10; Each incremental production class has its own min and max GBWP values

Examples of good applications of WaPOR data for Water Productivity:

- Identify champion farmers that can be used as target values of WP
- Visit champion farmers for reporting practices of the list of interventions that worked well under local practical field conditions
- The deviations between actual and target values of WP will show the scope of real water savings for closed basins or water scarcity conditions in general
- Relating variability of WP to variability in weather conditions (ET_0 and P) for appraising controllable and un-controllable influences on WP dynamics
- Assess relationship between soil type, soil fertility, soil water holding capacities and WP for detecting regional differences arising from soil properties
- Assess gap by comparing actual and target WP per AEZ zone
- Define priority areas for rural investment plans
- Understand efficiency of rainfed, water harvesting and irrigation cropping systems
- Assess the ultimate result of existing irrigation systems
- Study impact of donor related investments with the aim to increase water productivity
- Survey the net effect of subsidies to switch from flood to micro-irrigation

3.4 Irrigation management

Irrigation receives and consumes large volumes of renewable water resources. Overall, the satisfaction of managing current irrigation systems is low. This is often related to the fact that irrigation is focussing on the engineering part of the work (reservoir and canal operations), and not so much on the institutional aspects and the on-farm processes. Another reason is that water flows are hardly measured, which limits the monitoring and evaluation side of irrigation operations. The latter is unthinkable in a water utilization network. Budget constraints and limited staff capacity is also forming a limitation in Africa and NENA region, the area where WaPOR is focussing on. The generic problems in the irrigation sector are:

- Genuine lack of discharge measurements and flow information; a bit “wild west”
- Irrigated acreages, crop types and crop development stages often based on obsolete planning and design data
- Water supply and water demand not being synchronized, leading to over- and under irrigation = unnecessarily loss of land, water and energy resources
- Water productivity is currently sub-optimal (benefits from a cubic meter of water is low; more food; more profits; more labor are feasible)
- Water losses from canals and fields; while this water is partially recovered, it is uncontrollable, requires huge infrastructure, loses quality and costs energy
- Lack of water stewardship in agriculture leading to individual actions by absence of proper guidelines
- Uncontrolled groundwater withdrawals and falling water tables
- Manipulated water distribution and unauthorized water abstractions
- Irrigation performance framework not applied; malfunctioning practices continue
- Insufficient regulations and inforcement due to lack of information (besides weak governance)
- Lack of maintenance in canals and structures, hence water does not flow according to intentions
- Water logging and salinization
- Competition by other water use sectors
- Climate change decrease water resources availability

The irrigation sector is genuinely known as the sector using vast amounts of renewable water resources. Indeed this can be up to 90% in certain countries. Yet, the efficiency of transporting water from the main river and reservoir to the crop is sadly bad. Water losses occur in the conveyance process of bringing water from the dam via the head regulator to the farm gate, albeit unauthorized and non-intentionally water use occurs, and the planned volume of water hardly reaching its destination. Once flown through the farm gate, the next challenge is distribute applied water equally across a certain field. Furthermore, the amount of applied water should match with the crop water requirements and the capacity of the soil to retain irrigation water within the soil matrix. This process of water delivery and storage in the root zone is hardly convenient. Accordingly irrigation efficiencies are often lower than 50% (Bos and Nugteren, 1974; Wolters, 2000; Machibya et al., 2004; Schutllemeijer, 2017).

Irrigation efficiency (IE) is the ratio of the amount of water consumed by the crop to the amount of water supplied through irrigation (surface, sprinkler or drip irrigation).

While certain stakeholders are ashamed regarding this low performance, other stakeholders believe all “water losses” are recycled. In fact, both sides of the equation have valid points and reality is not as contumacious as sketched. Runoff and percolation are to a large extent recaptured and reused downstream in a natural manner; runoff goes to drains and ditches and percolation recharges the aquifer. Farmers withdraw water from these locations. This is also known as recapturing of non-consumptive use water. But is an example of uncontrolled water flow, and the water-food-energy nexus learns us that this goes together with a huge energy consumption (why pumping water up when it in the end is spilled ?), and water quality degradation. Agriculture has significant non-source pollutions, and the pollutants end up in the return flows of irrigation. If the electric conductivity of the return flow water exceeds a certain threshold, it cannot be reused. So while the water is not consumed, it is cannot be recapture. Hence, low efficiencies should not be stimulated, despite that “losses” are reused. A different manner to express successful irrigation is the determination of consumptive use and non-consumptive use (Perry, 2009; Simons et al., 2019).

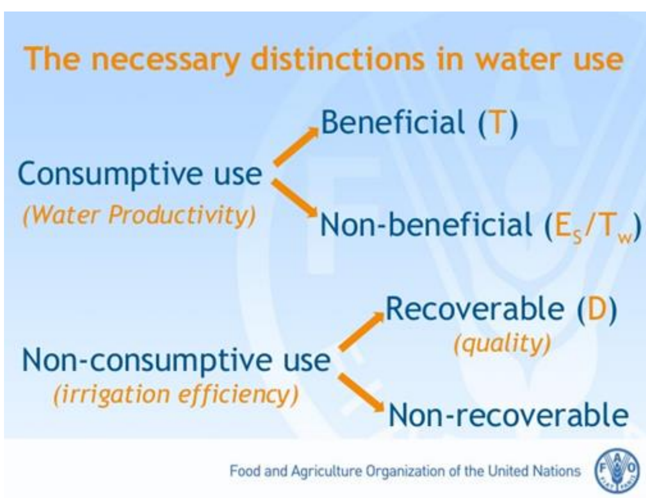


Figure 17: Irrigation terminology proposed by the International Commission on Irrigation and Drainage

While the irrigation sector remains to be plagued by its low efficiencies, it is advisable to study also other aspects of irrigation performance. Bastiaanssen and Bos (1999) reviewed a number of irrigation performance indicators based on remote sensing data. As a matter of fact, there is a long list of different perspectives on successful irrigation processes, and this is related to the purpose of irrigation. The large irrigation systems in India and Pakistan focus on equity; all farmers – small or large – have a similar right to water per unit area. Other systems, want to maximize water productivity or aim at match supply and demand so that adequacy is reached. In a certain way, any good performing irrigation system starts with adequate knowledge of the (i) Area, (ii) Crop Water Requirements (CWR) and (iii) Irrigation Water Requirements (IWR) and (iv) Renewable Water Resources. There is a fundamental difference between CWR and IWE, and they are often mixed up:

$$CWR = ET_{pot}$$

The potential ET is the consumptive use that occurs when ET is not constraint by soil moisture. The Transpiration flux (T) is under these circumstances reaching the maximum possible value as constrained by the opening of the stomates. Crops with higher Leaf Area Index (LAI) such as maize or sugarbeet will have a higher T than for instance onions of grapes that not fully cover the soil. The Evaporation flux from bare soil (E) depends on rainfall and type of irrigation. A flood irrigation system will unavoidable have a larger E than a drip system. In the former the entire field is wetted while in the case of the latter, wet soil is avoided. One interim conclusion is that E depends on the irrigation system in place and the local weather conditions. In monsoonal climates, E is high due to frequent wetting of the top soil. Because of the different nature of the T and E processes, it is customary to define a dual crop coefficient that incorporates wetness of the topsoil that affects E and wetness of the subsoil that affects T:

$$ET_{pot} = (K_e + K_s K_{cb}) ET_0$$

Where K_e represents top soil moisture conditions and E, K_s is the stress coefficient for water in the root zone and K_{cb} is the basal crop coefficient that mainly varies with vegetation cover (Allen et al., 1998). In case of $ET=ET_{pot}$, K_s=1.0. If $ET<ET_{pot}$, K_s<1.0 applies. The Level-1 data in WaPOR provides ET and ET_0. The Translator computes ET_{pot} from K_{cb} as 0.95 x veg cover (see Table 7). The FAO56 solution of K_c is to assume the top soil to be dry and K_e approaches 0.2. So in a nutshell the Crop Water Requirements can be approximated as a climatological ET_0 value and a fractional vegetation cover.

The amount of water that needs to be allocated depends on the expected rainfall during the period of planning. The gross rainfall is not fully available for crop ET and instead an effective rainfall of 70% is taken. Hence, 70% of the rainfall is assumed to infiltrate into the soil and stored in the root zone for water uptake by roots. This amount of water can be subtracted from the irrigation applications. There are unavoidable within-field irrigation water losses that has to be taken into account for converting ET_{pot}-P_{net} into IWR. In our case we use an on-farm efficiency of 65%. This is perhaps somewhat optimistic because the review described above suggests the overall efficiency to be lower than 50%, there should also be a stimulus for water managers to execute good irrigation water management practices:

$$IWR = (ET_{pot} – 0.7\ P) / 0.65$$

IWR in WaPOR should be interpreted as representing the water demand for every pixel of 100 m x 100 m, being equivalent to the water demand at the farm gate. IWR is a theoretical value of water that needs to be supplied to prevent crop water stress. The real amount of Applied Water is the volume of water actually provided, and thus differs from IWR. The Gross Irrigation Water Supply (GIWS) is the amount that is actually applied (Applied Water). GIWS is computed from the soil water balance as specified in Table 7 using proxies for surface runoff and deep percolation, as opposed to a fixed efficiency term. The difference between CWR and Applied Water is an indication of adequacy or water scarcity. It can be ascribed to insufficient water resources availability in the reservoir, but also due to vast amount of water losses from canals, water theft by upstream farmers and cultivation of high water demanding crops not in line with the design criteria of the irrigation scheme. Hence, farmers can also create their own water scarcity by over-requesting water resources. Water scarcity is certainly not related solely to a lack of renewable water resources.

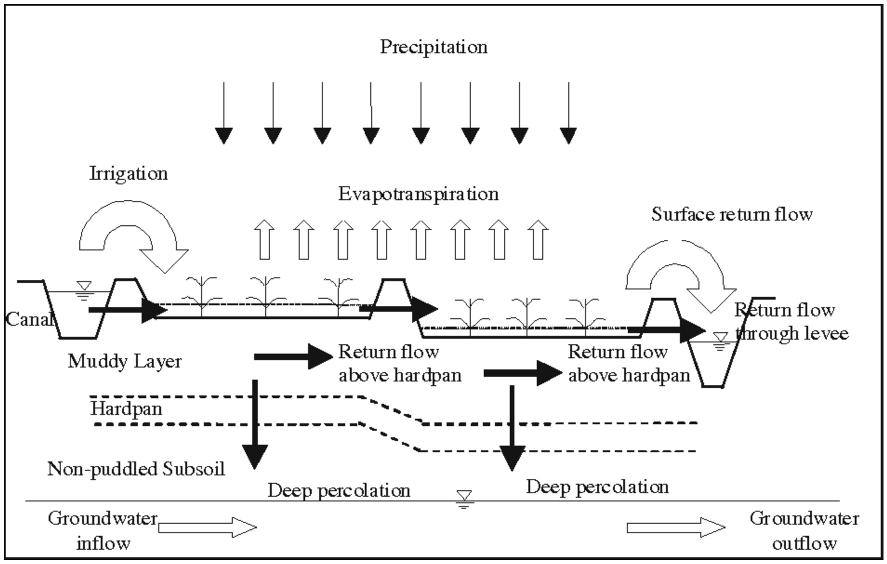


Figure 18: Field irrigation losses from classical surface irrigation

The distribution of irrigation water has to be organized by a set of rules set by the Governments, Irrigation Departments, Water User Associations and farmers. Often Governments are responsible for the operations of the main and secondary canals. Farmers and their cooperatives manage for the tertiary and quarterly canals. So both parties need information on IWR and GIWS, and it is not common that this type of data is at hand, and certainly not sharing it among stakeholders. In fact, it is a nice example of WaPOR Level 3 data to bring more transparency in the distribution of irrigation water for society.

The Translator is computing irrigation-related flows and fluxes according to Table 7. The perfect irrigation water distribution should lead to avoidance of crop water stress and prevent water spillage at the other hand. Not too much and not too little. Different indicators exist to express the adequacy of water supply. Relative Water Supply (RWS) relates GIWS with CWR (i.e. ET_{pot}). RWS should typically be 1.2 to 1.5. Many irrigation benchmarking studies are based on RWS (e.g. Sakthivadivel, 1993). A more specific expression for adequate supplies is the Relative Irrigation Water Supply (RIWS) that relates GIWS to IWR (see Table 7). While the supply at the farm gate can be proficient, that is no guarantee that the crop receives the intended water resources due to challenges in on-farm water distribution. The latter can be related to improper advanced and recession waves, pressure losses in pipes or undulating fields with ponding water surfaces. The soil moisture in relation to the critical soil moisture below which stress is triggered provides direct information on the sufficiency of soil moisture (and thus indirectly whether irrigation water has reached the crop). If θ/θ_{crit} is lower than 1.0, then the soil is too dry and the overall irrigation process failed. If θ/θ_{FC} is more than 1.0, then over-irrigation occurs due to leaking fields. More irrigation is not always better. If the soil moisture exceeds its field capacity θ_{FC}, the unsaturated soil will start losing a lot of water by leakage, or if permeability is low, it can create a ponding surface with anaerobic environments that negatively affects photosynthesis. While soil moisture is crucial for assessing under-irrigation, the Crop Water Deficit (ET_{pot} – ET) is even a greater parameter to check whether the crop is really experiencing the stress expected. In the end consumptive use should be at a level that sap-flow through the crop is not hampered so that the crop is cooled and all required nutrients and transported in solution from the soil into to crop.

Water conservation – and in particular introducing caps of consumptive use – can lead to restoration of the environment. This relates to irrigation systems with rapidly declining groundwater tables and streams and lakes that fall dry due to interrupted baseflow. Pixels with the lowest ET values are searched and verified whether they have sufficient or good production. If so, it is demonstrated that agriculture is not necessarily hampered if certain targets of lower ET are introduced. This is referred to in the Translator as the target ET. The decadal ET savings are based on the difference between actual ET and the lower target ET.

Murray-Rust and Snellen (1993) defined a number of performance indicators, each of them having a special contribution to describe the functioning of an irrigation system:

Adequacy	: A system is inadequate at insufficient supply of water due to restricted supplies, water thefts or overwhelming Irrigation Water Requirements not in par with canal water supplies
Equity	: Equal amount of water to all irrigators, independent of crop water requirement or size of land holding; the main principle is to share scarce water equally among all users and generate uniform conditions for socio-economic development
Reliability	: Realization of a certain amount of irrigation water to be delivered according to an agreed schedule; it helps farmers to know when and how much water is coming sothat they can plan and operate a certain cropping system
Productivity	: Ultimate result of irrigation in terms of crop yield or monetary unit per unit of water. Preferably the unit of water should be expressed as a consumptive use, but some use Applied Water. So be cautious on this definition

Soil moisture in the root zone is the ultimate indicator on whether irrigation has reached the crop. Spatial equity is defined as the standard deviation of soil moisture across a certain domain divided by the average value of that domain. Spatial equity is reached if $\Theta_{std}(x,y)$ /$\theta_{mean}(x,y)$ is lower than 0.1 because there is always a certain level of non-uniformity. Unacceptable spatial non-uniformities arise if $\Theta_{std}(x,y)$ /$\theta_{mean}(x,y)$ exceeds 0.5. That will reveal a situation with where certain fields receive much more water than other fields. For larger fields, the concept of spatial equity can also be applied within the field. It is interesting to study equity within plantations such as Wonji. There the uniformity should be high as they are all under the same management. If not, then commercial irrigation systems should improve their operations.

Conjunctive use of canal water and groundwater resources usually increase equity and adequacy. If for instance the canal water supply is unreliable or insufficient to grow perennial crops (e.g. stone fruits, tropical fruits, sugarcane), farmers may invest in tubewells. When properly operated, this will undoubtedly lead to more uniformities. The reliability of irrigation water supply is important for a farmer to invest in for instance a high quality seed and good quality fertilizers. He/she has to trust canal water is coming according to the agreed schedule provided by the Irrigation Department. Trust in the canal operations may prompt to plant higher value crops (e.g. from sorghum to cotton). Investments are at risk if irrigation systems are unreliable. Following Alexdridris et al. (1999), the reliability in the Translator is computed as a temporal variability $\Theta_{std}(t)$ /$\theta_{mean}(t)$, thus one particular pixel is followed in time. If the variation of soil moisture during the season is mild, then irrigation water is delivered on time. If one observes significant fluctuations in soil moisture, then it is obvious that the service of irrigation water delivering is improper. Reliability of the canal and hydraulic structure operations will have adverse impacts on the food production and WP values. Adequacy, equity and reliability indicators can thus be used to explain certain findings of land and water productivity.

Table 8: Mathematical formulation of irrigation related indicators

Data component	Unit	Equation	Data in equation
Irrigation Water Requirement	mm/decade	$IWR = \frac{(ET_{pot} - 0.7 * P)}{0.65}$	*ET_{pot} = Crop Water Requirement* *P = Precipitation*
Gross Irrigation Water Supply	mm/decade	$GIWS = MAX(0, (net_{\pm -} + q \downarrow + R_p) * (1 + S\ )$	*net_{+-} = net supply (+), net drainage (-)* *q↓ = deep percolation* *R_p = Surface runoff* *S = Surface runoff coefficient*
Relative Water Supply	-	$RWS = \frac{(GIWS + P\ )}{ET_{pot}}$	*GIWS = Gross Irrigation Water Supply* *P = Precipitation* *ET_{pot} = Crop Water Requirement*
Relative Irrigation Water Supply	-	RIWS= $\frac{GIWS}{IWR}$	*GIWS = Gross Irrigation Water Supply* *IWR = Irrigation Water Requirement*
Degree of under-irrigation	-	$= \frac{\Theta}{\theta crit}$	*Θ = Soil Moisture Root Zone* *Θcrit = Critical Soil Moisture below which water stress is triggered*
Degree of over-irrigation	-	$= \frac{\Theta}{\theta FC}$	*Θ = Soil Moisture Root Zone* *θFC = Soil moisture at Field Capacity*
Crop Water Deficit	mm/decade	$CWD = ET_{pot} - ET$	*ET_{pot} = Crop Water Requirement* *ET = Actual Evapotranspiration and Interception*
Equity	-	$\Theta_{std}(x,y) / \theta_{mean}(x,y)$	*Θ = soil moisture in root zone* *Std = standard deviation* *x,y = spatial variability*
Reliability		$\Theta_{std}(t) / \theta_{mean}(t)$	*Θ = soil moisture in root zone* *Std = standard deviation* *t = temporal variability*
On-farm irrigation efficieny	%	$Eff = MIN(95\ ; \frac{ET_{blue}}{GIWS} * 100)$	*ET_{blue} = Consumptive use due to irrigation* *GIWS = Gross Irrigation Water Supply*
Consumptive use due to irrigation (ET_{blue})	mm/decade	$= If((ET > 0.7 * P)\ ; (ET - 0.7 * P)\ ; 0)$	*ET = Actual Evapotranspiration and Interception* *P = Precipitation*
Non-consumptive use due to irrigation	mm/decade	$= MAX(0\ ; GIWS - ET_{blue})$	*GIWS = Gross Irrigation Water Supply* *ET_{blue} = Consumptive use due to irrigation*
Non-beneficial water losses	mm/decade	$= (E + I)$	*E = Evaporation* *I = Interception*
Decadal ET savings – spatial	mm/decade	$= MIN(0\ ; ET_{target} - ET)$	*ET_{target} = Lowest ET with good to very good crop production*

Hence, the management of irrigation systems depends really on the targets and goals set out at the start of the design of the scheme and at the start of rehabilitation projects. Water distribution according to adequacy is something else then according to equity or reliability. Having a fleet of irrigation performance indicators available (see Table 8), it is now possible to conduct a standard analysis.

Table 9: Specification of the folder structure of data components feeding into “Irrigation Management”

Folder name	Unit	Purpose
Irrigation_Water_Requirement	mm/decade	Amount of water required at the farm gate
Gross_Irrigation_Water_Supply (GIWS)	mm/decade	Applied Water at the farm gate
Adequacy_Relative_Water_Supply	-	Planning irrigation water roster
Adequacy_Relative_Irrigation_Water_Supply	-	Checking supply at the farm gate being in agreement with the irrigation water requirements
Degree_of_Over_Irrigation		Pinpointing careless irrigation practices
Degree_of_Under_Irrigation	-	Pinpointing general lack of water and need to supplement by water transfers or groundwater investments
Adequacy_Crop_Water_Deficit	mm/decade	Checking whether insufficient irrigation water is affecting crop ET and crop production
Equity_Soil_Moisture	-	Uniformity of irrigation water distribution in the space domain
Reliability_Soil_Moisture	-	Reducing intolerable fluctuations of soil moisture due to improper water supply services
ET_Savings_Spatial	mm/decade	Determination scope of savings on consumptive use by checking spatial variabilities within area of interest
ET_Target_Spatial	mm/decade	Moet die er wel in ?
ETblue	mm/decade	Consumptive use due to irrigation water supply
Non_Consumptive_Use_Due_To_Irrigation	mm/decade	Non-consumptive use due to irrigation water supply
On_Farm_Irrigation_Efficiency	%	Percentage of irrigation applied water that reaches the crop
ETgap	mm/decade	?
Feasible_Water_Conservation	mm/decade	Absolute amount of water that could be saved from introducing water conservation measures
Mean_Long_Term_Evapotranspiration	mm/decade	Longer term average water consumption in irrigated crops

Examples of good applications of WaPOR data for irrigation management

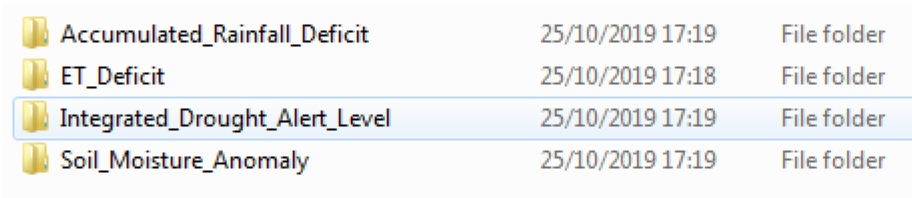
- Determine monthly or decade values of area truly irrigated
- Pinpoint area with over- and under irrigation
- Unauthorized water usage
- Compute decadal Irrigation Water Requirements and compare with water flows in main canals
- Express the performance of given irrigation systems into efficiency, adequacy, reliability and equity on a decade-by-decade basis and for every 1 ha area (i.e. 1 pixel)
- Alternatively diagnose an irrigation system in terms of consumptive use – non consumptive use and recaptured water
- Aggregate the performance assessment to different canal hierarchies, i.e. tertiary, secondary canal command areas
- Detect areas of low and high water productivity and relate these areas to the system performance indicators; what are the causing factors for productivity variations ?
- Breakdown the analysis by decades
- Spatially identify unauthorized water users
- Organize field surveys and farmer meetings for discussing their perceptions
- Show responsible organizations their hotspots
- Update the water allocation plan and monitor it
- Provide capacity building on WaPOR irrigation management information to responsible agencies
- Evaluate the need of new infrastructure and expansion of irrigated land
- Prioritize rehabilitation areas
- Define water fees on the basis of consumptive use
- Improve society engagement in on-farm water management improvements

3.5 Drought

Droughts arise after anomalies of weather conditions, such as a deviating rainfall, snowfall and cloud cover. Cloud cover controls the availability of solar radiation for ET and photosynthesis. Lush green and healthy vegetation arises only if there is sufficient sunshine and precipitation. Irrigation can also be drought affected because the amount of runoff from mountainous catchments into reservoirs is diminished or the Crop Water Requirements have risen due to abundant solar radiation and higher temperatures. Drought should not be confused with a high level of aridity being more a longer term climatological phenomenon. The Sahara is arid and dry but does not have necessarily droughts. It is referred to as droughts if rainfed farmers in Sahel will not get the required 300 mm of rainfall sothat they cannot plant crops. Or the water levels in reservoirs from preceding Winter season is reaching a level that certain areas cannot longer be irrigated.

Drought in WaPOR – Translator is related to rainfall, soil moisture, ET and crop production.

Table 10

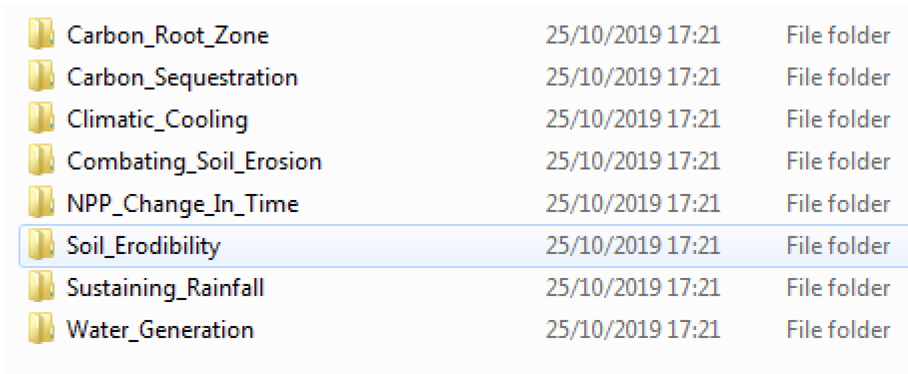


3.6 Climate smart agriculture

Hier moeten de vergelijkingen komen

Data component	Unit	Equation	Data in equation
Carbon pool root zone – cropland	kg/ha	$= (carbon\ stock_{5-15\ cm} +\ carbon\ stock_{15-30\ cm} +\ carbon\ stock_{30-60\ cm}) * 1000$	*Carbon stock$_{5\text{-}15cm}$ = Soil Organic carbon stock 5 – 15 cm* *Carbon stock$_{15\text{-}30cm}$ = Soil Organic carbon stock 15 – 30 cm* *Carbon stock$_{30\text{-}60cm}$ = Soil Organic carbon stock 30 – 60 cm*
Carbon pool root zone – pasture	kg/ha	$= (carbon\ stock_{5-15\ cm} +\ carbon\ stock_{15-30\ cm}) * 1000$	*Carbon stock$_{5\text{-}15cm}$ = Soil Organic carbon stock 5 – 15 cm* *Carbon stock$_{15\text{-}30cm}$ = Soil Organic carbon stock 15 – 30 cm*
Carbon sequestration – cropland	kg/ha/decade	$= 10 * NPP * \left(\frac{1-4}{(4+1)}\right) * number\ of\ days * 0.3$	*NPP = Net Primary Production*
Carbon sequestration – pastures	kg/ha/decade	$= 10 * NPP * \left(\frac{1-1.5}{(1.5+1)}\right) * number\ of\ days * 0.7$	*NPP = Net Primary Production*
Climate cooling	°C/decade	$= \frac{\left((0.7 * R_n - (1 - EF) * R_n) * \left(\frac{208}{wind\ speed}\right)\right)}{(1.15 * 1004)}$	*R_n = net radiation* *EF = Evaporative Fraction* *Wind speed = 24hr wind speed*
Water generator or total runoff generation	m^3/ha/decade	$= (R_P + \text{q} \downarrow) * 10$	*R_p = Surface runoff* *q↓ = deep percolation*
Soil Erodibility (K)	-	$= \frac{\left(\frac{0.043 * PH + 0.062}{(carbon_{0\ cm} * 10) + 0.0082 * F_{sand} - 0.0062 * F_{clay}}\right) * F_{silt}}{10}$	*PH = Soil PH x 10 in H_2O – 0 cm* *Carbon$_{0\ cm}$ = Soil Organic Carbon – 0 cm* *F_{sand} = Sand fraction* *F_{clay} = Clay fraction* *F_{silt} = Silt fraction*
Combatting soil erosion	kg/ha/decade	$= 50 * TRG * K * 1 * Slope * Vc * 0.5$	*TRG = Total runoff generation* *K = Soil Erodibility*

			Vc = Fractional Vegetation Cover
Sustaining rainfall	m^3/ha/decade	$= 0.2 * ET * number\ of\ days$	*ET = Actual Evapotranspiration and Interception*



4. Diagnoses

4.1 Food security

4.2 Water productivity

4.3 Irrigation management

4.4 Drought

4.5 Climate smart agriculture

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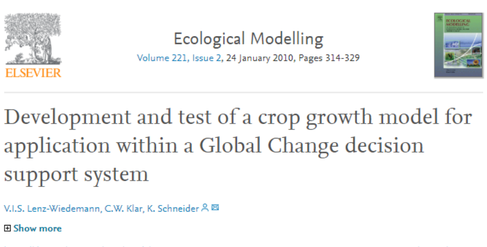
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Appendix A: Crop dependent conversion factors between accumulated biomass production and crop yield

Crop	Typical Harvest index	Range Harvest Index	Moisture content (harvestable product)
	(-)	(-)	(Weight %)
Alfalfa	0.5	0.20 – 0.70	10
Apple	0.4	0.3 – 0.65	80
Avocado	0.45		55 to 65
Banana	0.6		76
Barley	0.38	0.10 – 0.57	
Beans	0.32	0.16 – 0.65	33
Cassava	0.60		65
Chickpeas	0.37	0.13 – 0.55	10 to 20
Chili peppers	0.6		130
Chrisanthemum (flowers)	0.46		
Coconut	0.34		Not applicable
Coffee (beans)	0.10	0.05 – 0.10	45 to 55
Cotton (bolls)	0.14	0.07 – 0.23	2
Dates	0.3	0.3 – 0.4	20 to 35
Eucalypt	0.5		50
Garlic	0.72		70
Grapes	0.22	0.11 – 0.43	75
Grass	0.45	0.40 – 0.55	60
Lentil	0.33	0.10 – 0.51	
Lucerne	0.60		
Maize – rainfed	0.32	0.20 – 0.47	26
Maize – irrigated	0.39	0.40 – 0.62	26
Mango	0.20	0.14 to 0.24	84
Mangosteen	0.02		80
Oat	0.21	0.11 – 0.48	
Olives	0.012		20
Onions	0.55		85
Oranges	0.22	15 – 35	85
Palm oil	0.185		1
Pea	0.36	0.10 – 0.58	
Peanut (pods)	0.35	0.20 – 0.57	13 – 18
Pecan	0.12 – 0.13		18 – 22
Pineapple	0.80		80 – 90
Potato	0.80	0.75 to 0.85	78 – 82
Rapeseed	0.28	0.10 to 0.41	
Rice – rainfed	0.33	0.20 – 0.50	14 – 19
Rice – irrigated	0.42	0.20 – 0.55	14 – 19
Rubber	0.013		63
Sorghum	0.46	0.10 – 0.60	35
Soybean	0.20	0.10 – 0.40	15
Sugar beet	0.60		80
Sugar cane	0.69	0.65 – 0.85	65

Sunflower (seeds)	0.50		
Sweet potato	0.65		
Tapioca			
Tea	0.12	0.03 – 0.15	50
Tulip (flowers)	0.20		
Vetch	0.38	0.16 – 0.47	
Wheat	0.37	0.10 - 0.56	14 - 17