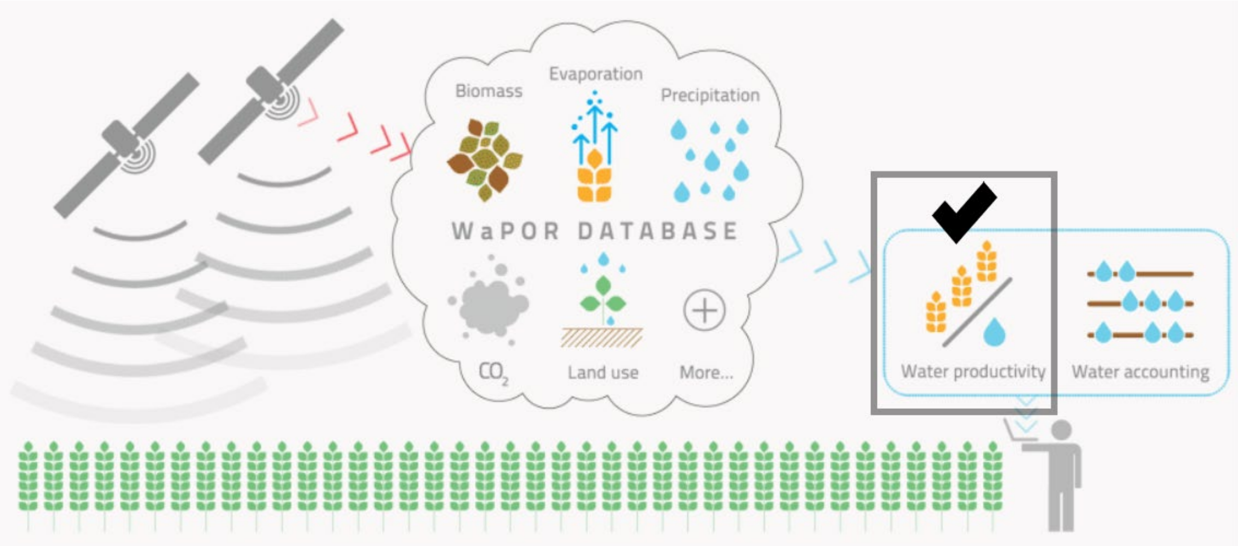
Standardized protocol for the land and water productivity analyses using WaPOR



Water Productivity Improvement in Practice (Water-PIP)

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1 Introduction

Productivity is defined as a measure of gains per unit of resource use (Zwart and Bastiaanssen, 2004). For agriculture purposes, the most important indicators are biophysical, economic or social gains compared to the amount of land and water used. The most commonly used productivity indicator in agriculture is yield which defines the biophysical gain per unit of land (also called land productivity). With increasing concerns about the available water resources, water productivity has gained interest.

1.1 Importance

The increased gains per unit of water and land would benefit the farmer and scheme manager as well as being beneficial at the basin level.

Farmers often aim to maximize the benefit generated per unit of land, as this is their main constraint. While the top priority of the river basin authority is to allocate water resources in an equitable, efficient, and sustainable manner between different water uses/ users. Thus, at the river basin level, the interest is to optimize the productivity of water use while maintaining equity and sustainability as core values. Policymakers are often interested to increase production and thus national income as well as increase employment.

1.2 WaPOR data

FAO's portal to monitor Water Productivity through Open-access of Remotely sensed derived (WaPOR) was "created to provide relevant and specific information on water and biomass status to develop solutions to sustainably increase agricultural land and water productivity"[1]. WaPOR is the first comprehensive dataset that combines water use (actual evaporation, transpiration and interception), production (net primary production), land use (land cover classification), phenology, climate (precipitation and reference evapotranspiration) and water productivity layers covering sub-Saharan Africa and the Near East and North African regions. The data is available at decadal time steps and in near real-time for the period between 2009 to present day. WaPOR datasets are available at the continental scale (Level 1 at 250 m), country and river basin (Level 2 at 100 m) and project level (Level 3 at 30 m). The latest WaPOR portal (WaPOR v2.1), was improved from WaPOR v1.0 following the independent quality assessment by IHE Delft and ITC (FAO and IHE, 2019). The methodology used for compiling the WaPOR database is provided in FAO (2020a) .

1.3 Ground data

Ground data such as the boundary of the farm (to download WaPOR data and filter non cropped area), moisture content of fresh biomass (to convert dry matter to biomass), above ground over total biomass (to estimate the above ground biomass), start and end of seasons (to aggregate water and climate data per crop season), harvest index (to derive crop yield from above ground biomass) and crop coefficient (to estimate potential evapotranspiration from reference evapotranspiration) are required.

1.4 Protocol: objectives, scope and target audience

The protocol is aimed at guiding users to understand the different layers contained in the FAO Water Productivity Open-access portal (WaPOR) which can be used for land and water productivity analyses. It provides python scripts which can be used to calculate land and water productivity and other performance indicators such as uniformity, efficiency (beneficial fraction), adequacy, relative water deficit as well as estimating productivity gaps. For each step, the protocol provides information about the assumptions used and provides links to reference materials.

Scope: The protocol is tailored to biophysical water productivity with respect to consumed water use and land productivity at areas (fields, and schemes) in similar agro-climatic zones. The protocol can be applied to single water management unit and crop production regardless of the water sources (e.g. from exclusively rainfall (rainfed), or irrigation (augmented through surface water and/or groundwater, or flood /spate)). The protocol is developed for agricultural areas with a single crop and same cropping season, which can vary between years. Implementing the protocol beyond fields/ scheme level such as a river basin and country levels, which could fall in different agro-climatic zones, require normalization for climate variation – which is outside the scope of the protocol.

Target: The protocol is developed for project leads, irrigation managers and researchers who have a basic understanding of python and agricultural practices.

2 Installation requirements

The scripts to download and process the WaPOR data for land and water productivity assessment are developed in the python programming language. The scripts can be downloaded from the water

[1] http://www.fao.org/in-action/remote-sensing-for-water-productivity/overview/objectives/en/

accounting repository on GitHub[2] and run in Jupyter Notebook. Beginners of python programming are advised to follow the OCW of IHE Delft on python scripting before starting with implementing the provided scripts[3]. A beginning programmer should be able to run the scripts, it is advised to run them using Jupyter notebook. The following sections describe the installation requirements.

2.1 Running from Jupyter notebook

The requirement of the python and libraries used in the protocol

- python 3.7.3
- numpy 1.16.4
- pandas 0.24.2
- GDAL 2.3.3
- pyshp 2.1.0

2.2 Install python, Jupyter notebook and libraries (packages)

i) Install python and Jupyter notebook using the Anaconda distribution: https://www.anaconda.com/products/individual. Use the anaconda installer, which is tailored to different operating systems: window (64-Bit and 32-Bit), MacOS (64-Bit) or Linux system.

Read more on Jupyter notebook: https://jupyter.org/, https://packaging.python.org/overview/

ii) Install packages:

Packages such as GDAL, pyshp can be installed using pip or conda.

a) Pip is the Python Packaging Authority's recommended tool for installing packages from the Python Package Index (PyPI), which is a repository of software for the Python programming language (https://pypi.org/). **Pip** installs python **packages** in any environment. Type the following codes to **Install a pip package in the current Jupyter kernel:**

```
import sys
!{sys.executable} -m pip install 'package'
```

b) Conda is a cross platform package and environment manager that installs and manages conda packages from the Anaconda repository (https://repo.anaconda.com/) and the Anaconda Cloud (https://anaconda.org/). **Conda** installs any package in **conda environments**. Type the following codes to **Install a conda package in the current Jupyter kernel:**

```
import sys
!conda install --yes --prefix {sys.prefix} 'package'
```

Example: screen shot of installing gdal package

[2] https://github.com/wateraccounting/WAPORWP
[3] OCW link

```
import sys
!{sys.executable} -m pip install gdal
```

```
Requirement already satisfied: gdal in c:\users\ach006\appdata\local\continuum\anaconda3\lib\site-packages (2.3.3)
```

```
import sys
!conda install --yes --prefix {sys.prefix} gdal
```

```
Collecting package metadata (current_repodata.json): ...working... done
Solving environment: ...working... done

# All requested packages already installed.
```

```
import sys
!{sys.executable} -m pip install pyshp
```

```
Requirement already satisfied: pyshp in c:\users\ach006\appdata\local\continuum\anaconda3\lib\site-packages (2.1.2)
```

```
import sys
!conda install --yes --prefix {sys.prefix} pyshp
```

```
Collecting package metadata (current_repodata.json): ...working... done
Solving environment: ...working... done

# All requested packages already installed.
```

More tutorials on **conda** commands: https://docs.conda.io/projects/conda/en/latest/user-guide/index.html

3 Structure of the protocol

The protocol has six modules, which are described in detail in the following sections. For each of the modules, a Jupyter notebook was developed, containing the scripts. Module 0 focuses on downloading WaPOR data on actual water consumption (ET), actual transpiration, reference evapotranspiration and net primary production. In Module 1, the pre-processing of the data to match the spatial resolution and remove non-crop pixels is conducted. In Module 2, the seasonal water consumption (transpiration, actual evapotranspiration, reference evapotranspiration and potential evapotranspiration) and seasonal net primary production are computed. In Module 3, different performance indicators are calculated. In Module 4, land and water productivity are computed. And finally in Module 5, bright spots and productivity gaps are calculated.

Figure 1. Flow chart for downloading WaPOR data and calculate performance indicators, land and water productivity and productivity gaps (a) and a screenshot of the Jupyter notebook for the six modules (b).

3.1 Download WaPOR data (Module 0)

https://github.com/wateraccounting/WAPORWP/blob/master/Notebooks/Module_0_WaPOR_data_bulk_download.ipynb

Step 0a Import modules/libraries
Step 0b Read the geographical extent of the study area
Step 0c Bulk-download WaPOR data for the study area extent

The main objective of this module is to download the relevant data for the water productivity analysis protocol in the correct units. For these analyses, we need to download 6 different WaPOR layers (Table 1). The precipitation and reference evapotranspiration layer are available at 5 and 20 km resolution respectively. The other four layers, actual evapotranspiration and interception, transpiration, net primary production and land cover classification are all available at three different resolutions (250, 100 and 30 m). All layers, except land cover classification, are available at decadal, monthly and yearly temporal resolution. The land cover classification at 30 m is available at decadal and annual resolution; and at 250 and 100 m resolution it is available at annual resolution. For the analyses we are using the decadal data set, except land cover classification is annual data set. The WaPOR data is available for Africa and the Near East at 250 m resolution. The availability of the higher resolution data (100 and 30m) is dependent on your location (Table 2).

Table 1 WaPOR data used for the Water Productivity analyses

No.	WaPOR Data	Spatial resolution	Temporal resolution	Unit	Temporal coverage
1	Actual Evapotranspiration & interception (AETI)	250/100/30 m	Decadal	mm d^{-1}	2009-present
2	Transpiration (T)	250/100/30 m	Decadal	mm d^{-1}	2009-present
3	Net Primary Production (NPP)	250/100/30 m	Decadal	gC $m^{-2}d^{-1}$	2009-present
4	Land cover classification (LCC)	250/100/30 m	Annual		2009-present
5	Precipitation (PCP)	5 km	Decadal	mm d^{-1}	2009-present
6	Reference Evapotranspiration (RET)	20 km	Decadal	mm d^{-1}	2009-present

Table 2 Spatial resolution and extent of the three WaPOR Levels

Level	Spatial resolution	Extent
1	250m	Africa and Near East
2	100m	Countries: Morocco, Tunisia, Egypt, Lebanon, Syrian Arab Republic, Jordan, Ghana, Kenya, South Sudan, Mali, Benin, Ethiopia, Rwanda, Burundi, Mozambique, Uganda, West Bank and Gaza Strip, Yemen, Iraq, Niger and Sudan. River basins: Jordan / Litani, Nile, Awash and Niger
3	30m	Bekaa (Lebanon), Koga and Awash (Ethiopia), Office du Niger (Mali), Zankalon (Egypt), Busia County (Kenya), Lamego (Mozambique) and Gezira (Sudan).

The scripts in this step first determine the geographical extent of the study area. By reading the shapefile of the area, it will use the outer extent to download the relevant data. The scripts for the bulk download correct the data for the conversion factor and correct for the units from an average daily value to the total amount in a decade by multiplying by the number of days in a decade. An example of the download script is provided in box 1.

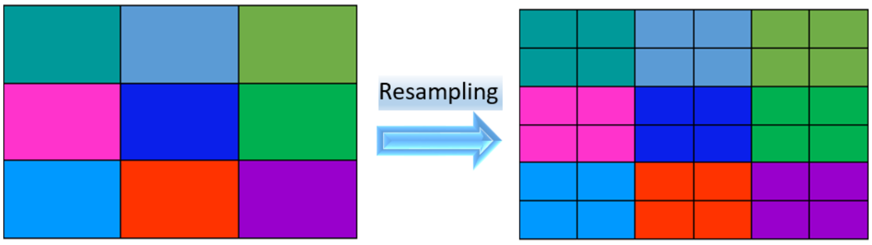
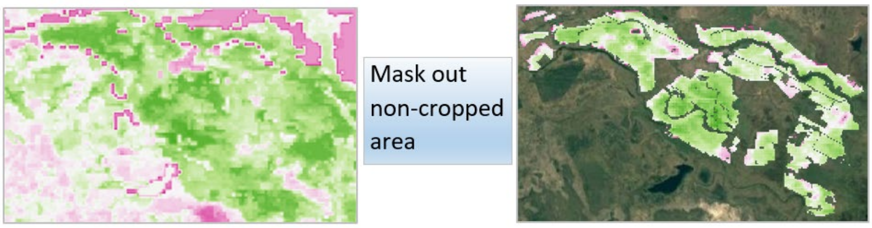
Box 1 Example of bulk download script

```
WaPOR.AET_dekadal(output_dir, Startdate='2009-01-01', Enddate='2019-12-31',
          latlim=[ymin, ymax], lonlim=[xmin, xmax],level=2,
          version = 2, Waitbar = 1)
```

The script is pre-set at downloading decadal data from 1 January 2009 to 31 December 2019 and for level 2. These settings can be manually changed to fit your purpose. One can adjust the dates. If there is no level 2 data available at your site, or you have level 3 data available you can change the setting. There is also a facility to directly download monthly and yearly data, this can be done by changing the extension ‘decadal’ to ‘monthly’ or ‘yearly’. The script is pre-set to download WaPOR version 2, if there is another version available this can be easily changed. The settings which can be changed are highlighted red in box 1.

3.2 Pre-processing WaPOR data (Module 1)

https://github.com/wateraccounting/WAPORWP/blob/master/Notebooks/STEP_1_WaPOR_data_preparation.ipynb

Step 1a Import modules/libraries	
Step 1b Resample raster data	
Step 1c Filter non-cropped area using land cover map and project boundary	

The main objective of this module is to prepare the data for analyses. Firstly, all data is sampled to the same resolution, even though many of the datasets are available at the same resolution, more coarse data such as reference evapotranspiration and precipitation need to be resampled.

In the example case, we identified the area for analysis using a shapefile (project boundary) to crop out the area of investigation, this is followed by a procedure to mask out non-irrigated areas. Of course there are different ways to extract the area for analyses, which can be applied, but these are not elaborated upon in this protocol.

For the analyses it is important to select a homogeneous area with one single crop type and similar crop season.

3.3 Computing Seasonal Water Consumption & Net Primary Production (Module 2)

https://github.com/wateraccounting/WAPORWP/blob/master/Notebooks/STEP_2_SeasonalWaterConsumption%26NetPrimaryProduction.ipynb

Step 2a Set up: Import modules/libraries
Step 2b Defining function and crop season

Step 2b Calculate seasonal T, ET, RET, ETp, NPP

For agricultural purposes the seasonal values are important, these are calculated by summing the decadal amounts over a specified cropping season, defined by a start and end of crop season (SOS and EOS) (equation 1).

$$X_s = \sum_{SOS}^{EOS} X \qquad \text{Equation 1}$$

where X_s is the seasonal amount in mm/season for P, ET_a, T, REF, ETp or NPP, X is the decadal amount for P, ET_a, T, REF or NPP in mm/dec. A local function is defined for calculating the seasonal values. The SOS and EOS are user-defined. Table 3 shows an example of such a crop season table which is used for the calculations. Table 3 is input data in excel format (df_SosEos.xlsx), which is read into Module 2 of the script. Users could edit the dates (starting of season (SOS) and ending of season (EOS)). The rows should end on the last month of the ending of season (EOS).

Table 3 Example SOS and EOS table

	Seasons	**SOS**	**EOS**
0	1	2009-10-01	2010-09-30
1	2	2010-10-01	2011-09-30
2	3	2011-10-01	2012-09-30
3	4	2012-10-01	2013-09-30
4	5	2013-10-01	2014-09-30
5	6	2014-10-01	2015-09-30
6	7	2015-10-01	2016-09-30
7	8	2016-10-01	2017-09-30
8	9	2017-10-01	2018-09-30
9	10	2018-10-01	2019-09-30

ETp is calculated by multiplying crop coefficient (Kc) by reference evapotranspiration at monthly as well as seasonal time steps. Edit only the '**Kc'** values and the corresponding '**Months'** in the **df_Kc.xlsx** file in the data folder (Table 4), which is read into Module 2 of the script. The rows should end on the last month of the late-season stage.

Table 4 Example Kc table

	A	B	C
1	**Months**	**Kc**	Crops stage
2	October	0.400	Initial
3	November	0.613	
4	December	1.038	
5	January	1.250	
6	February	1.250	
7	March	1.250	
8	April	1.250	
9	May	1.250	
10	June	1.250	
11	July	1.083	
12	August	1.000	
13	September	0.833	Late-season

3.4 Calculate performance indicators (Module 3)

https://github.com/wateraccounting/WAPORWP/blob/master/Notebooks/Module_3_CalculatePerformanceIndicators.ipynb

Step 3a Set up
Step 3b Calculate Uniformity
Step 3c Calculate Efficiency (Beneficial fraction)
Step 3d Calculate Adequacy
Step 3e Calculate Relative Water Deficit

This module is used to calculate a number of performance indicators, namely uniformity, beneficial fraction, adequacy and relative water deficit.

Uniformity and Equity

Uniformity measures the evenness of the irrigation application in different parts of a field. This can be calculated by assessing the spatial uniformity of seasonal ET pixels that are within a field or plot of land.

Equity is the measure of equitable distribution of water to different users (i.e. farmers), which can be water users at a tertiary unit or among tertiary units under a particular secondary canal. Ideally, for equity, pixel values must be aggregated and averaged per field (or a block if comparisons are made between blocks), to arrive with an average seasonal ET per unit of area in each field. The coefficient variation of these values would then can be taken as an indication of equity in the scheme. In the absence of plot (or block) boundaries, the spatial uniformity of evapotranspiration per unit area (pixel) bases can be used to measure uniformity or equity. It is calculated as the coefficients of variation (CV) of seasonal ET_a in the area of interest. A CV of 0 to 10 % is defined as good uniformity, CV of 10 to 25 % as fair uniformity and CV > 25 % as poor uniformity (Bastiaanssen et al., 1996; Molden and Gates, 1990; Karimi et al., 2019).

$$CV_{ET} = \frac{SD}{\sigma} * 100\% \qquad \text{Equation 2}$$

With SD being the standard deviation and σ the mean of evapotranspiration.

Beneficial fraction (BF) is an indication of the efficiency of on-farm water and agronomic practices in converting water use to crop growth. It is the percentage of the water that is consumed as transpiration compared to overall field water consumption (ET_a). Beneficial fraction is calculated as follow (Equation 3):

$$BF = \frac{T_a}{ET_a} \qquad \text{Equation 3}$$

where T_a and ET_a are seasonal transpiration and actual evapotranspiration.

Adequacy (A) is the measure of the degree of agreement between available water and crop water requirements in an irrigation system (Bastiaanssen and Bos, 1999; Clemmens and Molden, 2007). It is calculated as the relative evapotranspiration, which is the ratio of actual evapotranspiration over potential evaporation (Equation 3) (Kharrou et al., 2013; Karimi et al., 2019).

$$A = \frac{ET_a}{ET_p} \qquad \text{Equation 4}$$

Where ET_a and ET_p are the actual and potential evapotranspiration in mm/season. Potential evaporation is estimated as the product of average k_c and *RET* as in Equation 5.

$$ET_p = \sum_i^n kc_i * RET_i \qquad \text{Equation 5}$$

where $ET_{a,}$ is the potential evapotranspiration in mm/season, Kc and *RET* are the crop coefficient and reference evapotranspiration in mm/month. i months from the first month at the initial stage of the crop to last month (n) at the end of the crop season.

Relative Water Deficit (RWD) provides an indication of the level of water shortage found in the irrigation system. It is calculated using the equation described in FAO 66 (Steduto et al., 2012) by applying for a mono-crop system, where the actual ET is compared to the maximum ET (equation 6).

$$RWD = 1 - \frac{ET_a}{ET_x} \qquad \text{Equation 6}$$

With

$$ET_x, the\ \max ET = 99\ percentile\ of\ ET_a \qquad \text{Equation 7}$$

3.5 Land and water productivity (Module 4)

https://github.com/wateraccounting/WAPORWP/blob/master/Notebooks/Module_4_CalculateLand%26WaterProductivity.ipynb

Step 4a Set up
Step 4b Calculate land productivity: i) biomass and ii) crop yield
Step 4c Calculate i) biomass water productivity and ii) crop water productivity

This step is used to calculate the seasonal land and water productivity for the study area.

Land productivity is defined as the above-ground biomass production or yield in ton/ha/season, which are estimated from the seasonal net primary production using the following equations:

$$B \ = AOT * f_c * \frac{NPP*22.222}{(1-mc)} \qquad \text{Equation 8}$$

$$Y \ = HI * B \qquad \text{Equation 9}$$

The parameters used in these equations are crop-specific and vary under different climatic conditions. There are several resource documents that can be consulted to obtain these parameters (Table 4). It is important to keep in mind that these parameters are based on literature and therefore stresses and management practices affecting the H_I and m_c cannot be incorporated. If there is local information, it is better to use that information.

Table 4 overview of parameters used for calculating biomass and yield

Parameter	Definition	Unit	Source documents
AOT	above ground over total biomass production ratio	[-]	Appendix A
f_c	Light use efficiency correction factor: the ratio between the actual LUE and the LUE applied for the NPP data in WaPOR	[-]	Appendix A and WaPOR database methodology document of Version 2 release (FAO, 2020a)
HI	harvest index[4]	[-]	Appendix A, page 182 in Villalobos and Fereres (2016), AquaCrop Annexes: http://www.fao.org/fileadmin/user_upload/faowater/docs/Annexes.pdf
m_c	moisture content in the fresh biomass	[-]	Appendix A, page 495 in Villalobos and Fereres (2016)

Validation
Comparison WaPOR data and results vs observed (if available) is recommended. It helps to fine-tune the crop parameters to get results closer to the observed one. The comparison can be done with the aid of visual graph interpretation (against 1:1 line), coefficient of determination, and coefficient of correlation.

Note: It is recommended to interpret the WaPOR data and results using quality layer.

Biomass and crop Water productivity is estimated as the ratio of above-ground biomass or yield over actual evapotranspiration (Equation 10 and 11):

$$WP_b = \frac{B}{ET_a} \qquad \text{Equation 10}$$

[4] http://www.fao.org/fileadmin/user_upload/faowater/docs/Annexes.pdf

$WP_c = \frac{Y}{ET_a}$ Equation 11

To obtain $WP_{(b)}$ in kg/m³/season from *B* in kg/ha and ET_a in mm/season, the unit conversion factor of 0.1 is used in the equation. Likewise $WP_{(c)}$ is obtained from *Y.*

Table 5 Summary of irrigation performance assessment criteria and indicators
Calculate performance indicators

Criteria	Indicator	Equation
Adequacy	Relative evapotranspiration (RET)	$RET = \frac{ET_{a,s}}{ET_{p,s}}$
	Relative water deficit (RWD)	$RET = 1 - \frac{ET_{a,s}}{ET_x}$ $ET_x = ET_{p,s}\ or\ 99\ percentile\ of\ ET_{a,s}$
Equity	CV of ET	Accumulated seasonal average ETa per field inside the scheme/block
Uniformity	CV of ET	Accumulated seasonal average ETa per pixel inside a field
Productivity	Biomass production	$B = AOT * f_c * \frac{NPP * 22.222}{(1 - mc)}$
	Yield	Yield = B*HI
	Biomass WP	$WP_b = \frac{B}{ET_{a,s}}$
	Crop WP	$WP_y = \frac{Y_a}{ET_{a,s}}$
Efficiency	Beneficial fraction (BF)	$BF = \frac{T_{a,s}}{ET_{p,s}}$

3.6 Productivity gaps and production projection (Module 5)

https://github.com/wateraccounting/WAPORWP/blob/master/Notebooks/Module_5_BrighSpots%26ProductivityGaps.ipynb

Step 5a Set up
Step 5b Calculate the target productivity
Step 5c Identify bright spots
Step 5d Calculate productivity gaps¶

The **target productivity** is a target for land and water productivity which is attainable under the local climatic conditions. This step of the script describes how the target is set and how bright spots are identified and how the productivity gap (related to the target) is estimated.

The target can be set for individual years to incorporate specific wet or dry conditions during that particular year. In our case we set the target at the 95 percentile of the land or water productivity for each year (Figure 2), this can be changed in the script. The corresponding ET_a is also defined as the target ET_a.

Box 2 Example of calculating target land and water productivity using percentile

```
# targets biomass productivity
  Target_biomass = round(np.nanpercentile(Biomass, 95), 0)#Yield at 95 percentile
  Target_WPb     = round(np.nanpercentile(WPb, 95), 1)      #WP at 95 percentile
```

```
# targets crop productivity
  Target_yield = round(np.nanpercentile(Crop_yield, 95), 0)#Yield at 95 percentil
e
  Target_WPc    = round(np.nanpercentile(WPc, 95), 1)          #WP at 95 percentile
```

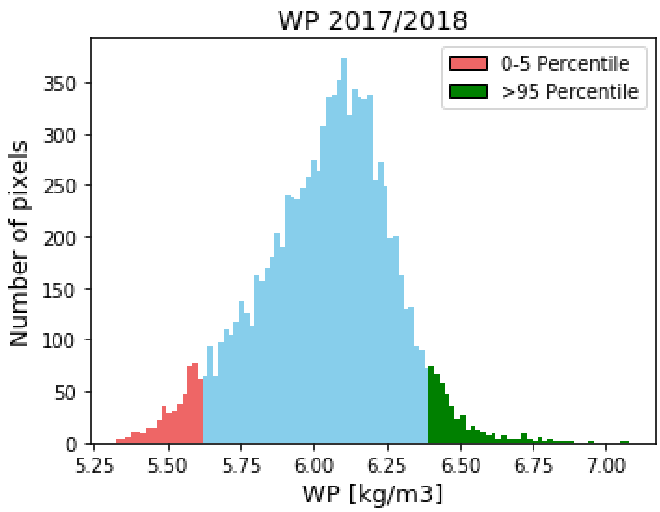


Figure 2 WP distribution and 95 percentile

The **bright spots** are fields that have both land and water productivity equal to or greater than the targets. The location of the bright spots is then mapped for the individual targets (biomass or yield and water productivity as well as areas where both targets are exceeded (Figure 3).

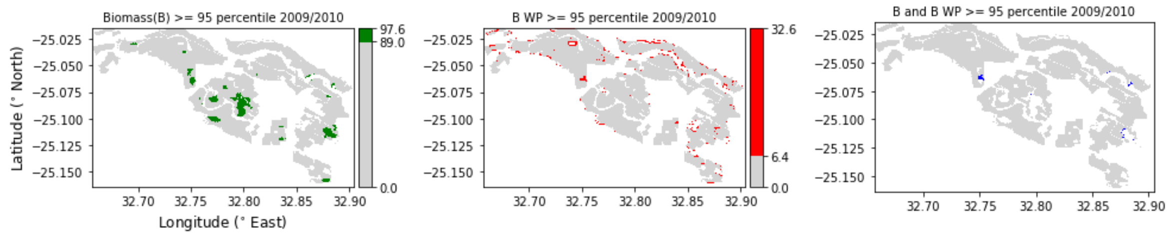


Figure 3 Example of results of the bright spot analyses

Productivity gap is defined as the difference between productivity at the plot level and the target productivity. The production gap is defined as the sum of the land productivity gaps of a particular crop over area. The potential increase in biomass/ yield production of a particular crop in an area of interest is calculated by adding the productivity gap across the area (Equation 12a, b).

$$BP_b = \sum_i^n (B_i - B_t), \quad B_i < B_t \qquad \text{(Equation 12a)}$$
$$YP_b = \sum_i^n (Y_i - Y_t), \quad Y_i < Y_t \qquad \text{(Equation 12b)}$$

where BP_b and YP_b are the projected increase in biomass and crop production in ton/ha/season. B_i and Y_i are biomass and crop yield of a plot i in ton/ha/season. B_t and Y_t are target biomass and crop yield in ton/ha/season.

4 Example: Protocol applied at Xinavane irrigation scheme

4.1 Data

Case: crop = sugarcane, country = Mozambique, project = Xinavane

WaPOR and local data of Table 6 are used to implement the protocol. The Level 2 data used in this study include actual evapotranspiration and interception and net primary production at a decadal timescale and annual land cover classification. In addition, decadal precipitation at 5 km resolution, decadal reference evapotranspiration at 25 km resolution. The precipitation and reference evapotranspiration datasets were downscaled to 100 m resolution.

Table 6 Data use as input to implement the protocol at the example case study

No.	WaPOR data	Spatial resolution	Temporary resolution	Temporal coverage
1	Actual evapotranspiration & interception (*AETI*)	100 m	Decadal	(2009-2019)
2	Transpiration (*T*)	100 m		
3	Net primary production (*NPP*)	100 m		
4	Precipitation (*P*)	5 km		
5	Reference evapotranspiration (*REF*)	25 km		
6	Land cover classification (*LCC*)	100 m	Annual	
	Local data			
7	Boundary of case study is delineated from Google Earth and IWACATECH project			
8	Start of season (*SOS*) and end of season (*EOS*), 1 October to 30 September			
9	Moisture content (m_c) of fresh crop biomass = 0.59 (Yilma et al., 2017)			
10	Ratio of Light use efficiency (LUE) of C4 and C3 crops = 1.8 (Villalobos and Fereres, 2016)			
11	The ratio of above ground over total biomass (AOT) = 0.8 (Smith et al., 2005)			
12	Crop coefficient (k_c) at initial, mid-season and harvest are 0.4, 1.25 and 0.75, respectively (Allen et al., 1998; Doorenbos and Kassam, 1979)			

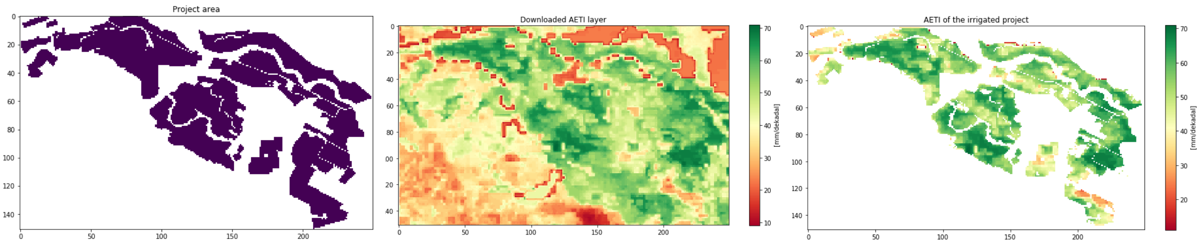
13	The duration of the initial, development, mid-season and late-season stages are 30 days, 60 days, 180 days and 95 days (Allen et al., 1998; Doorenbos and Kassam, 1979)

4.2 WaPOR data consistency

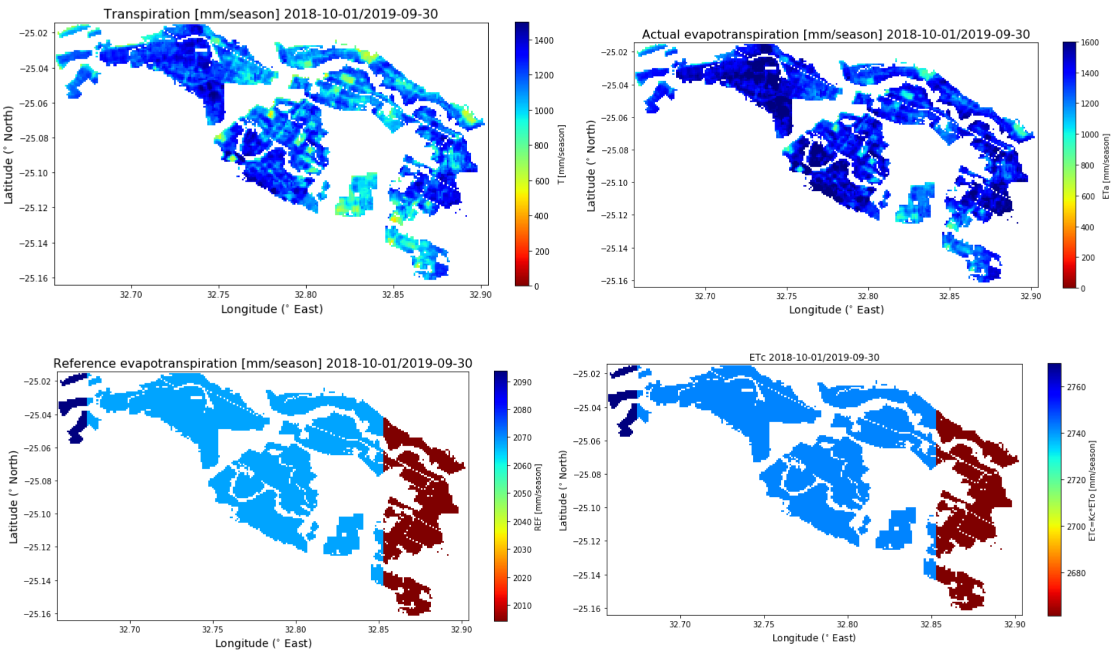
The Level 2 data source of the WaPOR data is not consistent throughout the 10 years. Before 2014, the data is derived from the MODIS satellite (250 m resolution), which is resampled to 100 m. In 2014, PROBA-V came into orbit, which provides the WaPOR L2 data for the period after 2014. The analyses in this report show a clear break 2009-2013 and 2014 onwards in the data (e.g., the noise in the biomass-transpiration and biomasses relationship are much even with patch of scatter pixels, such as high biomass at zero transpiration which cannot be explained agronomical).

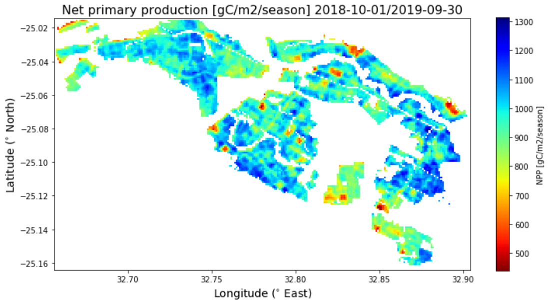
4.3 Results

Module 1: Project area (a), the downloaded actual evapotranspiration layer (b) and actual evapotranspiration after the non-irrigated crop area is filtered (c)

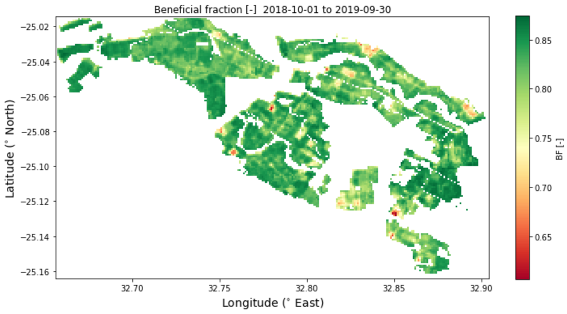


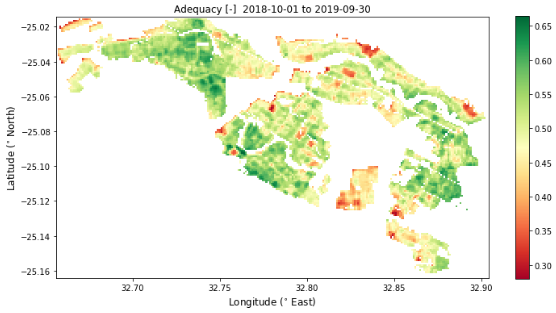
Module 2: Seasonal water consumption and net primary production



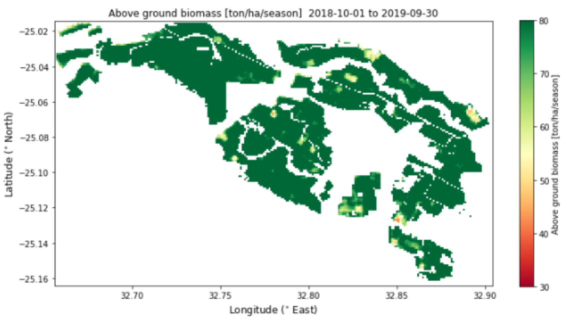


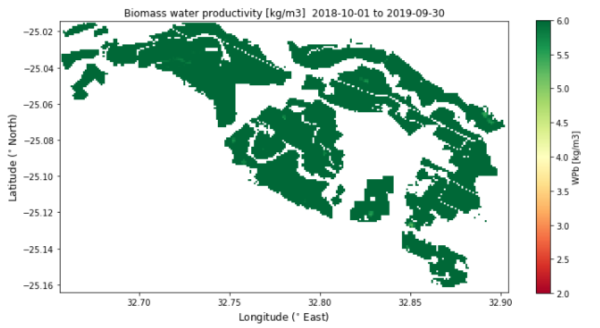
Module 3: Performance indicators



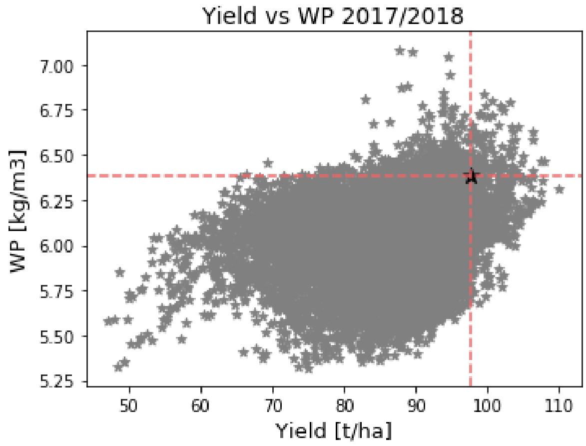


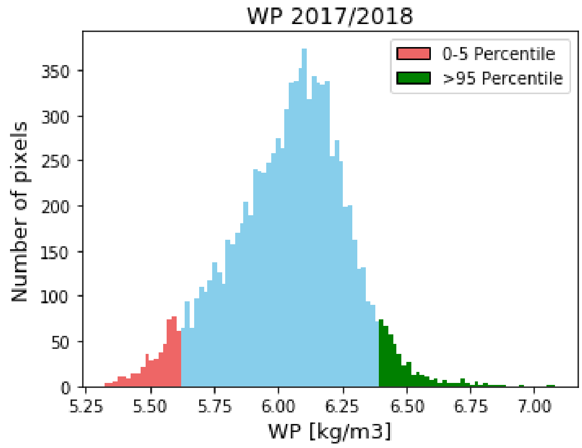
Module 4: Productivity

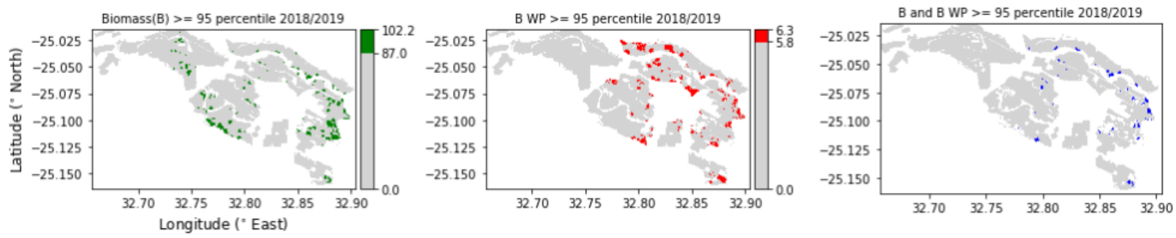


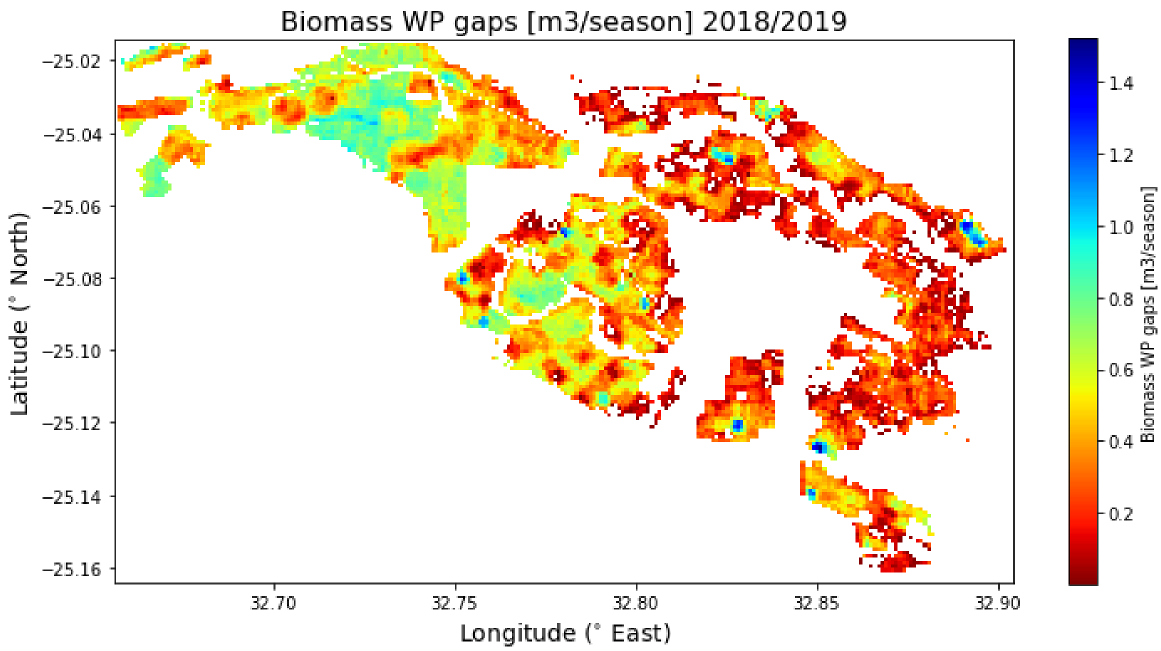


Module 5: Productivity gaps and bright spots








Biomass WP gaps [m3/season] 2018/2019
Latitude (° North)
Longitude (° East)
−25.02
−25.04
−25.06
−25.08
−25.10
−25.12
−25.14
−25.16
32.70
32.75
32.80
32.85
32.90
Biomass WP gaps [m3/season]
1.4
1.2
1.0
0.8
0.6
0.4
0.2

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Appendices

Appendix A: Default crop parameters used in WaPOR portal (FAO, 2020b)

Crop	Harvest index	Above ground over total biomass	Moisture content ratio
Cotton	0.2	0.8	0.15
Barley	0.3	0.85	0.15
Wheat	0.48	0.85	0.15
Maize (grain)	0.35	0.93	0.26
Sorghum	0.25	0.8	0.2
Rice	0.43	0.75	0.15
Tef	0.24	0.75	0.15

Sugarcane (ratoon)	1	1	0.7