WaterPIP

Water Productivity Improvement in Practice

Standardized protocol for diagnostic analysis for water productivity variations

October 2022

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1 Introduction

This protocol focuses on analyses that can be conducted to explain the reasons behind spatial and temporal biophysical water productivity (BWP) variations. BWP is defined here as the relation between crop production (biomass or yield) and water consumption; i.e. evapotranspiration (ET_a). In this protocol, this type of analysis is referred to as diagnostic analysis. To conduct such analysis, the factors that affect BWP need to be delineated. For this reason, the first aim of this protocol is to delineate the agronomic principles that affect water productivity (section 2). Second, this protocol aims to show how to make use of various existing tools that can provide diagnostic insights (section 3). On the basis of these, conclusions are drawn.

2 Agronomic principles of crop growth and spatial and temporal variations of BWP

BWP is generally defined as the relation between crop production and water use. Crop production can be expressed either as biomass or yield in kg/ha while water use refers to the water consumed by the crop. When biomass is used, the biophysical biomass water productivity (BWP_B) is calculated and when yield is used, the biophysical yield water productivity (BWP_Y) is calculated. In some cases, water consumption is confused with water application (i.e. the amount of water applied at field level, amounting to the sum of precipitation and irrigation water). This does not do justice to the concept of BWP and points towards other irrigation engineering concepts such as water use efficiency (WUE) (van Halsema and Vincent, 2012).

Water consumption might either refer to crop transpiration (T); only the beneficial consumption by the crop, or to crop evapotranspiration (ET_a); the sum of T and the non-beneficial consumption through evaporation from the plant and soil surface (E). Depending on the crop production definition (biomass or yield) and water consumption definition taken (T or ET_a), four biophysical water productivities can be calculated (i.e. BWP_B (T), BWP_B (ET_a), BWP_Y (T) and BWP_Y (ET_a). Considering the agronomic studies that indicate the linear relation between biomass and T (De Wit, 1958; Steduto et al., 2007; Perry et al., 2009; Steduto et al., 2012), improving BWP_B (T) is not possible under similar climatic and fertility conditions. Opportunities might exist in improving BWP_B (ET_a) and BWP_Y (ET_a) by managing the water consumed through evaporation and directing it towards transpiration and/or by managing the field practices (Molden et al., 2010). BWP is usually calculated with ET_a (and not T) as it is difficult to separate E from T (Steduto et al., 2007).

In this protocol, the biophysical biomass water productivity (BWP_B (ET_a)) and biophysical yield water productivity (BWP_Y (ET_a)) are defined as:

$$BWP_B\ (ET_a) = \text{Biomass} / ET_a\ (\text{kg/m}^3)$$

$$BWP_Y\ (ET_a) = \text{Yield} / ET_a\ (\text{kg/m}^3) = (\text{HI*Biomass}) / ET_a\ (\text{kg/m}^3),$$

where HI is the harvest index, i.e. the fraction of the biomass produced that is partitioned to the yield.

Even though it is sensible to use BWP_B (ET_a) for practical analyses of water productivity, the more simple definition BWP_B (T) is initially explored in order to explain the agronomic principles that affect water productivity under different conditions (section 2.1). Further, the E/T ratio and the total water consumption (ET_a) is explained in relation to the BWP_B (ET_a). Finally, moving from biomass to yield water productivity BWP_Y (ET_a) is also explored. These explanations aim to meet the first goal of this protocol to provide delineation on the factors affecting water productivity

2.1 Biophysical Biomass Water Productivity and Transpiration (BWP_B (T))

BWP_B (T) is a stable (conservative) ratio of productivity for a particular crop under similar climate and fertility conditions that describes a linear relation between biomass and T (De Wit, 1958; Steduto et al., 2007; Perry et al., 2009; Steduto et al., 2012), without the non-productive water use by evaporation (E). The B/T ratio is also known as the transpiration efficiency (de Wit, 1958; Steduto et al., 2007).

Under optimal abiotic and biotic conditions, BWP_B (T) is defined at large by the crop type. The BWP_B (T) slope is the lowest for C_3, higher for C_4 crops and the highest for CAM crops (Figure 2), ceteris paribus (Molden et al., 2012). Possible new photosynthetic pathways and genetically modified varieties can lead to the creation of more water productive crops in the future.

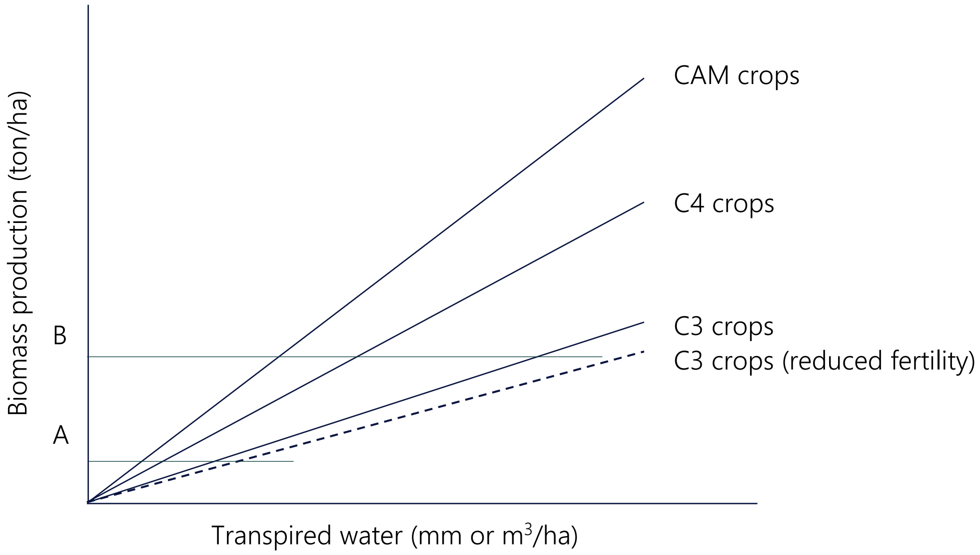

Figure 1. Linear relation between Biomass and T_a for different crop types (authors' elaboration)

Variations of biomass production are not necessarily related to variations of BWP_B (T). As there is a linear relation between B and T under the same growing conditions (biotic and abiotic stress), the BWP_B (T) will be the same across space under similar conditions. If there are spatial and temporal variations that primarily affect water use (water transpired)[1], the BWP_B (T) will remain the same while the biomass production will vary (point A has lower biomass production than point B in Figure 2 while both have the same BWP_B (T)). Such spatial and temporal variations in biomass production at field level are related to **variations of production along the stable BWP_B (T) slope**. This attribute is confusing when considering BWP_B (T) as a productivity ratio as the spatial or temporal variation in production does not necessarily translate into variation in BWP_B (T). If there are spatial and temporal variations in terms of other biotic and abiotic stresses (except those related to or caused by water stress) such as fertility, climatic conditions (affecting the E/T ratio) and pests or diseases, there is a **variation of BWP_B (T) slope**. Understanding the reasons behind the variation of the BWP_B (T) slope is essential in order to make water productivity improvements (move the slope upwards).

[1] Crop growth is highly dynamic and stresses (water, fertility, salinity etc) affect different aspects of the crop (biomass, yield, water use) in multiple ways. Primary effects of stresses are directly related to crop growth while secondary effects of stresses are a consequence of the primary effects of stresses. An example of this is water stress that primarily reduces transpiration. Depending on the severity of water stress, the caused reduced transpiration will have a secondary effect on fertility stress. Thus, it remains a challenge to be able to assign a specific stress to a specific effect on crop growth.

Next, the factors that result in these two different types of variations (production and slope) are explained. Table 1 summarizes these findings. Pointing towards possible interventions, the possibility to manage these factors by human interventions is specified.

2.1.1 Variations of production along the stable BWP_B (T) slope

Spatial and temporal variations of production along stable BWP_B (T) slope are related to water transpired (T), assuming that all other conditions (fertility, climate, biotic stresses) are the same. T is affected by three main factors, that cause reduced transpiration, namely i) **water stress**, ii) **water logging**, iii) **salinity stress**, and iv) **weed infestation**.

Water stress, under optimal fertility management and depending on the severity, might result in stomatal closure and thus reduced transpiration which in turn leads to biomass reduction (linear relation, Figure 2).

Water logging is a severe water stress resulting from too much water in the soil and too little oxygen for the uptake by plants. Crops affected by water logging (due to high water tables) will be subjected to stunted growth. The physiological primary effect is a reduced stomatal conductance and transpiration. The effect is the same as water stress induced by water scarcity, leading the crop to reduce its stomatal activity, reducing T. Biomass production will be less, as well as T, but the ratio of BWP_B (T) will remain the same – e.g. crops suffering from waterlogging will have the same BWP_B (T) slope as non-waterlogged crops (assuming all other conditions are the same), but for the same period of time, will produce less B and less T, ending lower along the line with the stable BWP_B (T) slope.

Salinity stress (either saline soils and/or saline water) will also lead to stunted growth. The primary effect is a heightened water stress, as salinity increases the suction power plants need to exert to abstract water from the soil. Plant roots contains a certain concentration of salts in the roots which creates natural water flow from soil to roots. As the salinity level of the soil increases, it pulls back water from root to soil. Though water exists in the saline soils, plants cannot uptake due to higher salinity which leads to physiological drought (Lisar et al., 2012). Salinity stress is more pronounced with high demanding climates and thus higher the ET_0 the higher the salinity stress. Salinity stress affects crop production in the same way as water stress: lower T leads to lower biomass production, and the crop will end at the lower side of the BWP_B (T) graph, but with the same BWP_B (T) slope (Figure 2). At higher concentrations salinity may lead to toxicity that will also affect other physiological processes. The sensitivity of crops to salinity (both in terms of water stress and toxicity) is crop type and crop variety dependent.

Weed infestation competes with the crop for water, as well as nutrients and light, effectively reducing the availability of these aspects for the crop. Focusing on the water stress, weed infestation reduces water consumed by the crop, resulting in reduced biomass production and thus leading to the lower side of the BWP_B (T) graph, but with the same BWP_B (T) slope (assuming optimal fertility management).

2.1.2 Variations of the BWP_B (T) slope

Despite this stable relation, spatial and temporal variations of BWP_B (T) slope might occur due to three possible physiological reasons namely i) **fertility stress**, ii) **weed infestation,** and iii) **pests and diseases**.

Soil fertility stress affects the slope of BWP_B (T). Crops suffering from nutrient stresses typically have less green and more yellowish leaves, reducing the photosynthetic efficiency of the crop. This results in lower biomass production per unit of water transpired, effectively reducing BWP_B (T). Fertility management can increase biomass water productivity (normalized for climate and CO2 concentration) by up to 33% for C3 crops and 17% for C4 crops (Raes et al., 2016).

Soil fertility stress might be induced as a secondary effect of water stress, especially if the water stress is severe. As nutrients are taken up by the plant through soil water, a prolonged and severe water stress will also reduce the capacity of the crop to take up nutrients. However, the extent of this secondary effect is limited as there is a linear decrease of the (canopy) requirements for nutrients due to the reduced biomass production (primary effect of water stress).

Weed infestation, when causing competition for nutrients can lead to soil fertility stress for the crop, thus moving the BWP_B (T) slope downwards.

Pests and diseases may affect crop production in numerous and diverse manners. Canopy devouring pests that reduce biomass production and distort BWP_B slopes. Diseases may affect the photosynthetic efficiency of the canopy which will translate in a reduction of biomass produced per unit of water, similarly to reduced soil fertility. This way, diseases might result in a shift of the BWP_B (T) slope.

Table 1. Factors that affect spatial and temporal variations of BWPB (T) and the possibilities for managing these factors to improve BWPB (T).

Factors	Variations	Effect on BWP_B (T)		Manageable or Non-manageable
Water stress	Variations of production along the stable BWP_B (T) slope	Causing reduced transpiration	Under optimal fertility management, severe water stress might result in severe biomass reduction due to stomatal closure.	Manageable (irrigated agriculture) Non-manageable (rainfed agriculture)
	Variations of the BWP_B (T) slope	Causing fertility stress	As a secondary effect of water stress, fertility stress might result in lower BWP_B (T) slopes.	
Water logging (aeration stress)	Variations of production along the stable BWP_B (T) slope	Causing reduced transpiration	Similarly to water stress, waterlogged fields will have the same WP_B slope as non-waterlogged crops, but for the same period of time, will produce less B and less T, ending lower on the line with the stable BWP_B (T) slope.	Manageable (to a certain degree through irrigation). Non-manageable (extreme weather events)
	Variations of the BWP_B (T) slope			
Salinity stress (unmanaged)	Variations of production along the stable BWP_B (T) slope	Causing reduced transpiration	Salinity stress, if unmanaged, exacerbates water stress, as salinity increased the suction power plants need to exert to abstract water from the soil resulting in less water uptake.	Manageable
	Variations of the BWP_B (T) slope			
Weed infestation	Variations of production along the stable BWP_B (T) slope	Causing reduced transpiration	Weed infestation competes with the crop for water, nutrient and light, effectively reducing the availability of these aspects for the crop.	Manageable
	Variations of the BWP_B (T) slope	Causing fertility stress	Competition for nutrients leading to fertility stress and lower BWP_B (T) slopes.	
Fertility stress	Variations of production along the stable BWP_B (T) slope			Manageable
	Variations of the BWP_B (T) slope	Causing reduced transpiration efficiency	Non-optimal soil fertility results in less green and more yellowish leaves, reducing the photosynthetic efficiency of the crop and thus lowering biomass production per unit of water transpired, effectively reducing BWP_B (T).	
Pests and diseases	Variations of production along the stable BWP_B (T) slope			Manageable (to a certain degree)
	Variations of the BWP_B (T) slope	Causing reduced transpiration efficiency	Through diverse ways, pest and diseases distort the datasets and can reduce the photosynthetic efficiency, affecting crop growth similarly to reduced soil fertility.	

2.2 The E/T ratio for ET_a Biophysical Biomass Water Productivity (BWP_B (ET_a))

BWP_B is commonly assessed through ET_a (not T, due to the linear relation between biomass and T which effectively limits opportunities for productivity improvements under optimal fertility management and the practical difficulties of ET separation). Small spatial and temporal variations are evident in ET_a and biomass for same crop types. Despite these variations, the slope of BWP_B (ET_a) follows a linear model for more than 69% of variation under similar growing conditions (Tolk and Howell, 2009; Sharma et al., 2017; Seijger et al., 2022), indicating a linear relationship between ET_a and biomass for same crops. In turn, this linear relationship limits the opportunities of increasing BWP_B (ET_a) for a specific crop.

The remaining small spatial and temporal variations of BWP_B (ET_a) are related to the growing conditions, some of which are manageable while others are non-manageable (see in Table 1) and the management practices that affect the E/T ratio that have effects on variations of production along a stable BWP_B (ET_a) slope and variations of the BWP_B (ET_a) slope. These effects are similar to the ones described in Table 1 but increased in complexity as related to the E/T ratios. The E/T ratios describe the amount of water beneficially consumed for biomass production through transpiration. For this reason, understanding the agronomic aspects that affect the E/T ratio is essential.

Some factors of Table 1 are further affected by the E/T ratios and thus influence the BWP_B (ET_a). These factors; i.e. i) **water logging**, ii) **salinity stress** and iii) **pests and diseases**, are further explained in this section. Moreover, two more factors; namely the iv) **climatic conditions**, v) **irrigation method** and vi) **mulching practices** are discussed on their effects on E/T ratios and BWP_B (ET_a) (see Table 2).

Water logging (aeration stress) is the effect of stagnant water that results in higher E/T ratio due to sufficient supply of water for evaporation. Assuming two fields under the same growing conditions and water consumption (ET_a), one of which is waterlogged, the waterlogged field will have higher evaporation due to the stagnant water and thus reduced transpiration that causes reduced biomass production. This in turn reduces the slope of BWP_B (ET_a) as ET_a is less productively used (same amount of ET_a is used to produce less biomass). This is different than the effect that water logging has on the BWP_B (T), which affects variations of production along the BWP_B (T) slope.

Salinity stress is commonly managed by frequent application of irrigation for salt leaching. The increased application of water supply effectively increases the evaporated water while also allows for increases in the water transpired. Assuming a non-managed field for salinity stress, transpiration is inhibited. By managing salinity and assuming that all other growing conditions remain the same, evaporation and transpiration and thus ET_a will increase. However, as all other growing conditions remain similar, BWP_B (ET_a) will remain the same (variations of production along the stable BWPB (ET_a) slope). Salinity management is about finding the balance between beneficial increases in T and non-beneficial increases in E. If the non-beneficial increases are higher than the increases in T, then the slope of BWP_B (ET_a) will be reduced.

Pests and diseases have diverse effects and manners for affecting crop growth (partly explained for BWP_B (T) in section 2.1.2). Regarding BWP_B (ET_a), canopy devouring pests will reduce biomass (after it has been produced by the crop) and distort the BWP_B; e.g. post-pest biomass values are too low for the accumulated ET_a values.

The climate is the most important factor that affects the E/T ratio. Warmer, drier and windier climates, with higher ET_0, will lead to higher E/T ratios. With a higher E/T ratio, ceteris paribus, the slope of BWP_B will be smaller as the higher evaporation ratio (assuming same ET_a values) does not contribute to biomass production.

Irrigation methods are also affecting the E/T ratio. Irrigation methods with higher E/T ratio will lead to lower BWP_B (ET_a), ceteris paribus. Centre pivots have the highest E/T ratio, followed by sprinkler and surface irrigation (Alemayehu et al., 2020).

Mulching practices influence the E/T ratio by effectively reducing evaporation and thus increasing the available water for transpiration. According to a study on maize production, plastic film mulching decreased the E/ET_a ratio by approximately 12% (Shen et al., 2019).

Table 2. Factors that affect spatial and temporal variations of BWP_B (ET_a) and the possibilities for managing these factors to improve BWP_B (ET_a).

Factors	Variations	Effect on BWP_B (ET_a)		Manageable or Non-manageable
Water logging (aeration stress)	Variations of production along the stable BWP_B (ET_a) slope	The same way as water stress and water logging as indicated in Table 1.		Manageable (to a certain degree through irrigation). Non-manageable (extreme weather events)
	Variations of the BWP_B (ET_a) slope	Causing increased E/T ratio	Assuming same growing conditions and ET_a, waterlogged field will have stagnant water which will increase the evaporation, resulting in increased water non-beneficially used and thus have less biomass production. Hence, the BWP_B (ET_a) slope moves downwards.	
Salinity stress (managed)	Variations of production along the stable BWP_B (ET_a) slope	If salinity stress is managed effectively in a field, increases in ETa will lead to increases in biomass along a stable BWP_B (ET_a) slope		Manageable
	Variations of the BWP_B (ET_a) slope	Causing increased E/T ratio	If the non-beneficial increases of E are higher than the beneficial increases in T, then the slope of BWP_B (ET_a) will be reduced.	
Pests and diseases	Variations of production along the stable BWP_B (ET_a) slope			Manageable (to a certain degree)
	Variations of the BWP_B (ET_a) slope	Causing distorted biomass production values	Canopy devouring pests will reduce biomass and distort the BWP_B (e.g. post-pest biomass values are too low for the accumulated ET_a values).	
Climate	Variations of production along the stable BWP_B (ET_a) slope			Non-manageable
	Variations of the BWP_B (ET_a) slope		Warmer, drier and windier climates, have higher ET_0 and thus higher E/T ratios, and thus lower biomass production and lower WP_B.	
Mulching practices	Variations of production along the stable BWP_B (ET_a) slope			Manageable
	Variations of the BWP_B (ET_a) slope		Mulching can reduce evaporation losses and increases the transpiration.	
Irrigation method	Variations of production along the stable BWP_B (ET_a) slope			Manageable
	Variations of the BWP_B (ET_a) slope		Centre pivots have the highest E/T ratio, followed by sprinkler and surface irrigation.	

2.3 From Biomass to Yield Water Productivity (Biophysical Yield Water Productivity, BWP_Y (ET_a))

In most cases, crop yield is more interesting than biomass as it represents the marketable or edible part of the crop. Yield only constitutes a fraction of the total biomass produced (e.g. the grain or fruit). Most production and productivity assessments are therefore interested in yield assessments.

The difference between BWP_Y and the BWP_B is the use of the HI; i.e. the percentage of harvestable biomass. As such, the agronomic principles that describe BWP_Y are the ones presented for the BWP_B (both T and ET_a in Table 1 and 2 respectively) and those that reflect the dynamic influence of these factors on the HI (Table 3), which will be explained in this section.

The HI is affected by two aspects, namely i) the **crop species and cultivars** and ii) the **environmental stresses** (Asefa, 2019). Increases for higher yields in different cultivars for wheat or other cereals has come through breeding for higher harvest index (Asefa, 2019). Regarding the environmental stresses, HI is highly sensitive and responsive to **water stress** and **temperature stress** (AquaCrop manual, FAO, 2018). Generally, crops tend to be particularly sensitive to stresses during their flowering and yield formation periods (FAO, 2018).

Water stress can have positive (increased) and negative (decreased) effect on the HI. During the vegetative growth and before the reproductive phase, water stress can positively affect the HI since the crop has spent less energy in its vegetative growth. However, when vegetative growth is possible in the flowering phase, a mild water stress can positively affect the harvest index due to the decrease of competition between leaf growth and reproductive growth. During flowering, water stress might lead to failure of pollination, negatively affecting the HI. During yield formation, the harvest index builds up and water stresses can negatively affect harvest index if stomatal closure is reached. If water stress is severe and permanent wilting point is reached, a 100% reduction of the harvest index will occur.

Temperature stress (cold and heat stress), depending on duration and severity, might affect pollination and thus reduce the HI. Heat stress can be managed to a certain degree through shading interventions that reduce temperatures (decreasing evaporation as well) while cold stress can be managed through manipulating the planting date.

Further, the sensitivity of the HI to these stresses is cultivar specific – e.g. drought resistant varieties will respond differently than non-resistant varieties. In addition, some stresses, like heat stress, may be very sensitive (high yield reduction) for a very short or specific time (e.g. rice is sensitive to heat for a period of 10 days during flowering).

Table 3. Factors that affect the HI and the yield, depending on the growth stage (FAO, 2018).

Factors	Growth stage	Crop Effect	Effect on HI and yield	Manageable or Non-manageable
Water stress	Vegetative growth	Canopy expansion is reduced	Canopy expansion (biomass) is reduced, resulting in reduced energy spent on vegetative growth. This has a positive effect on the HI.	Manageable (irrigated agriculture) Non-manageable (rainfed agriculture)
	Flowering	Failure of pollination	During flowering, water stress can lead to (depending on the severity of the stress) to reduction of the HI due to failure of pollination.	
	Yield formation phase	Stomatal closure	The HI is building up during this period and thus prolonged and	
Temperature stress	Flowering	Failure of pollination	During flowering, cold or heat stress can lead to (depending on the severity of the stress) to reduction of the HI due to failure of pollination.	Manageable (to a certain degree through shading and planting date)

2.4 Conclusions

In this section of the protocol, the aim is to delineate the agronomic principles that affect water productivity. This section discussed the agronomic background of the relations between crop production (biomass and yield), water consumption (T and ET_a) and the factors that affect this relation (i.e. water stress, water logging, salinity stress and management, weed infestation, fertility stress, pests and diseases, climate, irrigation methods and temperature stress), resulting in different variations of BWP.

Diagnostic analyses assess these factors and find the major contributing factors that if managed through interventions can improve BWP. However, climate and water-related stresses under rainfed agriculture (water stress and water logging) cannot be managed. Thus BWP variation that is related to climatic conditions cannot be improved physiologically.

Even if factors are identified as limiting BWP through the diagnostic analysis and can be managed, a common constraint for interventions relates to socio-economic aspects. For example, fertility improvements may be restricted by economic costs. Moreover, such interventions need to be assessed for their effectiveness, potentially through cost-benefit analyses (i.e. how much benefits will be induced against the inputs required?).

3 Tools to provide diagnostic insights

The second aim of the protocol is to show how to make use of various existing tools that can provide diagnostic insights. Each tool has its own advantages and disadvantages with different degree of reliability. In this section, first an overview of the tools and their main advantages and disadvantages is provided (section 3.1). Next, more detailed description of each tool is provided (section 3.2, 3.3 and 3.4) and the opportunities for complementary use of the tools is discussed (section 3.4).

3.1 Overview of tools

This protocol identifies three main tools, namely i) field surveys[2], focusing on the surveys developed through the WaterPIP project (section 3.1.1.), ii) crop growth modeling, focusing on AquaCrop software and simulations (section 3.1.2.), and iii) remote-sensing data, focusing on WaPOR in combination with other remotely sensed data (section 3.1.3.).

3.1.1 Field surveys[2] (developed through WaterPIP project)

Field surveys and campaigns can provide detailed and in-depth agronomic data (biotic and abiotic stress) for diagnostics analyses through field measurements (ETa, biomass production and canopy development) and interviews (yield, pests and diseases). Moreover, field surveys can provide insights on socio-economic constraints that affect production and the implementation of different interventions. As the purpose of diagnostic analyses is to understand why there is temporal and spatial variations of water productivity, the spatial and temporal extent of field surveys is crucial. Spatial coverage of field surveys is normally limited due to practical considerations (labour and willingness of farmers to be interviewed). Temporal coverage is usually limited to a season, providing limited insights into water productivity variations over time. As such, the main advantage of field surveys regards the richness and depth of the collected data while the main disadvantage regards the costs and labour that is required.

3.1.2 Crop growth modelling (AquaCrop simulation model)

Through crop growth models, such as AquaCrop, WOFOST, CropSys, EPIC, APEX, APSIM etc., complex crop yield response to environmental conditions (abiotic stresses) and management practices can be simulated. Such models are designed to simulate the crop growth cycle and assess the influence of abiotic stresses on water use and crop production (biomass, E, T, HI and yield). Crop growth modelling is the only way to capture the dynamic variability of HI in crops. As any modelling exercise it needs validation and/or calibration in order to produce reliable results. Once a model is validated, and if necessary calibrated, the diagnostic analysis can be conducted and conclusions on the reasons behind low water productivity can be drawn. Based on this diagnostic analysis and the validated/calibrated model, interventions can be simulated and assessed against their goal. For example, if the diagnostic analysis concludes that water productivity is limited by low fertility levels, related interventions might focus on optimizing fertility levels. The model can be re-run using optimal fertility management and be assessed against the effect of the intervention on the water productivity.

The main disadvantage of most of the models for crop growth, including AquaCrop, is that biotic stresses (pests and diseases) are not considered and thus such diagnoses cannot be made. Moreover, upscaling the information derived from models to the entire region (which is often the approach taken for policy interventions) is a major challenge due to significant spatiotemporal heterogeneity in the farming

[2] https://waterpip.un-ihe.org/sites/waterpip.un-ihe.org/files/1.fieldsurveys.xlsx

landscapes (Lobell, 2013). Lastly, validation and calibration of the models require a large number of reliable field data which might be challenging to obtain for each individual field.

3.1.3 Remote-sensing data (WaPOR in combination with other data)

Remote sensing based estimates of land and water productivity can be combined with several open access satellite data on yield limiting and water productivity reducing factors for diagnostic analysis. The FAO-WaPOR database has been developed in order to quantify and monitor water productivity in Africa and the MENA region. WaPOR database provides data on total biomass and water consumption at different spatial (30 – 250 m) and temporal scales (10 days, monthly, annual). While WaPOR provides the spatial and temporal water productivity variations[3], it does not provide the insights on the reasons behind these variations. For such diagnostic analysis, it is necessary to combine WaPOR with additional data. Current attempts have been made to combine WaPOR with other open access remotely sensed data for diagnostic analysis (Safi et al., 2022). Other studies have focused on how disaggregation of WaPOR data with field data on the irrigation method and climate have largely explained the biomass water productivity variations assessed through WaPOR (Seijger et al., 2022).

The main advantage of remote sensing based approach is the spatial and temporal coverage, capturing variations and allowing for periodic monitoring as well as the cost-effectiveness of this approach. The accuracy of the WaPOR water productivity estimations has been evaluated in recent studies (Blatchford et al.,2019; Swelam 2019). On the other hand, the main disadvantage of remotely sensed data is related to the difficulties in observing variations in HI and yield and thus being limited in BWP_B analyses. Arguably, the additional variations in BWP_Y are important to understand better.

3.2 Field Surveys

Another possible way to obtain some diagnostic insights regarding the performance of the field is through field surveys. Field surveys aim at reaching out to farmers or farm managers regarding their farming practices and environmental conditions. Field surveys should be applied at field level and capture the different practices at different fields. Once this information is gathered, insights can be gained on the possible reasons behind water productivity variations. Interventions to increase water productivity should be promoted with caution, as they might have other negative effects (see section 3.3.3. for wheat in Kenya).

To this end, a field survey excel file has been created to guide field surveys[4]. The survey asks farmers to elaborate on their farming practices and constraints. The survey also incorporates socio-economic considerations (e.g. access to markets) in order to explore possibilities of improving other types of water productivity (economic and social water productivity). Based on insights from this survey, rapid appraisal of the situation can be made with caution regarding biophysical water productivity and with more confidence regarding economic water productivity.

3.3 AquaCrop simulation model

AquaCrop is a crop growth model that focuses on water stresses. AquaCrop is designed for simulating green canopy and root growth under governing environmental conditions (Steduto et al., 2009). With a limited number of input requirements; rainfall, ET_0, air temperature and CO_2 concentration, AquaCrop simulates daily water balances in the root zones and crop development. To calculate the crop biomass and yield production, AquaCrop separates the ET into soil evaporation (E) and crop transpiration (T). This

[3] A standardized protocol for WaPOR and the analyses of the land and water productivity is available on the WaterPIP website: https://waterpip.un-ihe.org/sites/waterpip.un-ihe.org/files/protocol_wapor4productivity_ihe_2020.pdf

[4] https://waterpip.un-ihe.org/sites/waterpip.un-ihe.org/files/1.fieldsurveys.xlsx

separation makes sure that non-productive (soil evaporation) water consumption is not taken into account in the calculations for yield and biomass production. Through AquaCrop, the user is able to understand what is the reason why water productivity is low (or high) in the field, and thus AquaCrop can be used as a tool for field level interventions to improve water productivity.

There is a vast amount of resources related to the development and use of AquaCrop model[5]. As such, this protocol will only briefly discuss the data requirements (section 3.3.1) and the calibration and validation process (section 3.3.2). Most emphasis will be put on the interpretation of the outcomes of the software and how these can be used to inform interventions.

3.3.1 AquaCrop data requirements

AquaCrop require four categories of input, namely i) **climate**, ii) **crop**, iii) **soil** and iv) **management**.

The **climate** input includes data for rainfall, reference evapotranspiration (ET_0), temperature and atmospheric CO_2 concentration. AquaCrop calculates the ET_0 with the FAO Penman-Monteith equation. For this reason, additional data; i.e. air temperature, air humidity, radiation and wind speed, are required.

The **crop** input requires data regarding the crop (crop type, planting date, planting density, growth cycle, canopy cover) and the user can decide to consider or not the influence of soil fertility stress on canopy cover development. AquaCrop is mainly focused on staple crops[6] and has a maximum of growth cycle of 500 days (around 16.5 months). This is important to consider while simulating crops with big growth cycles like sugarcane. In the crop file, the user can define the mode of the simulation. AquaCrop provides two modes of running the simulations, running with calendar days; i.e. the amount of days required to reach the next growth stage, and running with growing degree days (GDDs); i.e. the amount of thermal units require to reach the next growth stage. Generally, field data regarding canopy cover are expressed in calendar days. AquaCrop provides the option to convert the observed calendar days into growing degree (or thermal) days (GDDs) using the climate file. Running the simulation with GDDs is generally more reliable as GDDs consider the influence of temperature stress, in addition to the other stresses. Moreover, running with GDDs is the only option when data for the growth cycle of the crop are not available. Based on AquaCrop's settings, AquaCrop uses presumed, default GDDs and simulates the plant growth and water productivity. However, special attention should be given to the validity of simulations run directly with GDDs, without data on the growth cycle.

The **management** data has two sub-categories, one regarding the irrigation and one regarding the field. Regarding irrigation, AquaCrop can run simulations for both irrigated and rainfed conditions. Under irrigated conditions, the irrigation method and schedule should be inserted while under rainfed conditions, this tab is left empty. Regarding the field sub-section, the user can define the soil fertility stress, the influence of mulches, the field surface and the weed infestation management. Even though soil fertility stress is considered in the crop file, it is 'activated' in the field sub-section of the management file.

The **soil** (-water interface) tab also has two sub-section that regard i) the soil profile of the farm (thickness, soil water, stoniness and permeability of soil) and ii) the groundwater table profile. In case that this information is not important or available, AquaCrop can be run without it.

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[5] https://www.youtube.com/playlist?list=PLzp5NgJ2-dK7H85cyEmGc8KSodqm8gCf2
http://www.fao.org/3/a-i6051e.pdf; http://www.fao.org/3/a-br248e.pdf; http://www.fao.org/3/a-br246e.pdf; http://www.fao.org/3/br267e/BR267E.pdf; http://www.fao.org/3/i2800e/i2800e00.htm

[6] Crops that can be analysed with AquaCrop: barley, cotton, dry bean, maize, paddy rice, potato, quinoa, sorghum, soybean, sugar beet, sugar cane, sunflower, tomato, wheat.

3.3.2 Validation, calibration and required data

AquaCrop can simulate crop growth with a ranging degree of reliability depending on the frequency and accuracy of the obtained data. As seen in Table 4, AquaCrop can produce a first order of estimation for crop growth based on a limited set of data required. However, this involves assumptions that are intrinsic to AquaCrop's default settings. In order to validate if the default settings can re-produce the field conditions, the reported yield is used for **validation**. Validation involves adjustments in the simulation parameters that are related to governing environmental and farming management conditions. These parameters are referred to as non-conservative parameters. In case that additional field data are available for canopy development at different dates of the growing cycle, the validity of the default AquaCrop settings can be further checked (Table 5). This kind of analysis does not involve calibration of AquaCrop but a higher degree of reliability for the simulation.

However, the default settings might result in significant differences between the observed and simulated values, thus the default settings cannot be considered as valid. If that is the case, more detailed **calibration** of the crop settings is necessary. This calibration requires additional and accurate field observations of the growth stages (emergence, max CC, senescence and maturity). Calibration involves adjustments in the specific physiological plant growth processes and the response mechanisms of the specific crop to farming practices and environmental conditions, i.e. the conservative parameters. In other words, this analysis involves a detailed parametrization of the crop file. The data requirements each level of reliability, including data requirements for calibration, are given in an excel file[7].

The calibration and validation of such crop models is a very laborious and a data intensive process. This is due to i) the complexity of crop growth and ii) the different conditions that are evident in different fields. The crop response mechanisms to environmental stress conditions are numerous and intricate, which need to be modelled and parameterised – e.g. crop development stages and their response to water and climate; canopy development (water, climate and fertility), harvest index (water, climate). Considering that such processes of validation and calibration need to be repeated for every field under investigation, data collection, validation and/or calibration need to take place for each of the fields, limiting the possibility to apply such approaches at scheme-level.

Table 4. Data requirements for AquaCrop modelling for first order of estimation (source: Hsiao et al., 2012)

AquaCrop tab	Absolute minimum (first order of estimations)
Crop	Yield (and indication of the HI)
	Planting and harvesting dates (indication)
	Seeding and germination rate
Climate (and ET_o)	10-day or monthly mean values of T_{max}, T_{min}, fraction of sunny days, wind, humidity, latitude and elevation (or) Pan evaporation data
	Daily rainfall data (10-day or monthly are not recommended)
Soil and fertility	Textual soil class and variation with depth (indication)
	Land slope and water holding capacity (indication)
	Native fertility of the soil (indication)
	General fertilization practice
Irrigation and water in the soil	Water application method and irrigation schedule (approximate)
	Soil water content at planting (indication)

[7] https://waterpip.un-ihe.org/sites/waterpip.un-ihe.org/files/2.aquacropcollectiondata.xlsx

Table 5. Additional data requirements for AquaCrop modelling for reliable simulation (validation) (source: Hsiao et al,. 2012)

AquaCrop tab	Absolute minimum (first order of estimations)
Crop	Above-ground biomass at harvest
	Date of emergence and date of maturity
	Planting density and maximum rooting depth
	Maximum green leaf area index (LAI) (or) Indication of the extent of maximum canopy cover or canopy cover at a given time
Climate (and ET)	Weekly or 10-day mean values of daily solar radiation, T_{max}, T_{min}, RH_{max}, RH_{max}, wind run
	Daily rainfall data
	Evapotranspiration (through long-term water balance)
Soil and fertility	Texture of soil layers, depth of any layer restrictive to root growth
	Kind, rate and time of fertilization
Irrigation and water in the soil	Irrigation date and amount
	Estimate or close observation of soil-water content

3.3.3 Diagnostics for CropMON case study with AquaCrop

WaterPIP CropMON case study is used to illustrate the application of AquaCrop for diagnostic analyses (WUR, 2020)[8]. The analysis of a commercial rainfed wheat field in Kenya shows the influence of different stresses in the crop growth (Figure 1) under certain assumptions, namely i) optimal salinity management and ii) no biotic stresses from pests and diseases. The model was validated with the observed yield and canopy cover and resulted in relatively moderate weed infestation and soil fertility stress (10% and 25% respectively), which is sensible under commercial farming. The water and temperature stresses were simulated.

The validation (using canopy cover data on specific dates) indicates that the crop is suffering from fertility stress (25%), and water stress affecting canopy expansion (21%), stomatal closure (29%) and weed infestation (10%). These stresses lead to a reduced biomass production (7.99 ton/ha instead of the potential 15.81 ton/ha) and lower yields due to the reduced HI (HI is simulated at 43.8% instead of the reference HI for wheat of 48%). The HI is reduced due to both the severity as well as the timing of the water stress. There is no temperature stress. The simulation assumes that there is no salinity stress or biotic stresses from pests and diseases.

[8] For this field of the CropMON case study, calibration was not necessary as validation of the default AquaCrop settings was successful.

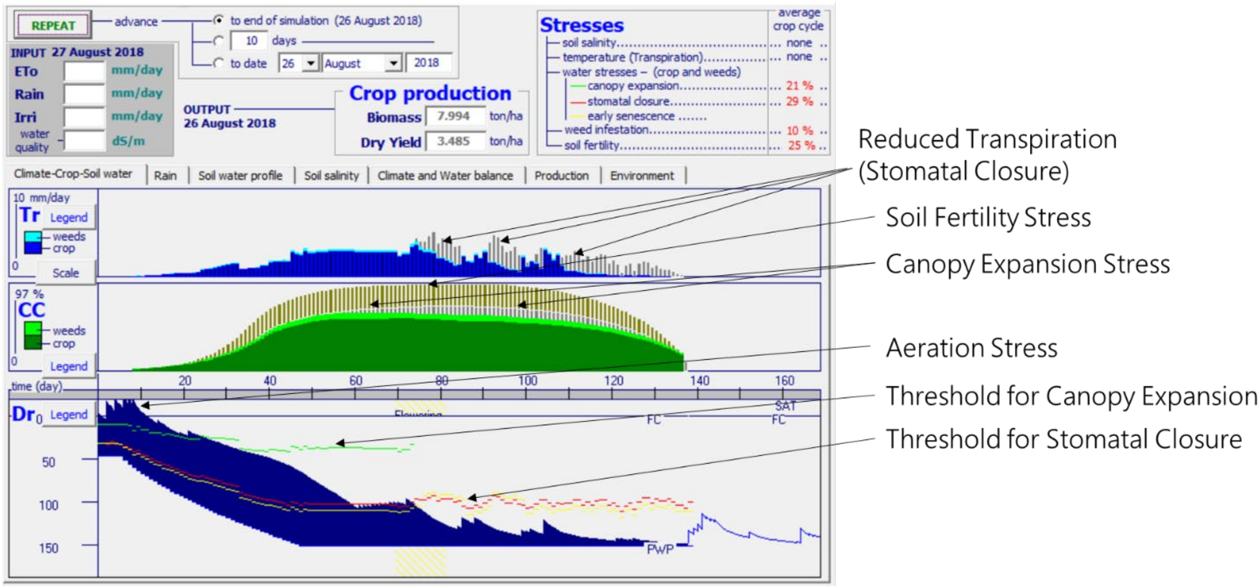

Figure 2. Validated simulation of commercial rainfed wheat field in Kenya with AquaCrop and the impact on water use and crop production, assuming no salinity and biotic stresses. AquaCrop direct output (WUR, 2020).

As the water stress in absence of irrigation is not a manageable factor and that weed infestation is rather limited (10%), the identified fertility stress could potentially be remedied by application of fertilizers. However, the subsequent simulation under optimal fertility management reveals that this will only have a very limited effect on overall crop performance. In the absence of fertility stress the crop will grow more vigorously during the vegetative growth (resulting in a larger canopy) which consumes more water (higher T) (Figure 2). During the critical flowering and yield formation stage, the crop suffers a more severe water stress in the absence of rainfall. Overall production and productivity are slightly better thanks to fertility, but still well below potential in the absence of favourable rains in the yield formation period. This illustrates how the cost-benefit ratio of additional fertilization in rainfed cereal crops can be rather low or negative, which explains its rather low uptake in Africa. As such, the gains of fertilisers are offset by higher water stress during the critical stage, making this strategy less suitable. Similar analysis can be done for optimal weed management as well as a combination of improvements in fertility and weed management.

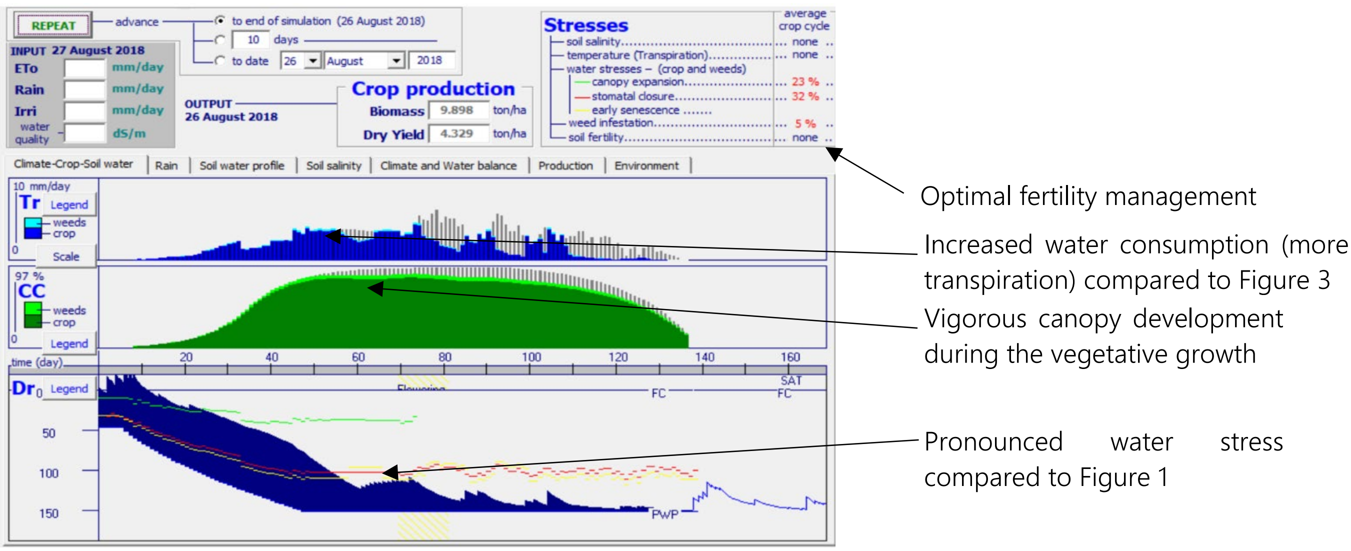

Figure 3. Assessment of optimal fertility management intervention, using the validated simulation of the commercial rainfed wheat field in Kenya with AquaCrop and the impact on water use and crop production, assuming no salinity and biotic stresses. AquaCrop direct output (WUR, 2020).

Here we illustrate an example of how RS based diagnostic can be implemented. The remote sensing approach is illustrated for the Bekaa valley where WaPOR level 3 data is available (incl. crop map). The level 3 WaPOR database can be used to identify the cluster of bright (high performing fields) and hot spots (low performing fields) in a region by plotting seasonal BWP_Y (ET_a) against the Yield per crop. As WaPOR does not provide data on the dynamic HI, the yield is calculated on the basis of user's input on the HI. The hot spots are compared with the bright spots (set as a benchmark) to find the main limiting factors of the WP. The causes of land and WP variations can be diagnosed by comparing the performance of bright with hot spots, considering all internal (genetic) and external (environmental) factors that affect crop production. Figure 3 shows the generic framework on diagnosing factors affecting spatial variability of Yield and WP.

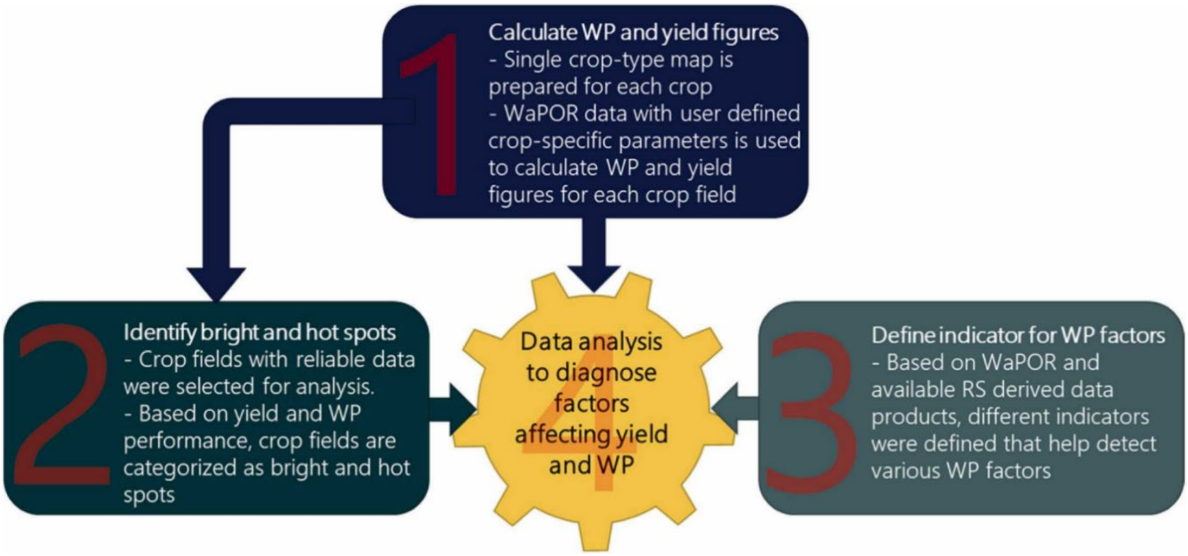

Figure 4. Analytical framework used to identify factors affecting yield and WP (Safi et al., 2022)

The stress factors (water, salinity, nitrogen, soil) are interrelated and they could have synergic or antagonistic effects on the yield and BWP_y. There is limited understanding and approaches to disentangle the effect of the individual factors on the crop yield and WP. Furthermore, some factors cannot be sensed remotely, such as crop genetic, socio-economic, and biotic factors, which require interviews and fieldwork. Thus, it is recommended to devise a customized list of remote-sensing-based WP factors for each study. Figure 4 lists indicators derived from remote sensing based indices to identify factors affecting the variability of WP (Safi et al., 2022). Seven WP factors and their corresponding indicators are shown. For identification of the water stress, the Stress Sensitivity Index (SSI) was introduced, which uses Net Primary Production (NPP) and Normalized Difference Moisture Index (NDMI). Within-farm irrigation heterogeneity is identified by estimating the Coefficient of variation ET_a (CVET). Near-Infrared (NIR) and Short-Wave infrared (SWIR), remote sensing data, are used for salinity identification. Leaf nitrogen content is identified with the Visible and Near Infrared (VNIR). Land Cover Classification from WaPOR and Soil data from SoilGrids were used to determine the influence of crop rotation and soil type on crop growth.

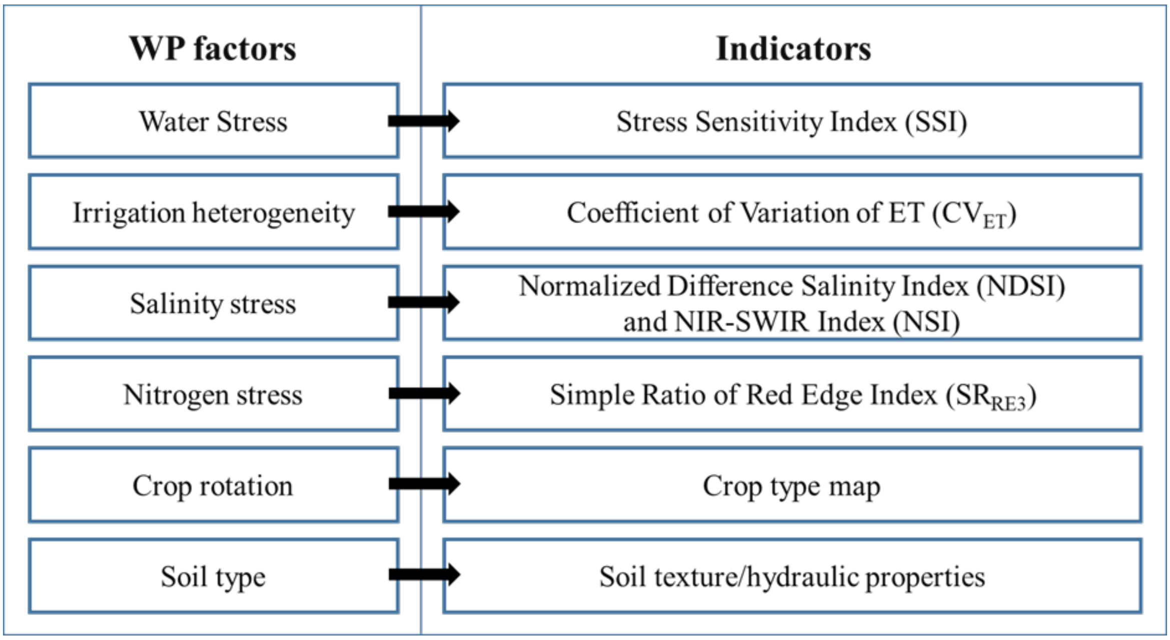

Figure 5. Remote sensing based indicators used to identify factors affecting WP

For the discrete indicators (eg soil type), the yield and WP figures of both groups were tested with the t-test to determine whether the difference between the means of the groups is significant or not. If the t-score exceeds its critical value (at $p < 0.05$), then the difference is significant and vice versa. A significant difference implies that the factor (soil type) has affected yield or WP. For continuous indicators (eg CV_{ET}, NDSI and NSI), all crop fields have a single value for a season, the individual crop fields were correlated with their corresponding yield and WP figures. Correlation evaluates the relationship between two variables quantitatively. A higher correlation indicates a stronger relationship between variables, whereas a weak correlation implies that the variables are not related to each other (See for more detail Safi et al., 2022).

3.4 Possible complementary use between the three tools

All three tools have advantages and disadvantages. Overcoming the disadvantages of each tool through complementary analysis using (partly) insights from the other tools can provide a more robust and inexpensive diagnostic analysis. Opportunities in complementary use of the tools may existing in i) developing targeted field surveys on the basis of findings of diagnostic insights through remote sensing, effectively reducing the labour and costs of field surveys and increasing the reliability of remote-sensed diagnostics, ii) identifying fields through remote sensing that require detailed diagnostics through crop growth modelling (determination of the water, climate, fertility stresses that determine crop performance), and evaluate the options for improvement within the boundaries of management options, iii) using high resolution remote-sensed data in crop growth modelling for validation and/or calibration purposes, such as the remote-sensed canopy cover development over the season(s), reducing the difficulties in canopy cover data collection from the field (see Abi Saab et al., 2021; Tenreiro et al., 2021) and iv) combining remote sensing data with field data for disaggregating remote-sensed ETa and biomass values for climate conditions and irrigation method (Seijger et al., 2022).

The last option for complementary use of the tools aims to disaggregate remote-sense data along physical field parameters (irrigation type, fertility, water logging, etc.). This will enable to disaggregate the analysis and attribute the BWP variation (or part of it) to the physical parameter (e.g. the correlation of the WP_B relation gets stronger along the disaggregated set). The richer the data set, the more means one will have to disaggregate the data and to attribute variation in output to a variation in physical parameters. Table 3 provides an overview of potential physical parameters that can be used for disaggregation.

Table 6. Parameters for disaggregation of remote-sensed data.

Parameter	Consideration
Crop Type	C3, C4, unique crop specific sensitivity to water stress
SOS – EOS (start and end of season)	Determination of the growing season over which ET and B are accumulated and EOS is sensitive to the climate & water stress
Fertility treatment	Disaggregate for fertility (yes/no, moderate/severe stress, etc)
Salinity	idem
Soil type	Sandy soils or clay soils may have different water stress and fertility regimes
Water logging	Water logged soils to disaggregate WP analysis
Irrigation type	idem
Small holders/commercial growers	Input level at smallholders may be less than at commercial farms affecting WP
Harvest (kg/ha)	Not applicable in WaPOR
Biotic stresses (pests and diseases)	Pests and diseases will lead to production losses thus disaggregate for such stresses (yes/no, severe/mild)

Note 1: all data to be collected for georeferenced plots, conduct analysis of WaPOR only on uniform pixels (e.g. avoid mixed pixels of crops, irrigation types, etc)

4 Conclusion

This diagnostic protocol discussed the agronomic principles behind the reasons that affect water productivity (section 2) and the different tools available for conducting a diagnostic analysis for water productivity (section 3). Diagnostic analysis is essential in order to propose meaningful interventions that will lead to water productivity improvements.

BWP is an agronomic factor that is related to different aspects of crop growth. Biotic and abiotic stresses influence BWP in multiple and intricate ways. Section 2 de-constructed these relations in three steps; first through understanding the relations between BWP_B and T, second through relations between BWP_B and ET_a, and third through BWP_Y and ET_a.

Next, three different tools for obtaining diagnostic insights have been described. **Field surveys** can provide extensive diagnostic insights, in combination with information about socio-economic constraints, that affect the water productivity variations and the adoption of possible interventions. Field surveys is the only tool that can assess and incorporate in the diagnostic analyses the possible influence of pests and diseases. However, such tools are laborious and costly, depending on the spatial coverage while the temporal coverage is often for one season. **Crop growth modelling** can also provide extensive diagnostic insights under certain condition that relate to the reliability of the model developed. Crop growth modelling, requires field data that are representing each field that is investigated. Data collection and simulation for each individual field, similar to field surveys, is laborious and costly while often focus on one season and limited number of fields, limiting the spatial and temporal coverage of the analyses. **Remote sensing**, where different sources of satellite-derived data are combined, can also provide some diagnostic insights, under certain conditions (focus on biomass or include field-derived data regarding the HI and convert biomass to yield).

Opportunities for complementary use of the three tools exist in four main aspects: i) developing targeted field surveys on the basis of findings of diagnostic analysis through remote sensing, ii) identifying selected fields on the basis of diagnostic analysis through remote sensing that require more detailed diagnostics through crop growth modelling, iii) the use of high resolution remote-sensed data in crop growth modelling, and iv) combining remote sensing data with field data for disaggregating remote-sensed ET_a and biomass values for physical parameters. Through this complementary use of the tools, more robust and inexpensive diagnostic analyses that minimizes the labour needs and costs can be performed.

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