# Water productivity

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## Introduction

Traditionally, agricultural yield has been expressed as Land Productivity, i.e., the mass of yield obtained from a unit area, common units being kg/ha or ton/ha. In contrast, agricultural Water Productivity (WP) is the ratio between the amount or value of agricultural yield per volume (or value) of water used or diverted in this production. The most common units for expressing water productivity are kg m‑3 or ton m‑3, i.e., the mass of agricultural yield per volume of water used. Although there is no unique definition of water productivity, defining it as mass per volume is a useful concept when comparing WP in various parts of the same system or hydrological unit and when comparing WP in agriculture with other possible uses of water (FAO, 2017).

Water extracted from the soil by plants is for more than 99% destined to transpiration. Transpiration from a crop canopy is inevitably linked to photosynthesis, as CO2 is absorbed from the air by wet surfaces within the stomata. A reduction in transpiration is triggered by plants under stressed conditions (too dry, too wet, too high solute concentration, too windy, etc.) increasing canopy resistance to gaseous diffusion by stomata closure. This increased resistance also leads to a reduction in CO2 uptake from the air, reducing the photosynthesis rate and dry matter accumulation. As it is difficult to separate transpiration from evaporation from the soil surface (which does not contribute directly to crop production), defining crop water productivity using *evapotranspiration* rather than *transpiration* makes practical sense at field and system level. In the specific case of irrigated agriculture in saline areas, the leaching requirement, i.e. the amount of water that needs to percolate to maintain rootzone salinity at a satisfactory level, should also be included together with evapotranspiration in the amount of water that is necessarily depleted during plant growth.

A concept similar to WP is the Water Footprint (WF) conceptualized by Hoekstra et al. (2009). The WF is the inverse of WP, and for agricultural products it is expressed in m3/kg. It is an indicator of the amount of water used to produce a product along its production chain.

## Calculating water productivity or water footprint

When calculating WP, the decision about which water to include depends on the scale and on the specific problem or question. At basin level, the choice might be between water diverted from the source and the same minus water restored, whereas at field level one might consider transpired rainwater and irrigation water, or irrigation water alone.

Expressing WP in kg/m3, yield (Y) in kg ha‑1 and evapotranspiration (ET) in mm, the water productivity can be calculated by

  [1]

where the factor 10 in the denominator stands for the conversion between m3 ha‑1 and mm (1 mm = 10 m3 ha‑1). Reported data on water productivity with respect to evapotranspiration (WPET) show considerable variation, e.g. wheat 0.6-1.9 kg/m3, maize 1.2-2.3 kg/m3, rice 0.5-1.1 kg/m3, forage sorghum 7-8 kg/m3 and potato tubers 6.2-11.6 kg/m3. (FAO, 2017).

Regarding the Water Footprint, for agricultural production a so-called “Green WF” (WFG, m3 kg‑1) is defined based on transpired water that originated from rainfall, together with a “Blue WF” (WFB, m3 kg‑1) based on water originating from irrigation. The WFG can be determined or modelled using the evapotranspiration (ET, mm) and yield (Yr, kg ha‑1) under rainfed conditions by the following equation:

  [2]

where the factor 10 stands for the conversion between m3 ha‑1 and mm.

Under irrigated management, WFB is calculated as function of irrigation depth I (mm) and irrigated yield *Yi* (kg ha‑1), according to

  [3]

In these conditions, WFG is calculated based on the difference between (evaporated + transpired) and irrigated water:

  [4]

## Improving water productivity in agriculture

Despite concerns about the technical inefficiency of water use in agriculture, water productivity increased by at least 100 percent between 1961 and 2001. The major factor behind this growth has been yield increase. For many crops, the yield increase has occurred without increased water consumption, and sometimes with even less water given the increase in the harvesting index. It is estimated that the water needs for food per capita halved between 1961 and 2001 from about 6 m3/d to less than 3 m3/d (Renault, 2003).

The key principles for improving water productivity at field, farm and basin level, which apply regardless of whether the crop is grown under rainfed or irrigated conditions, are: (i) increase the yield of the crop per unit of water transpired; (ii) reduce all outflows (e.g. drainage, seepage and percolation), including evaporative outflows other than the crop stomatal transpiration; and (iii) increase the effective use of rainfall, stored water, and water of marginal quality.

At the level of plants, there are several options to improve water productivity, related to genetic improvement and agricultural management, e.g.:

* developing varieties with a deeper rooting system
* increasing the harvest index (the marketable part of the plant as part of its total biomass)
* enhancing photosynthetic efficiency
* optimizing the growth cycle making vegetative and reproductive periods to be well matched with the expected water supply

At field level WP can be improved by changes in crop, soil and water management. They include: selecting appropriate crops and cultivars, minimum tillage (reducing evaporation), timely irrigation to synchronize water application with the most sensitive growing periods, and more precise irrigation (drip irrigation, subsurface irrigation).

One of the field-level methods for increasing WP is deficit irrigation, where deliberately less water is applied than that required to meet the full crop water demand. The prescribed water deficit should result in a small yield reduction that is less than the concomitant reduction in transpiration. Therefore, it causes a gain in water productivity per unit of water transpired.

## Exercises

To get a feeling of Water Productivity and Water Footprint and the factors that affect it, we will perform some exercises using two main scenarios: Wheat in Qazvin, Iran, with available weather data from 23/Sep/2014 to 4/Jul/2015, and Maize in Piracicaba, Brazil, with available weather data from 1/Jan/2009 to 31/Dec/2010). To do so, four directories are available, two referring to rainfed conditions and two including irrigation scheduling:

1. WP rainfed Wheat - Qazvin (Iran)
2. WP rainfed Maize - Piracicaba (Brazil)
3. WP irrigated Wheat - Qazvin (Iran)
4. WP irrigated Maize - Piracicaba (Brazil)

### Water Productivity in rainfed crops

In this exercise we will perform a basic simulation for both Qazvin and Piracicaba, without irrigation, to calculate WP and WFG.

1. In both “rainfed” directories 1 and 2, double-click on “initial.bat”. The files needed to run SWAP will be copied to the directory. Check for both SWAP.SWP files, and verify
* specifications in the Meteorology Section (name, latitude)
* cropping dates for both locations (Wheat/Qazvin starting in 17/11/2014 and Maize/Piracicaba starting on 01/11/2009)
* Differences in soil hydraulic properties between both locations – *which major differences do you see from the soil hydraulic properties for both locations?*
1. Open both crop files, and check
* In the “Soil water extraction by plant roots” part, differences between limiting Feddes parameters. *According to these parameters, which crop is more sensitive to drought?*
* In the Irrigation Scheduling Section, SCHEDULE=0 (no irrigation scheduling).
1. Run a SWAP simulation in each directory double-clicking SWAP.bat.
2. Obtain the sum of evaporation and transpiration from the .BAL files, and the grain yield from the .CRP files, and calculate the rainfed water productivity (Eq. 1) as well as the water footprint WFG (Eq. 2) for both scenarios [WP for Qazvin should be about 1/10th of that of Piracicaba].
3. In the Brazilian climate, Maize can be sown anywhere between November and February. Check how different sowing dates will affect WP. To do so, change CROPSTART and CROPEND in the Crop Section, perform a simulation for every 15 days according to below table. Don’t forget to adapt also the simulation period (TSTART and TEND), keeping TSART 2 months before sowing and TEND 15 days after CROPEND.

*What trend do you observe in these results? Can you explain the trend?*

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Sowing Date | .BAL | .CRP |  |  |
|  | ET | Grain Yield | Water Productivity | Water Footprint |
|  | mm | kg/ha | kg/m3 | m3/kg |
| 01/11/2009 | 519 | 8455 | 1.63 | 0.614 |
| 16/11/2009 |  |  |  |  |
| 01/12/2009 |  |  |  |  |
| 16/12/2009 |  |  |  |  |
| 01/01/2010 |  |  |  |  |
| 16/01/2010 |  |  |  |  |
| 01/02/2010 |  |  |  |  |

### Water Productivity in irrigated crops

The next step is to evaluate water productivity and water footprint of irrigated crops. There are many scenarios that can be evaluated, but an interesting question is how irrigation management affects WP and WF. To test this, we will use the “irrigated” directories 3 and 4, with the same contents as the “rainfed” once used in the previous section, but now with automatic irrigation scheduling (switch SCHEDULE set to 1). Then we will check the effect of sowing date on WP and WF for the Piracicaba case, and the effect of some irrigation management alternatives for the Qazvin case.

1. In both directories 3 and 4, double-click Initial.bat to copy the original files back into the directory. Open the crop file (WheatD.CRP and MaizeD.CRP) and check that SCHEDULE=1. Check also if Field Capacity is ‑100 cm, TCS=1, Trel=0.95, DCS=1 and dI=0.
2. In the Maize-Piracicaba directory 4, run a SWAP simulation double-clicking SWAP.bat. Open the .BAL and .CRP file and fill in values of Evaporation, Transpiration, Irrigation, Grain Yield, Drainage (=Bottom Flux) and the number of irrigations (open the .IRG file to check for irrigations) in below table for sowing date 01/11. Calculate the WP and WF values (*hint*: you may use the spreadsheet “WP and WF calculation” for this). Repeat the exercise for the other sowing dates.

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Piracicaba, Brazil** | **.BAL** | **.BAL** |  | **.BAL** | **.CRP** |  |  |  | **.BAL** | **.IRG** |
| Sowing Date | **E** | **T** | ET | **Irr** | **Grain Yield** | WP | WFB | WFG | **D** | **Nirr** |
|  | **cm** | **cm** | mm | **mm** | **kg/ha** | kg/m3 | m3/kg | m3/kg | **cm** |  |
| 01/11/2009 | **18.77** | **33.15** | 519 | **0** | **8455** | 1.63 | 0 | 0.614 | **54.68** | **0** |
| 16/11/2009 |  |  |  |  |  |  |  |  |  |  |
| 01/12/2009 |  |  |  |  |  |  |  |  |  |  |
| 16/12/2009 |  |  |  |  |  |  |  |  |  |  |
| 01/01/2010 |  |  |  |  |  |  |  |  |  |  |
| 16/01/2010 |  |  |  |  |  |  |  |  |  |  |
| 01/02/2010 |  |  |  |  |  |  |  |  |  |  |

1. In the Wheat-Qazvin directory 3, run SWAP, open the .BAL and .CRP file and fill in values of Evaporation, Transpiration, Irrigation and Grain Yield in below table for Trel = 0.95. Calculate the WP and WF values. Repeat the exercise for the other Trel values in the table. Discuss the results.

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Qazvin, Iran** | **.BAL** | **.BAL** |  | **.BAL** | **.CRP** |  |  |  | **.BAL** | **.IRG** |
| Trel to irrigate | **E** | **T** | ET | **Irr** | **Grain Yield** | WP | WFB | WFG | **D** | **Nirr** |
|  | **cm** | **cm** | mm | **cm** | **kg/ha** | kg/m3 | m3/kg | m3/kg | **cm** |  |
| 1.0 |  |  |  |  |  |  |  |  |  |  |
| 0.95 | **22.14** | **30.33** | 525 | **32.97** | **5009** | 0.955 | 0.658 | 0.389 | **31.24** | **5** |
| 0.9 |  |  |  |  |  |  |  |  |  |  |
| 0.85 |  |  |  |  |  |  |  |  |  |  |
| 0.8 |  |  |  |  |  |  |  |  |  |  |
| 0.75 |  |  |  |  |  |  |  |  |  |  |
| 0.7 |  |  |  |  |  |  |  |  |  |  |
| 0.6 |  |  |  |  |  |  |  |  |  |  |
| 0.5 |  |  |  |  |  |  |  |  |  |  |

1. Another alternative for irrigation management would be to change the value for Field Capacity. In the WheatD.Crp file in the Wheat-Qazvin directory, set the value **Trel = 0.75** (just as an example, we could use other values too). Fill in the table and calculate the WP and WF values for the values of field capacity in the table. Discuss the results.

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Qazvin, Iran** | **.BAL** | **.BAL** |  | **.BAL** | **.CRP** |  |  |  | **.BAL** | **.IRG** |
| Field Capacity | **E** | **T** | ET | **Irr** | **Grain Yield** | WP | WFB | WFG | **D** | **Nirr** |
| (cm) | **cm** | **cm** | mm | **cm** | **kg/ha** | kg/m3 | m3/kg | m3/kg | **cm** |  |
| -330 |  |  |  |  |  |  |  |  |  |  |
| -100 | **20.85** | **28.72** | 496 | **27.54** | **3294** | 0.665 | 0.836 | 0.669 | **31.23** | **3** |
| -60 |  |  |  |  |  |  |  |  |  |  |
| -20 |  |  |  |  |  |  |  |  |  |  |

1. If there is time left, try out the sensitivity of water productivity to other system parameters, like rooting depth or excess/deficit irrigation, using soil hydraulic parameters of other soils or changing the drought sensitivity of the crop (Feddes *h*3 parameter).

## References

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