A note on

Water use efficiency and water productivity

Ragab Ragab – WP3 - W4C

This note is based on a number of discussions that took place in Bari and Bangalore and as the W4C project carries in its title the term “water use efficiency” and WP3 is dedicated to Water Use Efficiency, it is timely that we have a clear idea about the meaning of this term and how it differs from “water productivity”.

Water use efficiency (WUE) and water productivity (WP) are two different terms. However, they seem to cause some confusion only among agronomists. The fact is, both terms do exist and both have different definitions and applications. Unlike engineers, agronomists are likely to confuse the two and some consider the productivity is efficiency. The simple definition of any efficiency in our daily life is referred to as a ratio or percent. For example when considering energy, work performance and heat storage efficiencies, we say 90% or 70% efficiency which represents the percentage or ratio of output divided by input, both with the same units. In irrigation, for example, if one adds 10 mm of water to the plant and the plant used 8 mm through the root water uptake followed by transpiration and 2 mm is lost by drainage below the root zone or via bare soil evaporation from the surface, then the water use efficiency here is 80%. Productivity is a different term and refers to what we can produce from a unit of input, it is also a ratio of output to input but both do not need to have the same units, e.g. WP is 50kg grains per 1 m^3 of water.

These two terms are clear in the mind of the majority of researchers and if asked about the definition of WUE and WP they will answer correctly, giving the two different meanings. However, this is not the case with a minority of researchers who are still following literature perhaps dating back to the 1960’s when some authors confused the meaning of both terms. Those who are still using WUE with the meaning of WP, if asked about WUE, the answer is: “so many kg per cubic meter of water”. This in reality is water productivity (WP), not water use efficiency (WUE). Subsequently, if asked what the meaning and units of water productivity are, they do not have an answer and in some cases an excuse is provided by saying someone published it that way in journal A or B. However, this is not a good enough reason and definitely not a recipe to follow as, what is built on something wrong is also wrong. WUE is the % of water supplied to the plant that is effectively taken up by the plant, i.e., that was not lost to drainage, bare soil evaporation or interception.

Many high impact Journals such as Agriculture Water Management, Irrigation Science and Journal for Irrigation and Drainage do not accept papers substituting WP for WUE.

The Water Productivity term plays a crucial role in modern agriculture which aims to increase yield production per unit of water used, both under rainfed and irrigated conditions. This can be achieved either by 1) increasing the marketable yield of the crops for each unit of water transpired, 2) reducing the outflows/ losses, or 3) enhancing the effective use of rainfall, of the water stored in the soil, and of the marginal quality water. The first option refers to the need for improving crop yield; the second one intends to increase the beneficial use (water uptake - transpiration) of water supply against the non-beneficial losses (evaporation); the third aims to utilize efficiently the water resources, further than the water diverted from reservoirs, streams or groundwater sources. All these options lead to the improvement of the on-farm management aspects of crop growth, through the application of the best crop management practices which will permit to use less water for irrigation, decrease evaporation losses, optimize fertilizer supply, allow better pest control, minimize energy consumption and improve soil conditions. This is of particular importance in arid and semi-arid regions with limited water supply, where the farmers are frequently constrained to apply deficit irrigation strategies and to manage water supply in accordance with the sensitivity of crop’s growing stages to water stress. ***In those situations, the increase of WUE would lead to better WP*** and it would favour the farmer’s interest to improve economic return from the investments in irrigation water supply.

As ‘water productivity’ was originally referred to, in the literature of the 1960’s, as 'water use efficiency’, some of the confusion in the definition of water productivity comes from the fact that some researchers use it interchangeably with water use efficiency. The recent literature shows that what previously was wrongly defined as Water Use Efficiency has been renamed in “Water Productivity” in the early 1980’s.

In the sections hereafter, the reader will find some highlights of papers that addressed the issue of WP and WUE as two different terms and applications.

Molden (1997) mentioned that productivity takes different forms with different units but efficiency has only one form (dimensionless). The most recent paper on that subject (Heydari, 2014) indicated that WP is distinct from WUE as WP refers to crop production in relation to total water consumed while the ***WUE is a dimensionless ratio of total amount of water used to the total amount of water applied***, "as WP terms are not dimensionless, i.e. cannot be categorized in efficiency terms, they are just some ratios with different units in the numerator and denominator".

Passioura (2005) mentioned that: *''Water productivity'' means different things to different people .*To an economist it might mean the monetary value of outputs divided by that of the necessary inputs. To a geographer or irrigation engineer, it might mean the value of crops produced in a catchment in relation to the water supply of that catchment. But the quintessence of the idea is that it is quantifiable".

Ali and Talukder (2008) mentioned " In a crop production system, *water productivity (WP) is used to define the relationship between crop produced and the amount of water involved in crop production,* expressed as crop production per unit volume of water".

Perry et al. (2009) mentioned that, conventionally, water use efficiency was defined in the past as a productivity term "output of crop per unit of water ". However, the term was so widely misused and confused with the real term of WUE (the proportion of water used that is consumed by the crop) that it became meaningless and confusing for those who used the real meaning of the term *water productivity defined as output of crop per unit of water consumed*.

Lamaddalena et al. (2005) reported that, in the agricultural sector, the "Water-Use Efficiency" (WUE) term has been widely in use since the middle of sixties when Viets (1962) introduced it in his article on "Fertilizers and the efficient use of water". Since that time, the WUE term has become a common tool to describe, at different scales, the relationship between the crop growth development and the amount of water used. For example, at the leaf scale, the plant physiologists used the Photosynthetic Water-Use Efficiency referring to the ratio of net assimilation to transpiration; at the plant (canopy) scale, the agronomists employed both Biomass and Yield Water-Use Efficiency indicating the ratio between the biomass and crop transpiration, and yield and crop transpiration. However, in all these cases, the WUE terms were not non-dimensional values. In fact, they described the processes in which water is consumed and/or used to produce new entities (e.g. biomass, yield, etc.), indicating the quantity "produced" per surface area from the unit amount of water. For this reason, several alternatives have been proposed in recent years to convert these WUE terms into other, more appropriate terms. Among such attempts, *the "Water Productivity" (WP) term is used to describe better the ratio between the quantity of a product (biomass or yield) and the amount of water depleted or diverted. The WP term can be used from leaf to plant (canopy) and field scale where the choice of both the numerator and the denominator of the WP ratio may vary with the objectives and domain of interest of the study*.

Generally speaking, ***efficient water use is defined as the ratio between the actual volume of water used for a specific purpose and the volume extracted or derived from a supply source for that same purpose***. Functionally expressed as

$Ef = Vu/Ve$

where: Ef - Efficiency, dimensionless

Vu - Volume utilized, m^3

Ve - Volume extracted from the supply source, m^3.

In this case, water use efficiency refers exclusively to irrigation. In accordance with the definition proposed by the International Commission on Irrigation and Drainage (quoted by Burman et al. 1981) efficiency in the use of water for irrigation has several different components:

1. Storage efficiency Es

$Es = Vd/ Ve$

Ratio between the volume diverted for irrigation (Vd) and the volume entering a storage reservoir (Ve) for the same purpose.

2. Conveyance efficiency Ec

$Ec = Vp/ Vd$

Ratio between the volume of water delivered to irrigation plots (Vp) and the volume diverted from the supply source (Vd).

3. Irrigation efficiency Eu

Eu = Vu / Vp

Ratio between the volume of water used by plants throughout the evapotranspiration process (Vu) and the volume that reaches the irrigation plot (Vp).
Note that Vu is equal to the volume of evapotranspiration by plants minus the volume of effective rainfall.

Sadras et al. (2011) reported that "the term efficiency is widely used by irrigation specialists to express the ratio between water available at different points in the system". Thus 'conveyance efficiency' relates water delivered from a channel or system of channels to the water diverted into the channel (the excess going to spills, leakage and evaporation from the water surface). Similarly, 'field application efficiency' relates water delivered to the plant root zone to the total water delivered to the field (the excess typically going to runoff, percolation below the root zone, or evaporation from the wetted soil surface). *Efficiency is a dimensionless ratio and its theoretical limits are between 0 and 1, or between 0 and 100 if expressed as a percentage.*

It should be clear in our mind that t the terms WUE and WP do exist in life, have different meanings and are interlinked, e.g. in order to increase WP we need to increase the WUE, not the other way around.

There is a strong linkage between WUE and WP. Increase of WP follows the increase of WUE and other efficiencies such as weed control, fertilization, and pest and disease control. Kassam et al. (2007) reported that yield improvement research, including genetic enhancement and crop and natural resource management, has made an important contribution to global increases in agricultural WP over the last five decades or so. In contrast, little progress has been made in reducing losses such as evapotranspiration, the denominator in the WP term. Increasing the biomass productivity of water can be achieved through improving nutrient status, growing the crop during a cooler, more humid season, or through genetic improvements. Yield, on the other hand, can be influenced by ensuring that water is not restricted during critical growth stages, while curtailing supply at other times. Again, careful accounting must be applied, but productivity gains much in excess of 10% seem unlikely, and the level of management required is high. Plant breeding has delivered substantial productivity gains over recent decades—increasing the proportion of biomass going to grain, reducing the growing period, and breeding crops that tolerate lower temperatures. Genetic modification offers further promises – certainly in terms of reducing the impact of diseases and pests, possibly in terms of increased tolerance to drought – but to date the fundamental relationship between transpiration and biomass has not been changed.

Perry et al. (2009) reported ‘‘Raising irrigation water efficiency typically means shifting from the less efficient flood or furrow system to overhead sprinklers or drip irrigation, the gold standard of irrigation efficiency. Switching from flood or furrow to low pressure sprinkler systems reduces water use by an estimated 30%, while switching to drip irrigation typically cuts water use in half. A drip system also raises yields because it provides a steady supply of water with minimal losses to evaporation’’. This means that *any measures that improve WUE raise crop yields on irrigated land also raise the productivity of irrigation water*.

The International Commission on Irrigation and Drainage, ICID (Perry 2007) considers WUE as a dimensionless term, not to be misquoted or confused with WP.

Unlike water use efficiency, the productivity could refer to multi-use/user benefits from water use. For example, people using water for both irrigation and fisheries clearly contribute to their livelihoods and to the regional economy. Productivity refers to the benefits of water (income, jobs, crop production) as a ratio of water used. Productivity is an expression of the bio-economic output from the gross amount of water depleted.

Molden et al. (2010a) reported that “In its broadest sense, *water productivity, WP is the net return for a unit of water used”*. Improvement of water productivity aims at producing more food, income, better livelihoods and ecosystem services with less water. There is considerable scope for improving water productivity of crop, livestock and fisheries at field through to basin scale. Practices used to achieve this include water harvesting, supplemental irrigation, deficit irrigation, precision irrigation techniques and soil–water conservation practices. Practices not directly related to water management impact water productivity because of interactive effects such as those derived from improvements in soil fertility, pest and disease control, crop selection or access to better markets. Crop breeding has played an important role in increasing water productivity.

Higher water productivity results in either the same production from less water resources, or a higher production from the same water resources, so this is of direct benefit for other water users.

Water productivity, in its broader sense, defines the ratio of the net benefits from crop, forestry, fishery, livestock and mixed agricultural systems to the amount of water consumed to produce those benefits. We can distinguish physical water productivity, defined as the ratio of mass of product to the amount of water consumed (‘more crop per drop’) and economic water productivity, defined as the ‘value’ derived per unit of water used. In this case the ‘value’ can refer to economic return or to nutrition, or more broadly to any other economic and social benefit (e.g. jobs, welfare, environment, etc.).

Current levels of water productivity show a large variation by commodity (Table 1). Differences within a commodity reflect the effects of management, thereby implying that there is a scope for improvement. Table 2 shows how *the water use efficiency associated with the use of drip irrigation instead of surface irrigation has led to the increase in water productivity of a number of crops in India.*

The International Organizations are promoting the correct use of WUE and WP terminology.

Chawla and Vishwakarma (2012) reported that “the used terminology ‘water use efficiency’ as yield per unit of water used does not follow the classical concept of ‘efficiency’, which uses the same units for input and output. Therefore, the International Water Management Institute (IWMI) has proposed a change of the nomenclature from ‘water use efficiency’ to ‘water productivity’. The water productivity per unit of gross inflow (WPG) is the crop production divided by the rain plus irrigation flow. The water use efficiency in most irrigation systems in India is low and estimated to be in the range of 35 percent to 40 percent. The term “Efficiency” here means the ‘system efficiency’, i.e. the ratio of actual water consumed by the crops (evapotranspiration) for its growth to the total water supplied from the main source. The main causes of low efficiencies observed and also identified by the Indian Institutes of Management (IIMs), who carried out studies, are: deficiencies in water delivery system, inequitable delivery of water to the fields and inefficient management. There is scope for improving water efficiency by as much as 20%.

The international organizations such as IWMI (Tahir & Habib 2000, Bhattarai 2002, Molden 2010a &b, Cai et al. 2010), ICARDA (Oweis and Hachum 2006), ICID (Perry et al. 2009 & Perry , 2011), FAO (Sadras et al. 2011) , IRRI (Bouman and Tuong, 2000, Cabangon et al. 2002) are not using the term water productivity as substitute to WUE . Agricultural giant Monsanto (2014) has pledged to increase irrigation water efficiency across its global seed production operations by 25% by 2020. To reach the goal, Monsanto will expand implementation of drip irrigation systems, which enable water-use efficiency of up to 95%, compared with other systems that range from 50 - 65% efficiency. The company defines water-use efficiency as the percentage of applied water that is actively used by the plant for growth.

Table 1. Productivity from a unit of water for selected commodities (Molden et al. 2010a)

Product	Water productivity			
	Kilograms per cubic meter	Dollars per cubic meter	Protein grams per cubic meter	Calories per cubic meter
Cereal				
Wheat ($0.2 per kilogram)	0.2–1.2	0.04–0.30	50–150	660–4,000
Rice ($0.31 per kilogram)	0.15–1.6	0.05–0.18	12–50	500–2,000
Maize ($0.11 per kilogram)	0.30–2.00	0.03–0.22	30–200	1,000–7,000
Legumes				
Lentils ($0.3 per kilogram)	0.3–1.0	0.09–0.30	90–150	1,060–3,500
Fava beans ($0.3 per kilogram)	0.3–0.8	0.09–0.24	100–150	1,260–3,360
Groundnut ($0.8 per kilogram)	0.1–0.4	0.08–0.32	30–120	800–3,200
Vegetables				
Potatoes ($0.1 per kilogram)	3–7	0.3–0.7	50–120	3,000–7,000
Tomatoes ($0.15 per kilogram)	5–20	0.75–3.0	50–200	1,000–4,000
Onions ($0.1 per kilogram)	3–10	0.3–1.0	20–67	1,200–4,000
Fruits				
Apples ($0.8 per kilogram)	1.0–5.0	0.8–4.0	Negligible	520–2,600
Olives ($1.0 per kilogram)	1.0–3.0	1.0–3.0	10–30	1,150–3,450
Dates ($2.0 per kilogram)	0.4–0.8	0.8–1.6	8–16	1,120–2,240
Others				
Beef ($3.0 per kilogram)	0.03–0.1	0.09–0.3	10–30	60–210
Fish (aquaculture[a])	0.05–1.0	0.07–1.35	17–340	85–1,750

a. Includes extensive systems without additional nutritional inputs to superintensive systems.

Source: Muir 1993; Verdegem, Bosma, and Verreth 2006; Renault and Wallender 2000; Oweis and Hachum 2003, Zwart and Bastiaanssen 2004.

Table 2. Water productivity gains for various crops when shifting from conventional surface irrigation to drip irrigation in India Molden et al. (2007).

Crop	Increase in yield	Decline in water application	Gains in water productivity
Bananas	52	45	173
Cabbage	2	60	150
Cabbage (evapotranspiration)	54	40	157
Cotton	27	53	169
Cotton	25	60	212
Cotton (evapotranspiration)	35	15	55
Cotton	10	15	27
Grapes	23	48	134
Okra (evapotranspiration)	72	40	142
Potatoes	46	~0	46
Sugarcane	6	60	163
Sugarcane	20	30	70
Sugarcane	29	47	143
Sugarcane	33	65	280
Sugarcane	23	44	121
Sweet potatoes	39	60	243
Tomatoes	5	27	44
Tomatoes	50	39	145

Note: Water productivity is measured as crop yield per unit of irrigation water supplied or as the ratio of yield to evapotranspiration where evapotranspiration is indicated in parentheses.

Source: Adapted from Postel and others 2001; Tiwari, Singh, and Mal 2003 for cabbage row 2; Rajak and others 2006 for cotton row 3; Shah and others 2003 for cotton row 4; Tiwari and others 1998 for okra; and Narayanmoorthy 2004 for sugarcane row 5.

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