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Review of measured crop water productivity values for irrigated wheat, rice, cotton and maize

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Abstract

The great challenge of the agricultural sector is to produce more food from less water, which can be achieved by increasing Crop Water Productivity (CWP). Based on a review of 84 literature sources with results of experiments not older than 25 years, it was found that the ranges of CWP of wheat, rice, cotton and maize exceed in all cases those reported by FAO earlier. Globally measured average CWP values per unit water depletion are 1.09, 1.09, 0.65, 0.23 and 1.80 kg m^{-3} for wheat, rice, cotton$_{seed}$, cotton$_{lint}$ and maize, respectively. The range of CWP is very large (wheat, 0.6–1.7 kg m^{-3}; rice, 0.6–1.6 kg m^{-3}; cotton$_{seed}$, 0.41–0.95 kg m^{-3}; cotton$_{lint}$, 0.14–0.33 kg m^{-3} and maize, 1.1–2.7 kg m^{-3}) and thus offers tremendous opportunities for maintaining or increasing agricultural production with 20–40% less water resources. The variability of CWP can be ascribed to: (i) climate; (ii) irrigation water management and (iii) soil (nutrient) management, among others. The vapour pressure deficit is inversely related to CWP. Vapour pressure deficit decreases with latitude, and thus favourable areas for water wise irrigated agriculture are located at the higher latitudes. The most outstanding conclusion is that CWP can be increased significantly if irrigation is reduced and crop water deficit is intendently induced.

Keywords: Crop water productivity; Water scarcity; Wheat; Rice; Cotton; Maize

1. Introduction

With a rapidly growing world population, the pressure on limited fresh water resources increases. Irrigated agriculture is the largest water-consuming sector and it faces competing demands from other sectors, such as the industrial and the domestic sectors. With an increasing population and less water available for agricultural production, the food security

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for future generations is at stake. The agricultural sector faces the challenge to produce more food with less water by increasing Crop Water Productivity (CWP) (see Kijne et al., 2003a for a recent review). A higher CWP 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. In this study CWP ($\mathrm{kg\,m^{-3}}$), which is originally referred to in literature as 'water use efficiency', is defined as the marketable crop yield over actual evapotranspiration:

$$\mathrm{CWP} = \frac{Y_{\mathrm{act}}}{\mathrm{ET_{act}}} \quad (\mathrm{kg\,m^{-3}}) \tag{1}$$

where Y_{act} is the actual marketable crop yield ($\mathrm{kg\,ha^{-1}}$) and $\mathrm{ET_{act}}$ is the actual seasonal crop water consumption by evapotranspiration ($\mathrm{m^3\,ha^{-1}}$). When considering this relation from a physical point of view, one should consider transpiration only. The partitioning of evapotranspiration in evaporation and transpiration in field experiments is, however, difficult and therefore not a practical solution. Moreover, evaporation is always a component related to crop specific growth, tillage and water management practices, and this water is no longer available for other usage or reuse in the basin. Since evapotranspiration is based on root water uptake, supplies from rainfall, irrigation and capillary rise are integrated.

Despite that CWP is a key element in longer-term and strategic water resources planning, the actual and practically feasible values are hardly understood. The most complete international work so far is compiled by Doorenbos and Kassam (1979), who used crop yield response factors (k_{y}) for relating $\mathrm{ET_{act}}$ to Y_{act}. The problem with the standard 'FAO33-approach' is that the maximum yield ought to be known, which differs for given cultural practices. This implies that $Y_{\mathrm{act}} = f(k_{\mathrm{y}}, Y_{\mathrm{pot}}, \mathrm{ET_{act}}, \mathrm{ET_{pot}})$ is not straightforward, although it is often applied in absence of alternative expressions.

Kijne et al. (2003b) provide several strategies for enhancement of CWP by integrating varietal improvement and better resources management at plant level, field level and agro-climatic level. Examples of options and practices that can be taken are: increasing the harvest index, improving drought tolerance and salinity tolerance (plant level), applying deficit irrigation, adjusting the planting dates and tillage to reduce evaporation and to increase infiltration (field level), water reuse and spatial analysis for maximum production and minimum $\mathrm{ET_{act}}$ (agro-ecological level), to mention a few.

Due to agronomical research (e.g. plant breeding) and improved land and water management practices, CWP has increased during the years. For example Grismer (2002) conducted a study on CWP values for irrigated cotton in Arizona and California and concluded that CWP values exceed the range given by Doorenbos and Kassam (1979) in many cases. In rice production CWP increased due to shorter growing periods (Tuong, 1999) and due to increase in the ratio of photosynthesis to transpiration (Peng et al., 1998). It is likely that CWP for other crops has changed significantly as well.

Various studies have researched water use and yield relationship of specific crops, on specific locations, with specific cultural and water management practices. The current investigation summarizes the results of field experiments that have been conducted over the last 25 years and tries to find a range of plausible values for four major staple crops: wheat (*Triticum aestivum* L.), rice (*Oryza sativa* L.), cotton (*Gossypium* spp.) and maize (*Zea* *mays* L.). The second objective of this paper is to find some first order explanatory variables for the global scale CWP differences found.

2. Database and terminology

A database is established with CWP data collected from field experiments that were reported in the international literature, conference proceedings and technical reports. The majority of field experiments was conducted at experimental stations under varying growing conditions, including variations in climate, irrigation, fertilization, soils, cultural practices, etc. As the purpose of this research is to find plausible CWP ranges under farm management conditions, all measured CWP values of an experiment are included in the database.

To be included in the database, the results of the experiments should provide minimally the total seasonal measured actual evapotranspiration (ET_{act}), the method applied to determine ET_{act} and the crop yield, Y_{act}. Most studies do not measure ET_{act} and use the potential evapotranspiration (ET_{pot}) instead. These studies are not incorporated into the database and, hence, not used and discussed in this paper. Results from greenhouse experiments, pot experiments and water balance simulation models were excluded. Also, experiments based on the reference evapotranspiration method (Allen et al., 1998) has not been regarded as being suitable for the current review; evapotranspiration is not measured but estimated.

Lysimeters are a common instrument for determining ET_{act}. The soil water balance methods that monitor soil water content during the growing season by measurements of gravimetric soil moisture, or by neutron scattering equipment (neutron probes) or by time-domain-reflectometry (TDR), is also often used. Micro-meteorological in situ flux measurement techniques, such as the Bowen ratio and eddy-correlation methods are not common for agronomical studies (they are mainly used for micro-meteorological and climate studies in which yield is not reported).

Yield is defined as the marketable part of the total above ground biomass production; for wheat, maize and rice total grain yield is considered, and for cotton the total lint yield and/or total seed yield. Unfortunately, very few sources give the moisture content at which the yield was measured, which inevitably means an error exists in the final results. Siddique et al. (1990) investigated CWP of old and new wheat cultivars and found that older cultivars have lower CWP values due to lower harvest index. No significant difference in total biomass production between the old and new cultivars was found. For example in rice production CWP increased throughout the years due to developments in the new plants types with a higher ratio of photosynthesis to transpiration and due to a decrease in growth period (Peng et al., 1998; Tuong, 1999). Thus, experiments with results older than approximately 25 years are excluded to minimize the influence of older varieties with lower harvest index and longer growth period.

The results of experiments were first re-organized into a crop-wise database, that includes latitude/longitude, country, location, ET_{act}, Y_{act}, biomass production, harvest index, experimental year(s) and reference. Some of the references cited provide the results of each field experiments, while others give averages, e.g. each experimental year or each management strategy applied. Each value, whether it is reported as an average of more experiments or a unique value for one experiment, is considered as one value in the database.

3. Results

3.1. Database

An overview of the contents of the database is given in Table 1, while Appendix A depicts all results by crop and by source. A total of 84 publications was included. For wheat, 28 data sources across 13 countries on 5 continents were analysed. Data on rice is with 13 sources across 8 countries remarkably less. Many studies on rice production and water use were found to focus on irrigation water inputs, while few consider actual evapotranspiration (ET_{act}). For cotton, 16 experiments conducted in 9 different countries were found, while maize had 27 sources in 10 different countries on 4 continents. Research on CWP of maize is concentrated mainly in the USA (9 sources) and China (7 sources). Although the literature search was conducted in the Spanish and French language as well, few publications that meet the minimal data demands for all four crops could be found for the African, Latin American and European continents. Unfortunately many publications focus on either determination of crop water use or crop yields, whereas others only consider irrigation water applied.

3.2. Crop water productivity

Fig. 1a–d depict the frequency distribution histograms of wheat, rice, cotton and maize. For the purpose to exclude extreme values, the CWP range is determined by taking the 5 and 95 percentiles of the cumulative frequency distribution. The results are presented in Table 2.

Wheat has the largest number of experimental points ($n = 412$) and the CWP range is between 0.6 and 1.7 kg m^{-3}. Doorenbos and Kassam (1979) give a lower range of 0.8–1.0 kg m^{-3} (see Table 2). The maximum values are found by Jin et al. (1999) in China: application of manure led to higher production and straw mulching improved soil water and soil temperature conditions. CWP for the experiment with straw mulching was 2.67 and 2.41 kg m^{-3} for a combination of straw mulching and manure. ET_{act} in the winter season was tempered to 268 and 236 mm, respectively, while yields were relatively high with 7150 and 5707 kg ha^{-1} (see Fig. 2a).

CWP of rice ranges between 0.6 and 1.6 kg m^{-3} (Fig. 1b). Tuong and Bouman (2003) give a very similar range of 0.4–1.6 kg m^{-3} for lowland rice conditions. The maximum CWP value of 1.1 kg m^{-3} for rice given by Doorenbos and Kassam (1979) (Table 2) is

Table 1
Summary of the database

Crop	No. of publications	No. of continents	No. of countries[a]
Wheat	28	5	13
Rice	13	4	8
Cotton	16	5	9
Maize	27	4	10

[a] US states are considered as one country.

exceeded in 6 out of 13 data sources. The CWP range of rice is similar to wheat; the shape of the frequency distribution of rice is not as smooth as for wheat because less points are available. The maximum values go up to 2.20 kg m^{-3} and were measured in China on alternate wetting and drying rice plots (Dong et al., 2001). Rice grain yields of over 10 t/ha^{-1} were amongst the highest measured, whereas ET_{act} was on the lower side with 465 mm (Fig. 2b).

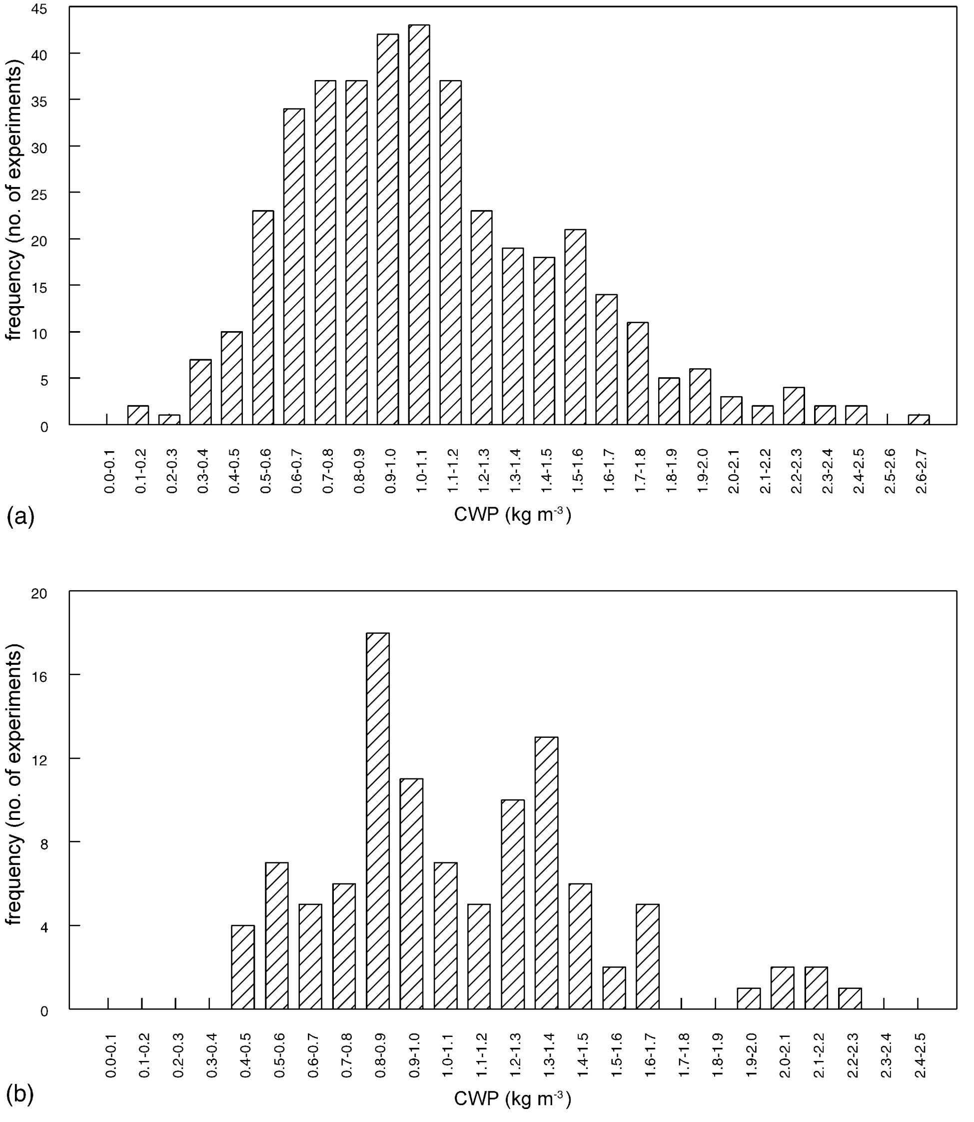


Fig. 1. Frequency of crop water productivity (CWP) per unit water depletion for wheat, rice, cotton and maize; (a) wheat ($n = 412$); (b) rice ($n = 105$); (c) cotton ($n_{seed} = 126$, $n_{lint} = 66$) and (d) maize ($n = 233$).

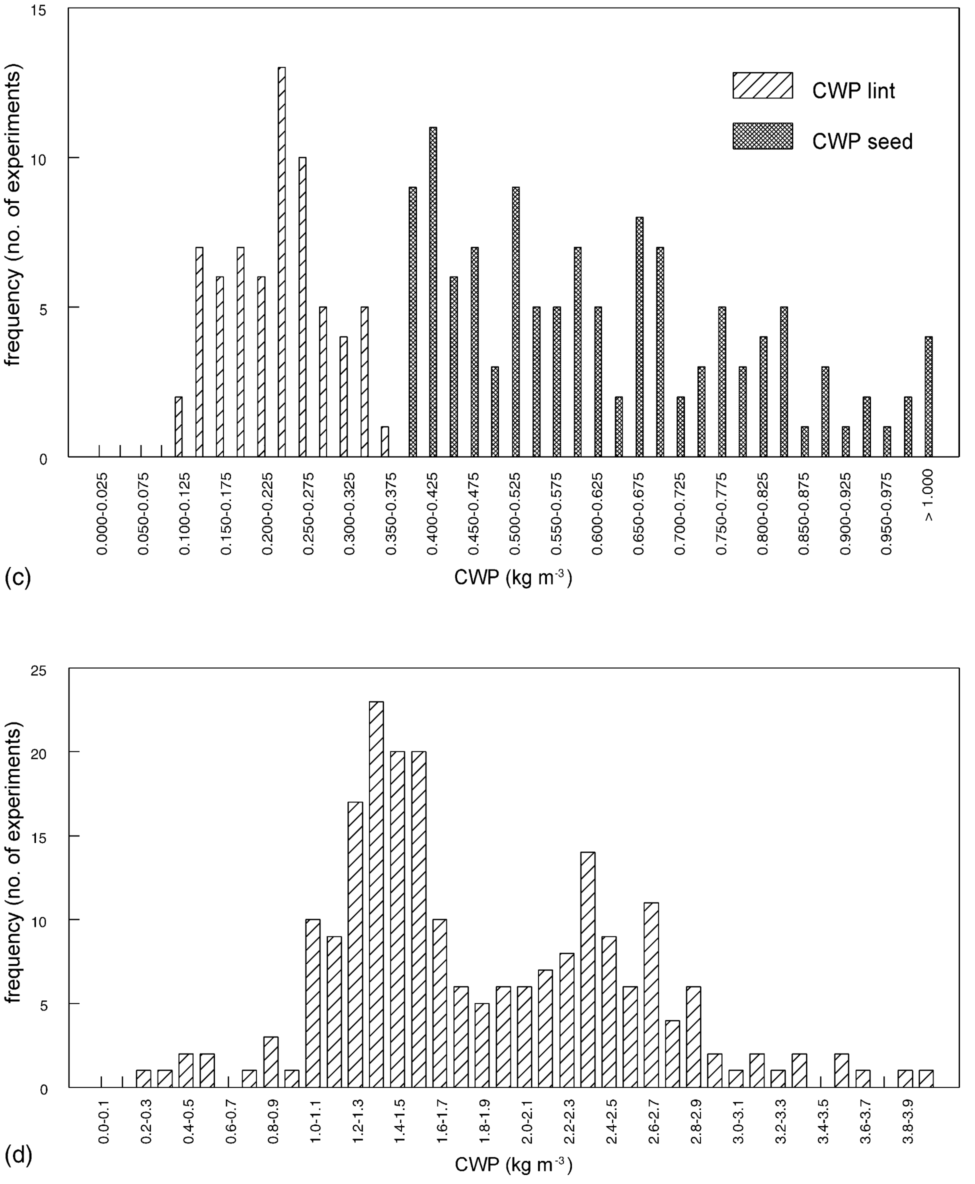


Fig. 1. (*Continued*).

CWP values of cotton CWP for lint yield range from 0.14 to 0.33 kg m^{-3}. The maximum values exceed 0.35 kg m^{-3} and are found by Jin et al. (1999) and Saranga et al. (1998) in China and Israel, respectively. Jin et al. (1999) conducted experiments in which cotton was planted in furrows and the soil covered with plastic leaving holes for infiltration near the plants, thus reducing soil evaporation and improving soil water status of the root zone. Saranga et al. (1998) measured average lint yield values of 1300 kg ha^{-1} in a field trial with deficit irrigation, while seasonal ET$_{act}$ was very low with 390 mm (see Fig. 2c). Howell et al. (1984) measured similar values (0.33 kg m^{-3}) in an experiment with high frequency trickle irrigation and reduced water deficits management for narrow row cotton in California (USA). Lint yield was more than 2000 kg m^{-3}, while seasonal ET$_{act}$ was relatively low (617 mm). The range for cotton seed yield is with 0.41–0.95 kg m^{-3} higher than the range given in FAO33 (0.4–0.6 kg m^{-3}). In Argentina maximum values were measured

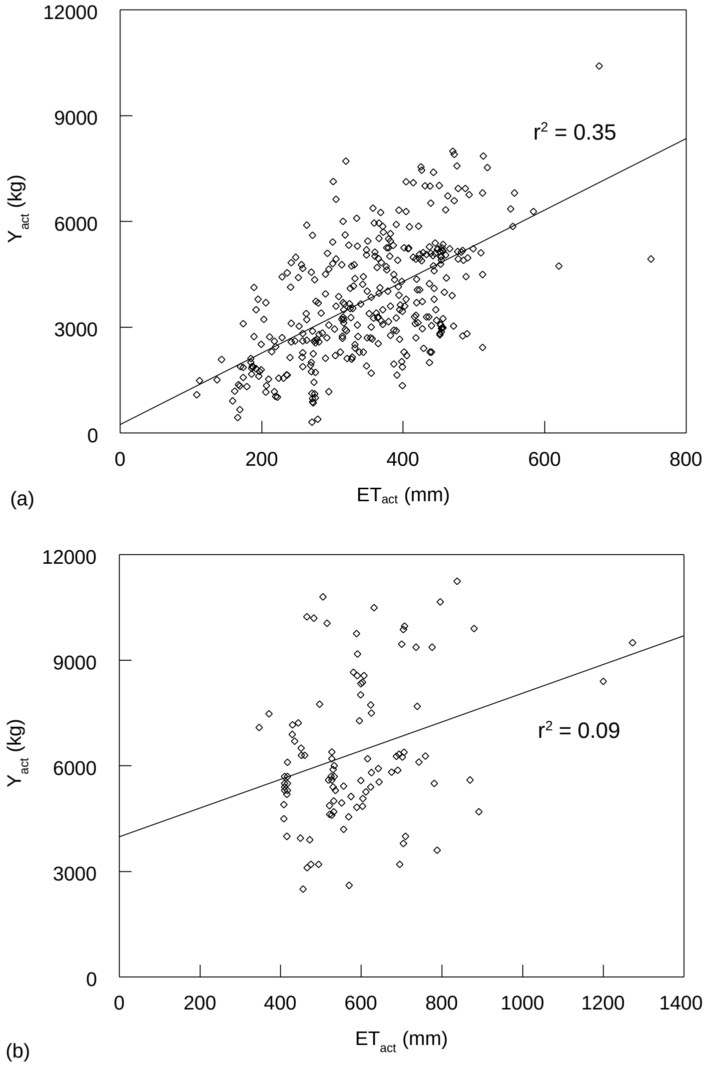
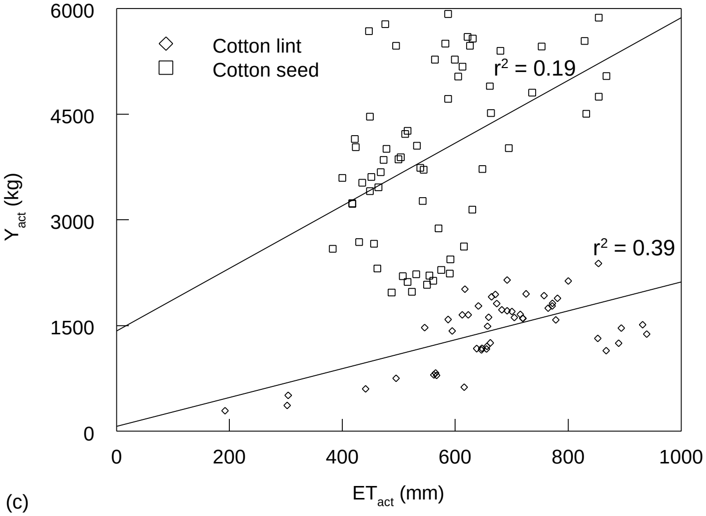


Fig. 2. Yield–evapotranspiration relations of (a) wheat, (b) rice, (c) cotton and (d) maize.



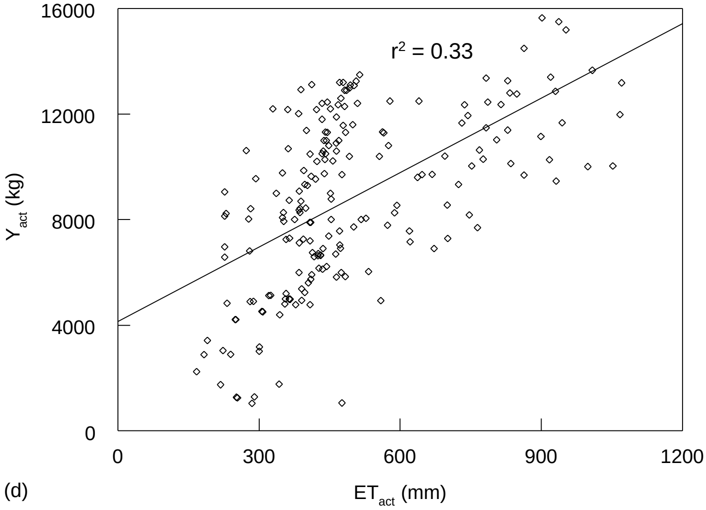


Fig. 2. (*Continued*).

exceeding 1.0 kg m^{-3} in experiments where water was applied during critical periods such as pre-seeding and flowering (Prieto and Angueira, 1999). Cotton seed yields did not differ compared to other treatments, though ET_{act} was lower (447–495 mm, see also Fig. 2c).

Finally, maize CWP values were measured ranging from 0.22 kg m^{-3} up to a maximum of 3.99 kg m^{-3} (Fig. 1d) which exhibits a large range of variation (CV = 0.38). In 67% of the publications the maximum value of the source exceeds the value of 1.6 kg m^{-3} provided by FAO33. The CWP range of 1.1–2.7 kg m^{-3} for maize, a C4-crop, is significantly higher than wheat, rice and cotton, which are C3-crops. The maximum values were measured by

Table 2
Crop water productivity (CWP) benchmark values per unit of water depletion according to "FAO33" (Doorenbos and Kassam, 1979), CWP ranges according to this study, the maximum, minimum, mean and median CWP values and the standard deviation (S.D.) and coefficient of variation (CV) of the data sets by crop

Crop	CWP-range ("FAO33"; $kg\,m^{-3}$)	CWP-range[a] (this research; $kg\,m^{-3}$)	*n*	Minimum	Maximum	Mean	Median	S.D.	CV
Wheat	0.8–1.0	0.6–1.7	412	0.11	2.67	1.09	1.02	0.44	0.40
Rice	0.7–1.1	0.6–1.6	105	0.46	2.20	1.09	1.02	0.40	0.36
$Cotton_{seed}$	0.4–0.6	0.41–0.95	126	0.38	1.70	0.65	0.58	0.23	0.35
$Cotton_{lint}$	Not given	0.14–0.33	66	0.10	0.37	0.23	0.23	0.064	0.28
Maize	0.8–1.6	1.1–2.7	233	0.22	3.99	1.80	1.60	0.69	0.39

[a] Defined as the 5 and 95 percentiles of the entire range.

Kang et al. (2000b) in a combination of alternate furrow irrigation and deficit irrigation experiments under Chinese conditions: low amounts of irrigation water were alternately applied to one of the two neighbouring furrows. ET_{act} was with 226 mm very low, whereas grain yield was still 9058 kg ha^{-1} (Fig. 2d).

4. Discussion

In Fig. 2a–d, the yield is plotted against the ET_{act} for each of the four crops. All four graphs show that the $Y_{act}-ET_{act}$ relation is not as straightforward as often as assumed: *r*-squared values are low; $cotton_{lint}$ has the highest correlation ($r^2 = 0.39$), followed by wheat ($r^2 = 0.35$), maize ($r^2 = 0.33$), $cotton_{seed}$ ($r^2 = 0.19$) and rice ($r^2 = 0.09$). The lesson learnt here is that $Y_{act}(ET_{act})$ functions are only locally valid and cannot be used in macro-scale planning of agricultural water management. A broad range in CWP values for all four crops exists (see Table 2), which is caused by the many factors that influence the soil–plant–water relationship. In a search for first order explanations for the wide ranges in CWP, only three aspects are discussed here: climate, irrigation water management and soil management.

De Wit (1958) was among the first to describe the photosynthesis–transpiration relationship. Bierhuizen and Slayter (1965) researched the influence of climatic parameters on this relationship and found a proportionally inverse relation (reviewed and confirmed by Tanner and Sinclair in 1983) between vapour pressure deficit of the air and CWP. Similar results were found by Stanhill (1960) for pastures grown at different latitudes. As the vapour pressure deficit generally decreases when moving away from the equator, CWP is expected to increase with increasing latitude. This proposition was tested for the current dataset: for each experimental site (defined as each unique geographic location), the maximum CWP of each crop is plotted against the latitude value of the experimental site. The maximum value is being taken to approach the optimal growing conditions with respect to soil fertility management and irrigation water application at a certain location. The result, depicted in Fig. 3, confirms that CWP decreases with lower latitude. It also shows that the highest CWP values occur between 30 and 40 degrees latitude where a factor 2–3

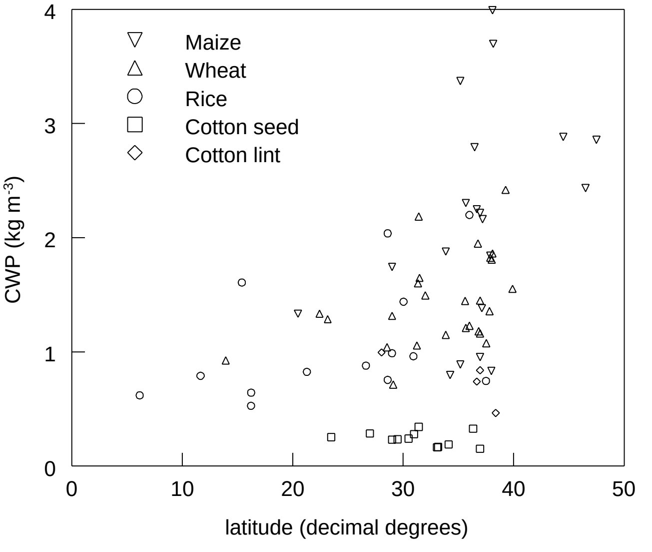


Fig. 3. Relation between latitude and maximum crop water productivity (CWP) value per unit water depletion per location and per crop (both northern and southern latitude are considered positive).

difference in CWP of wheat, rice and maize is detected when compared to areas between 10 and 20 degrees.

Many examples from literature describe the influence of irrigation water management on CWP (e.g. Oktem et al., 2003; Zhang et al., 1998; Yazar et al., 2002a; Kang et al., 2000a; Sharma et al., 1990). Deficit irrigation practices have been researched to quantify the effect on yield and to find optimum CWP values. In Fig. 4a and b, CWP of wheat and maize are plotted against the net amount of irrigation water applied in various experiments. It was found that without irrigation CWP in rainfed systems is low, but that CWP rapidly increases when a little irrigation water is applied. According to the database, optimum values for CWP are reached at approximately 150 and 280 mm of irrigation water applied for wheat and maize, respectively (in addition to rainfall). Fig. 4 demonstrates how CWP can be increased while simultaneously saving water by reduced irrigations. A maximum water productivity will often not coincide with farmers' interests, whose aim is a maximum land productivity or economic profitability. It requires a shift in irrigation science, irrigation water management and basin water allocation to move away from 'maximum irrigation-maximum yield' strategies to 'less irrigation-maximum CWP' policies. Besides the total amount of irrigation water applied, the timing of irrigation is important. Water stress during different growth stages affect CWP differently; lower CWP was measured in cotton experiments where water stress occurred during vegetative and early bud formation periods. Gentle stress during yield formation did not affect yield production, but reduced vegetative growth and would thus improve CWP (Prieto and Angueira, 1999).

The relationship between irrigation and CWP in rice is not the same as found for wheat and maize. In rice cultivation, instead of traditional continuous flooding, other water

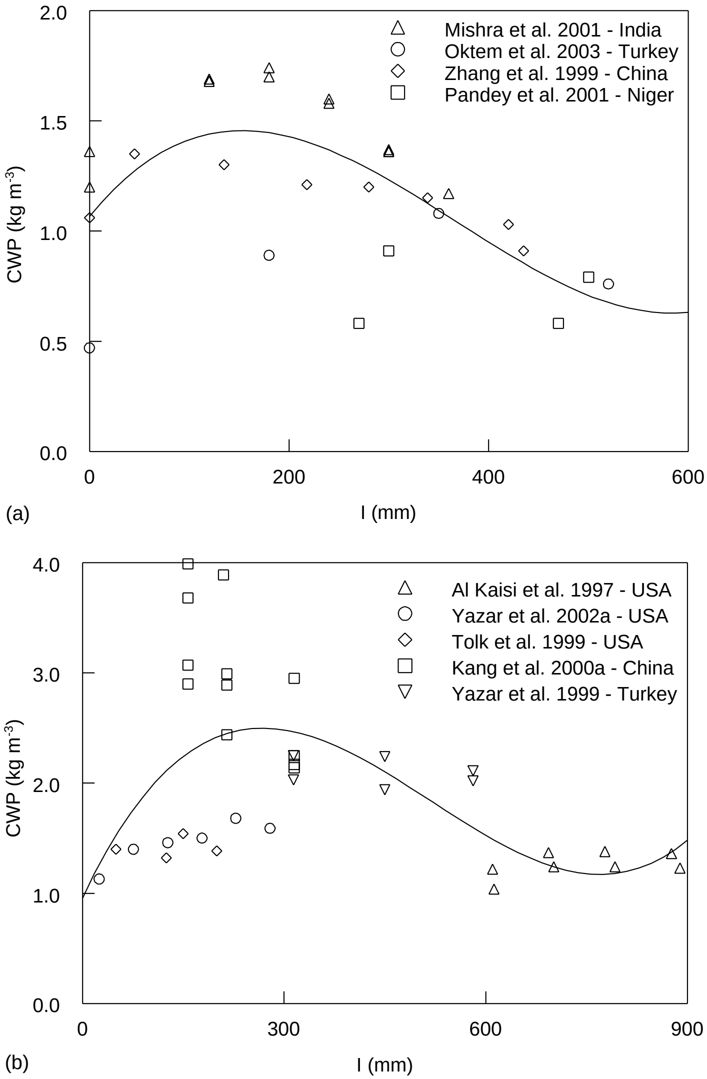


Fig. 4. Relation between amount of irrigation water applied (I) and measured crop water productivity (CWP) per unit water depletion for (a) wheat and (b) maize.

management strategies, such as alternate wetting and drying (intermittent irrigation) and saturated soil culture, were researched. Analysis of alternate wetting and drying experiments in India by Mishra et al. (1990) shows that, although irrigation water is saved, there is no significant improvement in CWP, which remains between 0.80 and 0.99 kg m^{-3} (n = 24). For this specific study in India, the ET_{act} was not reduced because irrigation application was in excess of ET_{act}. Dong et al. (2001) found similar results and concluded that there was no significant difference between continuous flooding and alternate wetting and drying experiments; 10 year average ET_{act} and CWP amounted 590 and 591 mm and 1.49 and 1.58 kg m^{-3} for continuous flooding and intermittent irrigation experiments, respectively. On the other hand, Shi et al. (2003) measured in lysimeter experiments higher CWP values for intermittent irrigation experiments (2.0 kg m^{-3}) compared with continuous flooding (1.6 kg m^{-3}), whereas yields were only 200 kg ha^{-1} lower). Moreover, ET_{act} in the intermittent experiment (347 mm) was 22% lower compared to continuous flooding. For the sake of clarity, Seckler (1996) distinguishes “dry” and “wet” water savings: reduction in ET_{act} is a wet saving because the evapotranspired water is lost for future use in the basin. On the other hand irrigation water savings are dry savings as the water may be recycled within the basin for future use (unless it is polluted). As is shown by the results from Mishra et al. (1990) and Dong et al. (2001) intermittent irrigation is merely an example of a dry water saving as ET_{act} is hardly affected by reduced supplies.

Hatfield et al. (2001) reviewed the effects of soil management on CWP by modification of the soil surface, such as tillage and mulching, and by improvement in soil nutrient status by adding nitrogen and/or phosphorus. A modification of the soil surface changes the processes of ET_{act} and is often found to be positively related to CWP. Nutrients indirectly affect the physiological efficiency of the plant. In Fig. 5 the nitrogen rate is plotted against the CWP of wheat during studies in Niger, Syria and Uruguay. CWP increases when nitrogen is applied and reaches an optimum at a rate of approximately 150 kg ha^{-1}. On the other hand Corbeels et al. (1998) and Fernández et al. (1996) did not measure significant differences when N fertilization was applied. Combined nutrient and irrigation supply levels are more commonly researched (e.g. Li et al., 2001; Pandey et al., 2001; Oweis et al., 2000; Zima Szalokine and Szaloki, 2002). Optimum values for amount nutrient and irrigation water application can be found to maximize CWP.

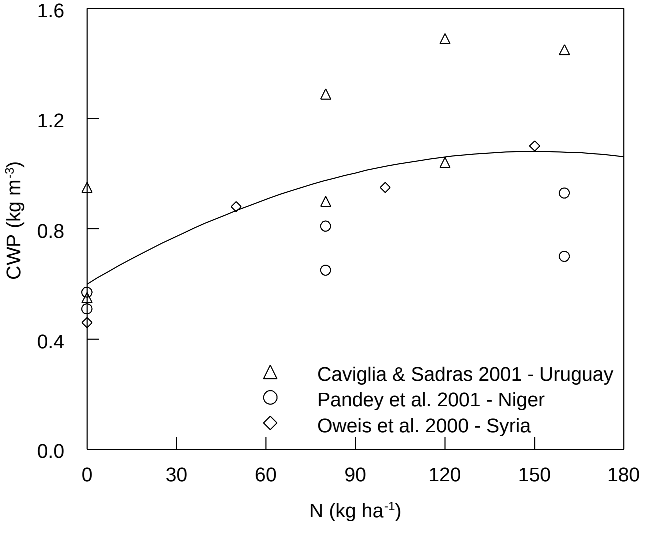


Fig. 5. Relation between amount of nitrogen applied (N) and measured crop water productivity (CWP) per unit water depletion for wheat from experiments in three different countries.

5. Conclusions

The CWP ranges for the four crops investigated are large as indicated by the high CV of 28–40% and are a logical consequence of the low correlation between ET_{act} and crop yield ($r^2 = 0.09-0.39$). This variability was mainly ascribed to: (1) climate; (2) irrigation water management and (3) soil (fertility) management, although more explanatory variables prevail. The climatic belt between 30 and 40 degrees latitude was found to be favourable for agriculture with regard to CWP and this is likely to be related to vapour pressure deficit. In areas with marginal soils, application of fertilizer offers large possibilities for improvement of CWP. The increase in CWP is highest if small amounts of nitrogen ($<80\,\mathrm{kg\,ha^{-1}}$) are applied. Deficit irrigation practices were found to improve CWP, sometimes even by more than 200%. Plants are more efficient with water when they are stressed. It is therefore tentatively concluded that to achieve optimum CWP in water short regions, it is wise to irrigate wheat and maize with less water as recommended for attaining maximized yields.

In rice cultivation the increase of CWP when less water was applied could not be confirmed from the database; during many of the alternate wetting and drying and continuous flooding experiments there was no significant difference in CWP. Water savings in rice are therefore a ‘dry saving’, because consumptive use is not or little affected.

The wide ranges in CWP found suggest that agricultural production can be maintained with 20–40% less water resources provided that new water management practices are adopted.

Acknowledgements

Dr. Yazar of the Department of Agricultural Engineering at Cukurova University in Turkey is kindly acknowledged for making available literature on CWP experiments published in Turkish language.

Appendix A. CWP values from literature

Location	Minimum–maximum ($\mathrm{kg\,m^{-3}}$)	Median ($\mathrm{kg\,m^{-3}}$)	*n*	Experimental year(s)	Reference
Wheat					
Parana, Argentina	0.55–1.49	1.04	7	1998–1999	Caviglia and Sadras (2001)
Merredin, Australia	0.56–1.14	0.95	11	1987	Siddique et al. (1990)
Merredin & Mullewa, Australia	0.55–1.65	0.88	21	1991–1995	Regan et al. (1997)
Benerpota, Bangladesh	0.52–1.34	0.91	16	1988–1992	Rahman et al. (1995)
Quzhou, China	1.38–1.95	1.58	12	1988–1989	Deju and Jingwen (1993)
Xifeng, China	0.65–1.21	0.84	3	1988–1991	Fengrui et al. (2000)
Wangtong, China	1.49–2.67	2.23	9	1995–1996	Jin et al. (1999)
Gansu, China	0.58–1.45	1.00	4	1997	Li et al. (2001)
Luancheng, China	1.07–1.29	1.26	3	1984–1996	Wang et al. (2001)
Yucheng, China	0.88–1.16	1.04	4	1986–1990	Xianqun (1996)
Beijing, China	0.92–1.55	1.19	10	1991–1995	Zhang et al. (1998)
various locations, China	0.85–1.86	1.17	28	1982–1995	Zhang et al. (1999)
Luancheng, China	1.28–1.82	1.63	18	1998–2000	Zhang et al. (2003)
West Bengal, India	1.11–1.29	1.19	3	1989–1991	Bandyopadhyay and Mallick (2003)
Pantnagar, India	0.86–1.31	1.11	22	1983–1985	Mishra et al. (1995)

Appendix A. (*Continued*)

Location	Minimum–maximum ($kg\,m^{-3}$)	Median ($kg\,m^{-3}$)	*n*	Experimental year(s)	Reference
Uttar Pradesh, India	0.48–0.71	0.64	12	1993–1994	Sharma et al. (2001)
Karnal, India	0.27–0.82	0.67	18	1986–1988	Sharma et al. (1990)
Pantnagar, India	1.06–1.23	1.10	6	1979–1985	Singh and Chauhan (1996)
Gilat, Israel	0.60–1.60	0.85	20	1977–1987	Amir et al. (1991)
Meknes, Morocco	0.11–1.15	0.58	4	1993–1995	Corbeels et al. (1998)
Sidi El Aydi, Morocco	0.32–1.06	0.61	20	1995–1999	Mrabet (2002)
Konni, Niger	0.42–0.93	0.61	18	1996–1998	Pandey et al. (2001)
Faisalabad, Pakistan	0.70–2.19	1.28	52	1991–1994	Waheed et al. (1999)
Tel Hadya, Syria	0.48–1.10	0.78	36	1991–1996	Oweis et al. (2000)
Cukurova, Turkey	1.33–1.45	1.39	5	1991–1992	Sezen and Yazar (1996)
Yellow Jacket (CO), USA	0.47–1.08	0.77	5	1993–1994	Al-Kaisi et al. (1997)
Grand Valley (CO), USA	1.53–2.42	1.72	14	1988–1989	Kruse et al. (1991)
Tashkent, Uzbekistan	0.44–1.02	0.73	8	2001–2002	Kamilov et al. (2002)
Rice					
Echuca, Australia	0.70–0.75	–	2	1997–1998	Bethune et al. (2001)
Zhanghe, China	1.04–2.20	1.41	20	1991–2000	Dong et al. (2001)
Nanchang, China	1.63–2.04	1.84	4	2002	Shi et al. (2003)
Pantnagar, India	0.80–0.99	0.89	24	1983–1984	Mishra et al. (1990)
Raipur, India	0.46–0.82	0.46	5	1979–1983	Sastri et al. (1985)
New Delhi, India	0.55–0.67	0.67	7	2001	Singh et al. (2002)
Punjab, India	0.87–1.46	1.15	24	1996–1997	Singh et al. (2001)
Muda, Malaysia	0.48–0.62	0.54	3	1988–1994	Cabangon et al. (2002)
Kadawa, Nigeria	0.50–0.79	0.59	3	1991–1992	Nwadukwe and Chude (1998)
Luzon, Philppines	1.39–1.61	–	2	1989–1991	Bhuiyan et al. (1995)
N'Diaye & Pont-Gendarme, Senegal	0.53–0.64	–	2	1990	Raes et al. (1992)
Beaumont (TX), USA	1.37–1.44	–	2	1995	Roel et al. (1999)
Belle Glade (FL), USA	0.88–1.34	1.21	7	1979–1980	Shih et al. (1983)
Cotton					
Santiago del Estero, Argentina[a]	0.50–1.27	0.84	30	1990–1995	Prieto and Angueira (1999)
various locations, Australia[b]	0.22–0.29	0.24	12	1996–1999	Tennakoon and Milroy (2003)
Wangtong, China[b]	0.20–0.37	0.32	4	1994–1997	Jin et al. (1999)
Yucheng, China[b]	0.15	–	1	1988	Xianqun (1996)
Be'eri, Israel[b]	0.22–0.35	0.28	12	1994	Saranga et al. (1998)
Faisalabad, Pakistan[a]	0.38–0.58	0.49	16	1991–1994	Waheed et al. (1999)
Cordoba, Spain[a]	0.45–0.71	0.61	28	1985–1986	Orgaz et al. (1992)
Bornova-Izmir, Turkey[a]	0.38–0.48	0.43	12	1993–1994	Anac et al. (1999)
Cukurova, Turkey[a]	0.38–0.84	0.56	24	1994–1995	Ertek and Kanber (2001)
Harran Plain, Turkey[b]	0.50–0.74	0.59	10	1999	Yazar et al. (2002b)
Wellman (TX), USA[b]	0.10–0.17	0.14	4	1992–1995	Baumhardt and Lascano (1999)
Halfway (TX), USA[b]	0.14–0.19	0.18	9	1995	Bordovsky and Lyle (1996)
Five points (CA), USA[b]	0.14–0.24	0.20	3	1981	Howell et al. (1984)
Five points (CA), USA[b]	0.22–0.33	0.27	15	1982–1983	Howell et al. (1987)
Maricopa (AZ), USA[b]	0.13–0.16	0.15	6	1993–1994	Hunsaker et al. (1998)
Tashkent, Uzbekistan[b]	0.54–1.70	1.06	6	2000–2001	Kamilov et al. (2003)
Maize					
Azul, Argentina	1.84–2.79	2.35	5	1991–1995	Navarro Dujmovich et al. (1996)
Guaira, Brazil	1.12–1.33	1.21	3	1994	Libardi et al. (1999)
Xifeng, China	1.26–2.31	2.00	3	1989–1991	Fengrui et al. (2000)
Wangtong, China	1.49–2.67	2.23	13	1995–1996	Jin et al. (1999)
Changwu, China	1.36–1.65	1.56	9	1987	Liu and Li (1995)
Changwu, China	2.11–3.37	2.56	18	1996–1997	Kang et al. (2000a)
Gansu province, China	2.14–3.99	2.92	12	1997–1998	Kang et al. (2000b)
Yucheng, China	1.63–2.22	–	2	1989	Xianqun (1996)
Luancheng, China	1.55–1.84	–	2	1998	Zhang et al. (2003)
Szarvas, Hungary	1.28–2.44	1.85	16	1978–1995	Zima Szalokine and Szaloki (2002)
Pantnagar, India	1.17–1.74	1.47	14	1993–1995	Mishra et al. (2001)
Tal Amara, Lebanon	1.36–1.89	1.64	6	1998	Karam et al. (2003)
Fundulea, Romania	2.34–2.88	2.64	5	1991–1994	Cracium and Cracium (1999)
Sevilla, Spain	1.50–2.16	1.73	4	1992–1993	Fernández et al. (1996)
Harran plain, Turkey	1.94–2.25	2.02	6	2000	Yazar et al. (2002a)

Appendix A. (*Continued*)

Location	Minimum–maximum ($kg\,m^{-3}$)	Median ($kg\,m^{-3}$)	*n*	Experimental year(s)	Reference
Harran plain, Turkey	1.04–1.38	1.24	8	1998–1999	Oktem et al. (2003)
Cukurova, Turkey	0.22–1.25	1.01	12	1993–1994	Gencoglan and Yazar (1999)
Bushland (TX), USA	1.12–1.39	1.31	6	1995	Evett et al. (1996)
Bushland (TX), USA	0.89–1.55	1.42	6	1993	Howell et al. (1995)
Bushland (TX), USA	1.47–1.74	1.60	6	1989–1994	Howell et al. (1996)
Garden City (KS), USA	0.83–1.61	1.26	16	1994–1997	Norwood (2000)
Blacksburg (VA), USA	1.34–3.26	2.67	6	1998–1999	Roygard et al. (2002)
Carolina Bays (SC), USA	0.36–1.57	0.65	8	1993	Sadler et al. (2000)
Oakes (ND), USA	2.03–2.86	2.55	24	1989–1991	Steele et al. (1994)
Bushland (TX), USA	1.26–1.54	1.42	14	1994–1995	Tolk et al. (1999)
Bushland (TX), USA	1.13–1.68	1.48	6	1992	Yazar et al. (1999)

[a] Seed yield.
[b] Lint yield.

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