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# Crop Water Productivity in Semi-arid Regions: From Field to Large Scales

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**Abstract:** The semi-arid regions of the world are marked by socio-economic disparities and environmental vulnerabilities. Water managers in river basins are faced with several challenges, such as competition among different water user groups, local over-exploitation of aquifers, climate and land use changes, non-source pollution, erosion, and sedimentation. Water policy makers have to work out strategies for integrated water management, which rely on a proper knowledge based on the physical conditions encountered in the river basins. The intensification of the land use change implies a necessity of a better knowledge of the water use and food production to improve crop water productivity for rational water resources planning. This paper presents an overview of the key concepts involved in water productivity analyses from field to regional scales in areas with quick land use change, with some examples in the semi-arid region in the Northeast Brazil. It is emphasized the use of tools for estimating spatially distributed water related variables to describe the water cycle in irrigated agriculture under semi-arid conditions. Moreover, they can be operationally implemented to monitor the intensification of agriculture avoiding the adverse impact on downstream water users. Conclusions and recommendations are given to improve the evaluation of irrigation in large areas in terms of crop water productivity and their impacts on water resources, by the intensification of irrigated agriculture in semi-arid regions.

**Key words:** Evapotranspiration, biomass production, remote sensing, energy balance, irrigation, water resources.

Water demand already exceeds supply in many parts of the world, and as world population continues to rise, many more areas are expected to experience water scarcity (Vörösmarty *et al*., 2000; Naiman *et al*., 2002; Smakhtin *et al*., 2004; Bos *et al*., 2005; Gourbesville, 2008). Population growth will continue into the 21$^{st}$ century, although more slowly. The world population is projected to grow from 6 billion in 2000 to more than 9 billion by 2050, an increase of 50%. As the human population is increasing, water use is multiplying (Seckler *et al*., 1998).

Water use is estimated to increase by about 50% after 30 years with an estimation of 4 billion people – one half of the world's population – living under conditions of severe water scarcity in 2025, particularly in Africa and in the Middle East and South Asia (Bos *et al*., 2005). Compounding the relative scarcity of water is the continuous deterioration of water quality in most developing countries, mainly in semi-arid regions of river basins with quick land use change.

The local solution of water scarcity related problems is hampered by: the lack of commitment to water and poverty, inadequate and inadequately targeted investment, insufficient human capacity, ineffective institutions, and poor governance (Molden *et al*., 2007b). A global picture of environmental water scarcity per river basin is provided in Figure 1. The water stress indicator of this figure is defined by the ratio of (or a percentage) total withdrawals to utilizable water. If the index exceeds 1, the basin is classified as water scarce. Smaller index values indicate progressively lower water resources exploitation, and consequently, lower risk of environmental water scarcity. **Red areas** show basins where too much of water is being withdrawn.

To achieve sustainable water resources development and secure water availability to competing user groups, future water management may take notice of the water accounting approach (Molden, 1997; Cai *et al*., 2002), which recognizes the various inhabitants of a basin and the water flows in terms of net water production or net water consumption.

Hydrologic problems downstream in basins located in semi-arid regions are mainly related to the effect of agricultural drainage water on river flows and the timing of peaks and troughs. Low flows are a particular problem because concentrations of pollutants are considerably higher during these periods. Hydrologic basin-wide studies are important to ascertain the impact of

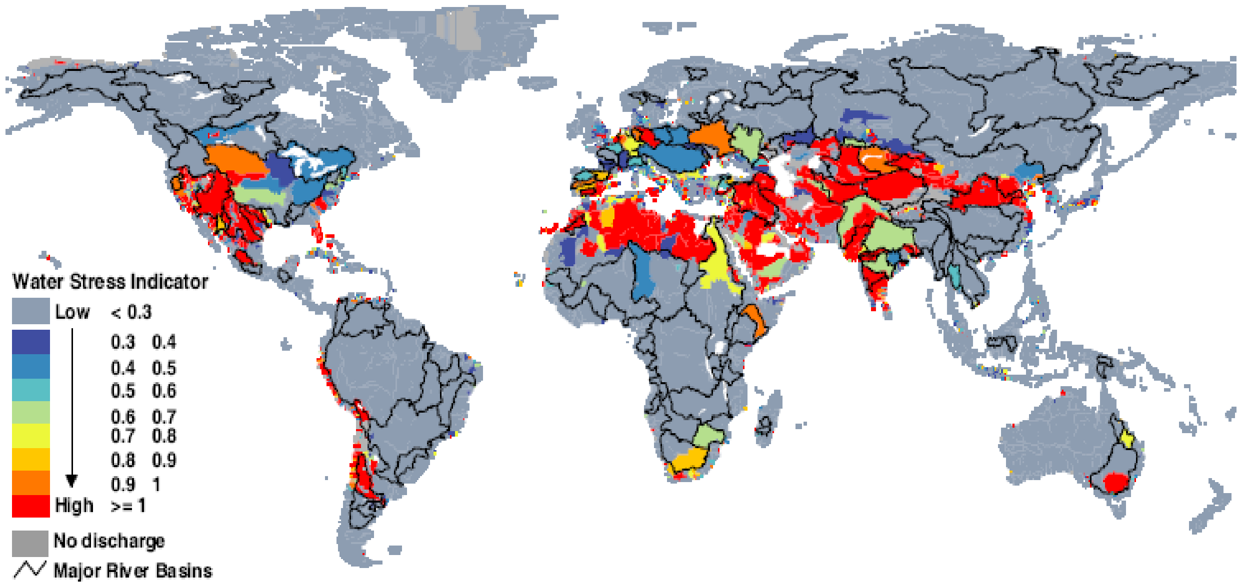


*Fig. 1. Environmental Water Scarcity Index by Basin (Source: Smakhtin et al., 2004).*

discharges (quantity, peak drainage flows, and the time of the peak flow) from a specific project area on the flows of the basin. Drainage flows can affect the proper ecological functioning of downstream river reaches, floodplains, wetlands, and estuaries in the same way that upstream abstractions for irrigation can affect the flow regime of a river (Gourbesville, 2008).

Agriculture in river basins of semi-arid regions reveals that water creates a boost for the rural economy; however, agricultural drainage can adversely affect the water quality; both locally and further downstream. With decreasing water quality, all water users (urban, industrial, agricultural, and ecological) will call for an appropriate and fair share of the fresh water resources.

Disputes over shared water resources continue to raise local, national, and even international tensions (Gleick, 2000). Rising conflicts are expected as populations expand, economies grow, and the competition for limited water supplies intensifies. Basin-level dialogues among different users, including local communities, to negotiate and agree on the allocation of water resources, are required. The success of any dialogue depends on the knowledge base and the general trust in (international) data sources. Minimum data sets include information on land use, water use, yield and the water accounts of each land use type.

The better knowledge of crop water productivity in semi-arid regions provides valuable information to achieve local water conservation practices without losing productivity levels of crops. For this knowledge its very important to have measured and modelled data available on actual evapotranspiration and crop production from field to regional scale.

## Actual Evapotranspiration

The physical process whereby water flows from the evaporating surfaces into the atmosphere is referred to as actual evapotranspiration (ETa). The ETa is critically important in semi-arid regions because besides being essential for crop production its increase means less water available for ecological and human uses in river basins.

Distinctions are made between reference crop evapotranspiration (ETo), potential evapotranspiration (ETp) and ETa. ETo is the water flux from a reference surface, not short of water, which can be a hypothetical grass surface with specific characteristics. ETp may be referred as the water flux from crops that are grown in large fields under optimum soil moisture, management and environmental conditions, and achieve full production under the given climatic conditions. ETa involves all situations of the vegetated surface. Due to sub-optimal crop management and environmental constraints in semi-arid environments that affect crop growth and limit evapotranspiration, ETa is generally smaller than ETp (Allen *et al.*, 1998).

The capability to predict levels of ETa is a valuable asset for water resource managers, as it describes the water consumption from vegetation. This consumption is paramount information for irrigation management, supply planning, water rights regulation, and river basin hydrologic studies, mainly in semi-arid regions where the irrigated crops are quickly replacing the natural vegetation.

Due to large rooting depths, ETa measurements in trees are very difficult to be made with weighing lysimeters. Separating actual transpiration (Ta) and actual evaporation (Ea) may be approached in several ways, all of them with its advantages and disadvantages. Ta can be measured directly with the heat pulse-sap flow technique, which has been applied in vineyards (Yunusa *et al.*, 2004) and olive groves (Testi *et al.*, 2006). This method may give good results, but is influenced by individual tree variability. Micro-meteorological and soil water balance methods for ETa measurements do not have these limitations (Bassoi *et al.*, 2004; Bassoi *et al.*, 2007; Teixeira *et al.*, 2007; Teixeira *et al.*, 2008).

## Regional Scale Modelling of Actual Evapotranspiration

Field methods provide values for specific sites and are not suitable to estimate ETa at a regional scale. The spatial variability in semi-arid regions is significant and the variation is caused by different amounts of precipitation, seepage, flooding, irrigation, hydraulic characteristics of soils, vegetation types (expressed as leaf area, moisture sensitivity, rooting depth) and densities. The temporal changes in ETa can be ascribed to weather conditions and vegetation development. Directly extrapolation of energy and water balance data to a surrounding landscape environment can lead to inaccurate regional estimates, because a few sites cannot provide a fair sample of a whole biome (Wylie *et al.*, 2003). A similar hydrological problem occurs with rainfall; few gauge readings will not necessarily reflect a proper reference value for a semi-arid region.

The difficulties to measure regional scale energy and water balances with field experiments prompted the use of remotely sensed data from satellites to evaluate ETa in composite terrains. Remote sensing excludes the need to quantify other complex hydrological processes, being an excellent means for determining and mapping the spatial and temporal structure of the water variables. Another advantage is that the ETa populations of a given land use type is feasible, making the spatial variation from irrigated crops in semi-arid conditions very well described. Hydrological models in these conditions can be too complex and costly because of non availability of data sets in different hydrological uniform sub-areas (Majumdar *et al.*, 2007) and with a lack of input data, these models may yield to ill-defined results.

Studies showed that the oversimplification of land surface complexity may cause eco-hydrological models to be considerably biased (Michell *et al.*, 2005). Yet, one of the biggest impediments to global, multi-temporal ETa monitoring is the conflicting requirement for algorithms that are biophysically realistic – albeit – simple enough for global parameterization and implementation (Cleugh *et al.*, 2007). According to Nagler *et al.* (2005), if species-specific algorithms were needed to scale field data to larger areas in river basins, detailed, species-level vegetation maps of each river stretch would be also needed. These are difficult to construct in semi-arid environments even with high-resolution aerial photography.

Liu *et al.* (2003) reported that adequate calculations of regional ETa should enhance the reliability of runoff estimations for watersheds in supporting hydroelectric power generation. Allen *et al.* (2005) provided an overview of potential remote sensing applications in Western US states, involving net depletion of river flows, administering water rights, crop water requirements and irrigation management. Moller *et al.* (2007) demonstrated the effectiveness of using very high resolution visible and thermal infrared images in an Israeli vineyard for scheduling irrigation. Naor (2006) concluded that thermal infrared measurements enable growers to produce maps of relative water stress in orchards. However, according to Kustas *et al.* (2006) the remote surface temperature and vegetation cover must be at high enough resolutions where different land surface conditions can be distinguished, being important the validation of flux distributions in semi-arid conditions where there are mixed irrigated crops together with natural vegetation.

Procedures for the validation of regional energy balance models with remote sensing data have been carried out in an agricultural growing area of the semi-arid region in Brazil by Teixeira *et al.* (2009a,b). These validations involved comparisons of satellite measurements with energy balance data from tower-based systems from eddy covariance and Bowen ratio methods in irrigated crops and natural vegetation. Data from flux towers together with agro-meteorological stations can make a valuable contribution to increase the confidence in remote sensing techniques in land composite terrains.

## Crop Production

Estimations of crop production at different scales are becoming more important in both developing and developed countries for supporting policy planning and decision-making in agriculture. The need for modelling in semi-arid regions is increasing with climate and land use changing together with the current emerging crisis in food security, due to the growing world population.

Agriculture is concerned with the conversion of solar radiation to energy usable by people for food, fibre, and fuel. Biomass production (BIO) is associated with photosynthetically active radiation (PAR) that is part of the short wave solar radiation which is absorbed by chlorophyll for photosynthesis in the plants, regulating primary productivity, or the rate of carbon fixed by the plants.

For obtaining estimates of carbon balance the light-use efficiency concept devised by Monteith (1972, 1977) can be applied. This model is based on the light-use efficiency (å) and the absorbed PAR. The slope of the linear regression between BIO and cumulative PAR intercepted by a crop has been used to determine å (e.g. Muchow *et al*., 1993; Muchow and Sinclair, 1994; Ceotto and Castelli, 2002; Tesfaye *et al*., 2006). This relationship is also employed to develop simple crop models.

Russell *et al*. (1989) expressed yield as a function of radiation intercepted by the crop, å, and a harvest index (HI). Radiation interception is variable throughout a crop growing period (Sivakumar and Virmani, 1984; Watiki *et al*., 1993, Tesfaye *et al*., 2006, Teixeira *et al*., 2007). Reductions in å due to water deficits have been reported (e.g. Hughes and Keatinge, 1983; Muchow, 1985; Green *et al*., 1985; Singh and Sri Rama, 1989). In general, å is stable across environments under optimal growing conditions (Sinclair and Muchow, 1999), because it is a relatively constant property of plants. Light harvesting can be adjusted to the availability of resources needed to use the absorbed light (Monteith, 1977; Bloom *et al*., 1985; Russell *et al*., 1989).

Several more sophisticated crop models have been developed not only to optimize agricultural management, but also to investigate the effect of climatic variability and soil hydrology on crop yields. They in general employ data of plant phenology and physiology (Eitzinger *et al*., 2004). Reviews about the general features and mechanisms of the process-based crop models are provided by Tubiello and Ewert (2002) who focus on the effects of elevated $CO_2$ concentrations and by Lipiec *et al*. (2003) who deals with crop growth, water movement and solute transport.

Monteith and Scott (1982) analyzed crop yield accounting temperature effects on leaf area development and crop ontogeny, and solar radiation effects on BIO. This approach was also later applied for soybean (Spaeth *et al*., 1987), corn (Muchow, 1990), wheat (Amir and Sinclair, 1991), and rice (Sheehy *et al*., 2004; Pirmoradian and Sepaskhah, 2005).

To acquire crop yield for a growing season (GS), $BIO_{GS}$ is multiplied by the apparent harvest index (AHI) and the harvested area (HA). AHI is the ratio of harvested product to above ground biomass. This index includes the water content and in most studies does not include roots. Although AHI is a crop-and variety-specific parameter and can be reduced by water stress, a constant value fine-tuned to the average condition on the estate will provide some first yield estimation.

## Regional Scale Modelling of Crop Production

The farmer decision making together with spatial variations in soil, hydrology and weather conditions makes parameterisation of crop models a difficult task. To avoid this problem, empirical equations have been developed for global scale applications (Fischer *et al*., 2002; Gervois *et al*., 2004; Osborne *et al*., 2007, Bondeau *et al*., 2007). Ecological planning models have been used to assess the availability of additional land for agriculture (e.g. Kenny *et al*., 2000; Fischer *et al*., 2002), to investigate the impact of climate change on future land use (Alcamo *et al*., 1998) or on future economic welfare (Matsuoka *et al*., 2001).

Regional estimates of crop yield are important for managing large agricultural lands (Macdonald and Hall, 1980; Hutchinson, 1991) and the main way to make these estimations include remote sensing-based calculations (Dadhwal and Ray, 2000; Prasad *et al*., 2006). Satellite images are efficient tools for crop area and BIO estimates in semi-arid regions because they provide spatial and temporal information of different kinds of vegetation in these conditions (Teixeira *et al*., 2009a,b). However, successful use of remote sensing requires that the measured radiance can be associated to physical plant properties and then to BIO or yield (Schlesinger, 1997).

To estimate crop yield by satellite data, a commonly applied method is the development of empirical relationships between the Normalized Difference Vegetation Index - NDVI, and actual crop yield - $Y_a$ (e.g. Groten, 1993; Sharma *et al*., 2000), being NDVI related to the reflected radiations in the near infrared and visible regions of the solar spectrum. To obtain the coefficients of the relationship of NDVI and $Y_a$, excessive field measurements need to be done, which at the regional scale are difficult and expensive.

Some papers of literature or studies suggest that the BIO model proposed by Monteith (1972) based on incident global solar radiation ($R_G$) and canopy development have acceptable accuracy, and that it can be used together with satellite data (e.g. Kumar and Monteith, 1982; Daughtry *et al*., 1992; Gower *et al*., 1999, Bastiaanssen and Ali, 2003). Although the PAR/$R_G$ fraction varies with visibility, optical depth and ozone amount, among others (Frouin and Pinker, 1995), the relation between PAR and RG can be obtained locally (Teixeira *et al*., 2009a). Having evapotranspiration and yield data the water productivity can be assessed at different scales.

## Water Productivity Indicators

Water productivity (WP) may be defined as the ratio of the net benefits from crop, forestry, fishery, livestock and mixed agricultural systems to the amount of water required to produce those benefits (Molden and Sakthivadivel, 1999, Kijne *et al*., 2003; Bos *et al*., 2005; Molden *et al*., 2007a). Considering vegetation, WP can be BIO per land (L) or per water consumed, including that originates from rainfall, irrigation, seepage and changes in soil storage.

Crop production and water consumption are two closely linked processes. The crop water productivity (CWP) may be considered as the ratio of $Y_a$ to cultivated land or to the amount of water consumed or applied. Many promised pathways for raising CWP in agriculture are available over the continuum from fully rainfed to fully irrigated farming systems. **Table 1** shows the different water productivity indicators.

*Table 1. Different water productivity indicators: Water productivity and crop water productivity based on land (L), irrigation (I), actual evapotranspiration (ETa) and actual transpiration (Ta), together with the economic values of these indices ($)*

| Output | Land (ha) | Irrigation ($m^3$) | Eta ($m^3$) | Ta ($m^3$) |
|---|---|---|---|---|
| BIO | $WP_L$ | $WP_I$ | $WP_{ETa}$ | $WP_{Ta}$ |
| (kg) | (kg $ha^{-1}$) | (kg $m^{-3}$) | (kg $m^{-3}$) | (kg $m^{-3}$) |
| Net benefit | $WP\$_L$ | $WP\$_I$ | $WP\$_{ETa}$ | $WP\$_{ETa}$ |
| ($) | ($ $ha^{-1}$) | ($ $m^{-3}$) | ($ $m^{-3}$) | ($ $m^{-3}$) |
| $Y_a$ | $CWP_L$ | $CWP_I$ | $CWP_{ETa}$ | $CW_{PTa}$ |
| (kg) | (kg $ha^{-1}$) | (kg $m^{-3}$) | (kg $m^{-3}$) | (kg $m^{-3}$) |
| Gross return | $CWP\$_L$ | $CWP\$_I$ | $CWP\$_{ETa}$ | $CWP\$_{Ta}$ |
| ($) | ($ $ha^{-1}$) | ($ $m^{-3}$) | ($ $m^{-3}$) | ($ $m^{-3}$) |

Organizations responsible for irrigation management are interested in yield per unit of applied irrigation water, as it is their duty to enhance yield through man-induced irrigation processes, but the drawback is that not all irrigation water is used for generating crop production. CWP is commonly expressed in yield per unit of applied water, including rainfall and irrigation (Peacock *et al*., 1977; Araujo *et al*., 1995; Srinivas *et al*., 1999), however, it is also important to analyze the CWP in terms of ETa and Ta, including capillary rise and soil moisture changes (e.g. Droogers and Kite, 1999). These water resources also contribute to crop production, and thus CWP cannot be related to rainfall and irrigation water supply only. The CWP for a growing season (GS) can be calculated considering the yield divided by the water applied (I) or water fluxes (ETa or Ta) during the GS.

The economic water productivity is the value derived per unit of water used. Increases in economic water productivity may indicate a shift towards high value crops, increase in yields or a saving in water input (Bos *et al*., 2005). According to Droogers *et al*. (2000) and Bos *et al*. (2005), the economic indicators (Table 1) are the standard gross value of production over the irrigation supply ($CWP\$_I$), over actual evapotranspiration ($CWP\$_{ETa}$) or over actual transpiration ($CWP\$_{Ta}$). Water productivity gains are context dependent and can be assessed only by taking an integrated basin perspective. Increasing CWP is an effective way of intensifying crop production and reducing environmental degradation in semi-arid regions.

In irrigated semi-arid regions it is common to document depletion of water more than it is renewable or renewed. Such areas include the Egypt's Nile (Keller and Keller, 1995), the Gediz Basin in Turkey (Droogers and Kite, 1999), the Christian subdivision in Pakistan (Molden *et al*., 2000), the Bhakra irrigation system in India (Molden *et al*., 2000), the Nilo Coelho in Brazil (Bastiaanssen *et al*., 2001), the Tunuyuan irrigated area in Argentina (Bos, 2004), Fayoum (Bos, 2004), the Rio Grande Basin in Mexico and the United States (Booker *et al*., 2005) and the Liu Yuan Ku irrigation system in China (Hafeez and Khan, 2006).

According to Molden *et al*. (2007b), the additional amount of water needed to support irrigated agriculture by incremental evapotranspiration depends on the gains in CWP. For a given crop variety, fertility level and climate there is a good linear relationship between BIO and Ta (Tanner and Sinclair, 1983, Steduto and Albrizio, 2005). High BIO requires high Ta because when stomata open, carbon dioxide flows into the leaves for photosynthesis and water flows out. Stomatal resistance increases with low levels of soil moisture limiting Ta, photosynthesis and actual yield (Ya).

The ratio Ta/ETa depends to a large extent on the type of irrigation in place. While there is a fixed relation between BIO and Ta, this is not true for Ya relative to ETa because of differences in Ea, AHI, climate conditions, water stress, pest and diseases, nutritional and soil moisture status, and agronomic practices. Thus there seems to be considerable scope for raising Ya/ETa before reaching the upper limit in semi-arid regions. The variability in CWP being due to crop and water management practices is very important because it offers hope of possible improvements in conditions of competitions for the use of water resources (Molden *et al*., 2007c).

Good agricultural practices – managing soil fertility and reducing land degradation – are important for increasing CWP. Higher physical and economic values of CWP reduce poverty in semi-arid regions in two ways. First, targeted interventions enable poor people or marginal producers to gain access to water or to use it more productively for nutrition and income generation. Second, the multiplier effects on food security, employment, and income can benefit the poor (Molden *et al*., 2007b).

## Crop Water Productivity

Benchmark values for water productivity are summarized for irrigated crops (wheat, rice, cotton, maize) by Zwart and Bastiaanssen (2004); for dryland crops by Oweis and Hachum (2006) and for rainfed crops by Rockstrom and Barron (2007). Yields of sorghum in Burkina Faso and maize in Kenya were increased with supplemental irrigation plus soil fertility management (Rockström *et al*., 2003). Bouman *et al*. (2005) carried out a special study on rice showing that several practices are applicable to increase CWP, such alternate wet and dry irrigation. On the other hand CWP can also be improved with deficit irrigation (Zhang, 2003).

In semi-arid regions, crops are in conditions of low precipitation and high evapotranspiration demand, and then irrigation becomes necessary. Data on yield will gain in importance if these informations are merged with water variables to arrive at crop water productivities based on water consumed (kg $m^{-3}$). A first crude estimation of ETa would be the application of the crop coefficient approach suggested by FAO for areas with minimal ground information (Allen *et al*., 1998).

As the crop coefficient values from Allen *et al*. (1998) are indicated for sub humid conditions and for specific crops, in the case of semi-arid regions it is best to use those obtained locally. Teixeira *et al*., 2002, 2003, 2007, 2008 and Bassoi *et al*. (2004) found these coefficients for banana, guava, grape and mango crops under the semi-arid conditions of the São Francisco River basin in Northeast Brazil.

Around 54% of the São Francisco River basin is in the semi-arid region of Brazil. Although according the Figure 1, this basin is not classified as water scarce, predictions for irrigated agricultural expansion are important for water managers, for increasing both the agricultural outputs and the rural employment. These predictions also help in

*Table 2. Water productivity parameters for fruit crops in the semi-arid region of Pernambuco State, Brazil, for 2005: actual evapotranspiration (ETa); harvested area (HA); production; crop water productivity per unit cultivated land ($CWP_L$); gross return (GR); and crop water productivity per actual evapotranspiration ($CWP_{ETa}$ – physical values; and $CWP\$_{ETa}$ – monetary values)*

| Variable / Crop | ETa | HA(ha) | Production (t) | CWPL (kg $ha^{-1}$) | GR ($10^2$ US$) | $CWP_{ETa}$ (kg $m^{-3}$) | $CWP\$_{ETa}$ (US$ $m^{-3}$) |
|---|---|---|---|---|---|---|---|
| Grape | 1,320 | 4,594 | 148,192 | 32,257 | 173,517 | 2.44 | 2.86 |
| Mango | 1,335 | 7,173 | 143,710 | 20,034 | 34,027 | 1.50 | 0.36 |
| Banana | 1,610 | 6,212 | 110,096 | 17,723 | 30,095 | 1.10 | 0.30 |
| Guava | 1,230 | 739 | 12,136 | 16,422 | 1,569 | 1.34 | 0.17 |

identifying areas of drought risk; and in measuring the extent of risk for rainfed agriculturalists, and the extent to which, water needs will not meet the irrigation requirements (Maneta *et al*., 2009a).

The main irrigated crops in the semi-arid region of the São Francisco River basin are fruits. The average values of crop coefficients for the main commercial fruit crops were then applied to estimate the water productivity in the irrigation schemes of the Brazilian states of Pernambuco (PE) and Bahia (BA), with yield data of 2005 from Geographic and Statistic Brazilian Institute (IBGE). For ETo, interpolated values from 7 agro-meteorological stations for the same year were used (Teixeira *et al*., 2009a).

The water productivity values, considering six fruit growing areas in the semi-arid region of Pernambuco State, Brazil, are presented in Table 2.

The largest cropped area in Pernambuco is with mango orchards, but the highest production as well as the highest water productivity is for vineyards.

The crop water productivity values, considering eight fruit growing areas in the semi-arid region of Bahia State, Brazil, are shown in Table 3.

The highest cropped area and production in the Bahia is for mangos, although all the values of water productivity for grapes are larger, showing scope for improvements in water management in mango orchards in this state.

Despite the small area under guava crop, the water productivity values are reasonably high when compared with those of mango, one of the most important commercial fruit crop in the Brazilian semi-arid region. Grapes rank the best for both, physical and economic values in the two states.

In water consumption studies of a vineyard and a mango orchard situated in two representative farms at Petrolina, Pernambuco states (Teixeira *et al*., 2007; 2008), the $CWP_{ETa}$ values were 3.18 and 3.68 kg $m^{-3}$, respectively, indicating that there is ample scope for improving in other farms according to the data in Tables 2 and 3, mainly in the case of the second crop.

Considering the other two important fruit crops in the semi-arid region of Brazil, banana and guava, Teixeira *et al*. (2002) found $CWP_{ETa}$ values of 1.60 kg $m^{-3}$ for the first crop while Teixeira *et al*. (2003) found values of 2.66 kg $m^{-3}$ for the second one. In relation to Tables 2 and 3, the needs of improvements in water management in guava crop are more evident than for banana crop, although the monetary values of CWP are lower for the first crop than for the second one in Pernambuco State.

*Table 3. Water productivity parameters for fruit crops in the semi-arid region of Bahia State, Brazil, for 2005: actual evapotranspiration (ETa); harvested area (HA); production; crop water productivity per cultivated land ($CWP_L$); gross return (GR); and crop water productivity per actual evapotranspiration ($CWP_{ETa}$ – physical values; and $CWP\$_{ETa}$ – monetary values)*

| Variable / Crop | ETa | HA (ha) | Production (t) | CWPL (kg $ha^{-1}$) | GR ($10^2$ US$) | $CWP_{ETa}$ (kg $m^{-3}$) | $CWP\$_{ETa}$ (US$ $m^{-3}$) |
|---|---|---|---|---|---|---|---|
| Grape | 1,260 | 3,586 | 107,280 | 29,916 | 183,429 | 2.37 | 3.84 |
| Mango | 1,270 | 11,434 | 270,848 | 23,687 | 153,952 | 1.87 | 0.23 |
| Banana | 1,640 | 4,203 | 91,125 | 21,680 | 36,355 | 1.32 | 0.44 |
| Guava | 1,160 | 289 | 5,636 | 19,501 | 2,415 | 1.68 | 0.45 |

## Regional Scale Modelling of Water Productivity

Remote sensing and Geographic Information System (GIS) have proved to be useful tools in identifying the range of possible values for CWP and, combined with ground data, can help to identify constraints for on-farm and system management improvements in semi-arid regions, however these tools need to be closely integrated into policy decision making processes.

By using remote sensing, Bastiaanssen *et al.* (1999) carried out a study to identify the spatially distributed patterns of wheat yield and ETa in the Bakhra irrigation system of Punjab and Haryana in India, and found that areas with the highest yield corresponded to those having the highest ETa. The spatial variations in crop production per unit ETa were less than spatial variations in productivity of land.

McVicar *et al.* (2000) applied GIS in China to assess if changes in management practices increased the regional $CWP_{ETa}$. From 1984 to 1996 the values for wheat increased from 0.70 kg $m^{-3}$ to 1.43 kg $m^{-3}$, while for corn the values increased from 0.90 kg $m^{-3}$ to 1.01 kg $m^{-3}$ for the same period. Regions with high average values, but somewhat inconsistent from year to year, were identified as those with the highest potential for water management improvement.

Zwart and Bastiaanssen (2007) applied the algorithm SEBAL to estimate $CWP_{ETa}$ of wheat in Yaqui Valley, Mexico. The average value was 1.37 kg $m^{-3}$, however with strong variation across fields and according to the authors a reduction of 14% in ETa could be achieved while maintaining the same yield. The variation in $CWP_{ETa}$ values was attributed to the management decisions of individual farmers, such as choice of seeds, fertilizers, and amount and time of irrigation.

To give special attention to the natural movements of water on landscapes, a CWP indicator was constructed by Maneta *et al.* (2009b) to identify areas and spatial patterns of low and high potentially agricultural water productivity. This CWP indicator is the ratio between the total gross values of all of the crops produced to the potentially available water at a given location. This CPW index is transferable allowing direct comparison between basins being useful to water resources decision makers. An application of this indicator to the São Francisco River basin, Brazil, showed that higher scores are found in Petrolina/Juazeiro development centre, located in the semi-arid region, where there are intensive public and private sector investments in irrigated crops.

Considering the quick expansion of irrigated fruit crops over the natural vegetation in the semi-arid region of the São Francisco River basin, Teixeira *et al.* (2009a,b) calibrated and validated the SEBAL algorithm with Landsat images for ETa calculations which were used together with biomass estimations (Bastiaanssen and Ali, 2003) to analyze water productivity of vineyards and mango orchard for growing seasons in the commercial farms of wine, grapes and mangos (Fig. 2).

The average value of $CWP_{ETa}$ for wine grape was 1.15 L $m^{-3}$ (i.e. 1.44 kg $m^{-3}$ per water consumed) with a corresponding monetary values ($CWP\$_{ETa}$) reaching a maximum of 1.55 US$ $m^{-3}$. Jairmain *et al.* (2007) found higher values in South Africa (4.70 kg $m^{-3}$) indicating scope for improvements in water management in wine grapes from Brazil.

For table grapes the average $CWP_{ETa}$ value was 2.80 kg $m^{-3}$ with a peak of 8.80 US$ $m^{-3}$ for the monetary counterpart. The physical values were lower than those found in Australia under drip (Yunusa *et al*., 1997a) and furrow irrigation (Yunusa *et al*., 1997b), where for drip irrigated table grapes were 8.60 kg $m^{-3}$ for grafted and 4.30 kg $m^{-3}$ for own-rooted vineyards. In the furrow irrigated vineyard, $CWP_{ETa}$ resulted in 1.33 and 4.05 kg $m^{-3}$ two different growing seasons, respectively. Jairmain *et al.* (2007) reported a mean value of 3.70 kg $m^{-3}$ for table grapes in South Africa.

The coefficient of variation for both vineyards was high, showing relatively large spatial variations in these crops in the Brazilian semi-arid region. The lower Brazilian values of vineyards CWP are related to the lower yields associated with higher daily water consumptions in comparison with other vineyard growing countries.

For mango orchard, the average physical value was 4.00 kg $m^{-3}$ with a maximum monetary value of 5.10 US$ $m^{-3}$. The lower value of the variation coefficient (CV) for mango orchard showed more uniformity than for vineyards (Fig. 2).

According to Teixeira *et al.* (2009b), economic water productivities in fruit crops in semi-arid regions are much higher than for irrigated annual crops. The agricultural water usage in the commercial fruit farms in these regions can be

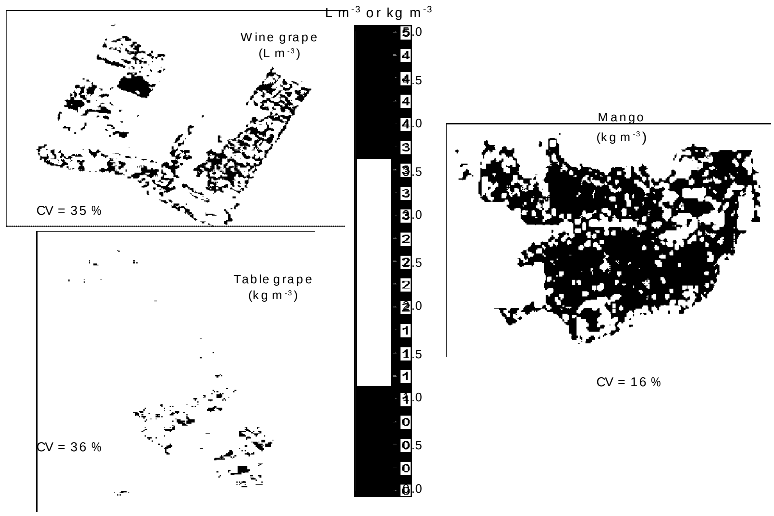


*Fig. 2. Crop water productivity based on evapotranspiration ($CWP_{ETa}$) for wine grape, table grape and mango orchard in the semi-arid region of Brazil (Source: Teixeira et al., 2009a,b).*

highly productive, creating considerable amount of jobs, with some cities increasing quickly in terms of exports and job creation, converting marginal savannah land into a booming rural development; however the water management requires full attention as under intensive land use change, the environment can be affected by the flow of polluted water to the rivers, being necessary to promote more efficient water use, water-resources management, and planning for the expansion of irrigated areas.

The reduction of the spatial and temporal variation in crop yield and ETa are crucial elements for increasing the total CWP in irrigation schemes in semi-arid regions. The combination of agro-meteorological data together with spatially distributed satellite images is technically feasible to acquire key elements of the regional water fluxes and water productivity.

## Final Remarks

The areas with irrigated crops in river basins of semi-arid regions are quickly expanding over natural vegetation. The water consumption of these crops in general is high due to high thermal availability. In general, the water is productively used, however the intensification of agriculture can adversely affect the water quality of the rivers, and this will require a more rational irrigation supply in the near-future. Knowledge of both the regional actual evapotranspiration and yield can help to optimize the necessary reduction in irrigation supplies.

The assessments of crop water productivity from field to regional scale can show the performance of irrigation areas in semi-arid regions, where there are rapid land use changes. With the use of algorithms for estimating spatially distributed water consumptive use in conjunction with a network of agrometeorological stations and a Geographic Information System, the water cycle in irrigated agriculture can be well described. The available tools can be operationally implemented to monitor the intensification of agriculture and the adverse impact on downstream water users in the semi-arid regions.

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