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Management interventions for enhancing agricultural production by improving water use efficiency

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Abstract
Traditional ways to increase yield by extending the area under cultivation, using high intensity of external inputs and breeding for yield potential in high input agro-ecosystems offer limited possibilities under limiting resource availability. Improved agricultural systems should ensure high yields via an efficient and sustainable use of natural resources such as water. The most management measures contribute to better water use efficiency by improving water availability to the crop while reducing unproductive water losses. The main effect of crop, soil and irrigation management is an increase of the transpiration component in relation to runoff, soil evaporation and drainage. Also the effect of deficit irrigation methods is achieved partially by reducing stomatal conductance that results in higher transpiration efficiency. Redistribution of water from soil evaporation to plant transpiration is the key for better water use efficiency.

Keywords: Water use efficiency, crop and soil management, losses

Introduction
Agriculture is confronted with the challenge of feeding the rapidly growing population under a scenario of decreasing land and water resources worldwide (Bossio and Geheb, 2008) [5] Since the 1990s yields have not increased at the pace registered since the 1950s, while world population continues to rise (Araus *et al*., 2008) [2]. The "yield-gap" is expected to further aggravate due to climatic change impacts such as extending soil degradation and higher frequency of droughts (IPCC, 2007) [18], water is the main abiotic stress limiting crop production in several regions of the world (Araus *et al*., 2008) [2]. In 2030, 47% of the world population will be living in areas of high water stress (WWAP, 2009) [42]. Even where water for irrigation is currently plentiful, there are increasing concerns about future availability (Falkenmark, 1997) [11]. Traditional approaches of yield maximization were based on (i) increase in area under cultivation, (ii) high intensity of external inputs (fertilizer, irrigation) and (iii) breeding for high yield potential in high input agroecosystems ("green revolution varieties") (Richards, 2004; Waines and Ehdaie, 2007) [8, 41]. With decreasing land and water resources, for the future these ways offer limited possibilities to satisfy the increasing food demand. Improved agricultural production systems are required that ensure high yield via an efficient and sustainable use of available natural resources. Improvements in agricultural water use can be achieved at several points along the production chain, such as (1) the irrigation system (2) the proportion of water attributed to plants use, and (3) the conversion of crop water consumption into yield (Hsiao *et al*. 2007) [16]. The present review focuses on agronomic approaches to improve water use efficiency.

Options for improving irrigation efficiency
Agronomic

1. Crop management to enhance precipitation capture or reduce water evaporation e.g., crop residues, conservation till, and plant spacing
2. Improved varieties

3. Advanced cropping strategies that maximize cropped area during periods of lower water demands and/or periods when rainfall may have greater likelihood of occurrence

Engineering
1. Irrigation systems that reduce application losses, improve distribution uniformity, or both
2. Cropping systems that can enhance rainfall capture e.g., crop residues, deep chiselling or para tilling, furrow disking.

Management
1. Demand-based irrigation scheduling
2. Slight to moderate deficit irrigation to promote deeper soil water extraction 3. Avoiding root zone salinity yield thresholds
3. Preventive equipment maintenance to reduce unexpected equipment failures

Institutional
1. User participation in an irrigation district or scheme operation and maintenance
2. Water pricing and legal incentives to reduce water use and penalties for inefficient use
3. Training and educational opportunities for learning newer, advanced techniques

Crop management practices

Crop management practices include decisions on sowing date, planting density, crop rotation, phytosanitary measures and cultivar selection. These practices influence agronomic water use efficiency by adapting the cropping system to the environmental site conditions and providing optimum growth conditions for the single crop in order to obtain maximum yield with available resources. Crop management practices influence water use efficiency at the level of field crop stands, single plants and physiological processes.

Sowing date of crops can significantly affect water use efficiency (Morrison and Stewart, 2002) [22]. Early sowing has frequently been found to improve yield and water use efficiency (Gregory, 2004) [13], while yields were reduced by delayed sowing (Faraji *et al*., 2009) [12]. An appropriate sowing date can enhance early vigour of the crop with better canopy cover of the soil surface. This reduces evaporation losses in favour of transpiration (Tambussi *et al*., 2007) [37]. Increased water use efficiency of early sown crops and winter-grown varieties is also related to the lower evaporative demand of the atmosphere during part of the growing period (Purcell *et al*., 2003) [30]. Humphreys *et al*., (2001) [17] showed that early sowing of winter crops immediately after rice harvest increased the water use efficiency of rice-based cropping systems by better use of stored soil water and capture of winter rainfall instead of losing it as runoff or deep percolation.

Using appropriate method of sowing can also help to improve water use efficiency. Particularly sowing depth can influence early vigour and hence soil evaporation (Ali and Talukder, 2008) [1]. Deeper sowing combined with cultivars with longer coleoptiles was found to increase growth vigour, yield and water use efficiency of wheat in environments with early droughts as seedlings could make better use of soil moisture (Rebetzke *et al*., 2007) [31]. Research in southern Queensland found that water use of rice grown on beds was 32% less than when grown using conventional permanent flood, while yields were maintained, resulting in a large increase in water use efficiency (Borrell *et al*., 1997) [4].

Crop rotation

Crop rotation can optimize water use efficiency by (i) increasing the number of crops grown per year, (ii) more effective use of available resources, and (iii) better phytosanitary conditions. Passioura, (2006) [27] indicates that water use efficiency depends not only on how a crop is managed during its life, but also how it is fitted into the whole management system. Continuous cropping that avoids fallow can increase single crop as well as system water use efficiency and avoids damages caused by bare fallows (Schillinger *et al*., 1999) [33]. Pala *et al*., (2007) [25] evaluated several wheat based crop rotations under Mediterranean conditions in Syria. Water use efficiency of wheat decreased in the following crop rotation sequence: fallow, medic, lentil, chickpea, and continuous wheat. Cover cropping is a common crop rotation practice to avoid negative environmental effects of autumn fallows after cash crop harvest by prolonging soil coverage and plant growth over the season (Bodner *et al*., 2007) [3]. It is intended to control erosion, prevent nutrient leaching, fix nitrogen and improve soil conditions. Additional water use of cover crops however could negatively affect soil water availability for the next crop. Bodner *et al*., (2007) [3] showed that water use efficiency of cover crops species is high compared to cash crops of similar habitat and same families. This is due to the substantially lower evaporative demand of the atmosphere during the vegetation period of the cover crops. Introducing a legume crop in a cereal rotation can improve soil fertility by nitrogen fixation and addition of organic matter in the soil, increase the yields of the subsequent cereal crops and help to control disease, pests, and weeds that build up in continuous cereal production systems (Papastylianou, 1993; Ali and Talukder, 2008) [26, 1].

Crop type and cultivar selection

Crop type and cultivar selection contributes to adapt the production system to environmental growth conditions and it is fundamental for site specific optimization of water use efficiency. Distinct response to water limiting conditions occurs due to (i) different photosynthetic pathway and (ii) different energy requirements for yield formation, as well as (iii) progress in breeding of adapted drought tolerant varieties. Plants with the C3 photosynthetic pathway are less efficient in water use than plants with the C4 pathway, especially at higher temperatures and lower CO2 concentrations (Condon *et al*., 2004; Ali and Talukder, 2008) [8, 1]. In species with C4 photosynthesis high photosynthetic rates can be associated with low stomatal conductance, leading to high water use efficiency (Cowan and Farquhar, 1977; Schulze and Hall, 1982) [9, 34].

Fertilizer management

Nitrogen (N) management is one of the major factors to attain higher crop productivity. Nitrogen effects have been described on gas exchange as well as integrative agronomic water use efficiency. Positive effects of nitrogenous fertilizers include increase in leaf area index, green crop duration and dry matter production that ultimately lead to increase in water use efficiency (Latiri-Souki *et al*., 1998) [20]. Increased water use efficiency due to nitrogen fertilization was reported for grain sorghum and maize by Varvel, (1995) [40] and Ogola *et al*., (2002) [23]. Higher water use efficiency due to increased biomass production with improved nitrogen supply have also been reported for wheat and corn by Campbell *et al*., (1992) [7] and Varvel (1994) [39], respectively. Kundu *et al*., (2008) [19] showed increasing leaf area index and higher water use efficiency of common bean with higher phosphorus supply. Addition of phosphatic fertilizer has been reported to enhance water use efficiency of different crops (Hatfield *et al*., 2001) [14], such as pearl millet (Payne *et al*., 1992) and chickpea (Singh and Bhushan, 1980) [35]. The positive effect of potassium (K) on water stress tolerance is related to several physiological processes. Potassium maintains the osmotic potential and turgor of the cells and regulates the stomatal functioning. Potassium enhances photosynthetic rate, yield and water use efficiency under stress conditions (Tiwari *et al*., 1998) [38]. Improvement of potassium nutritional status has also been found to protect plants against oxidative damage during drought stress (Cakmak, 2005) [6].

Water availability and nutrient supply are interacting factors in determining crop growth and crop water use efficiency. The efficiency of nutrients to increase yield depends on water supply according to the law of optimum: For higher production, the plant can make better use of the growth factor being in minimum, the more the other growth factors are within the optimum. With increasing water stress, nutrient availability as well as nutrient uptake capacity of the plant are impaired and the marginal return in terms of yield increase per unit of applied nutrient decreases (Ehlers and Goss, 2003) [10]. Nutrient uptake capacity is significantly influenced by root system parameters. Root growth and root distribution are modified by nutrient availability and distribution in the soil (Hodge, 2004) [15]. Plants respond to low nutrient availability by enhanced root growth and root exudation.

Soil management

Tillage operations can influence water use efficiency by (i) changing soil surface properties, (ii) modifying soil hydraulic properties, and (iii) influencing root system formation of crops. Tillage therefore influences water dynamics and water use efficiency via mechanical effect of the tillage implements, mulching effects related to the amount of residues cover remaining on the soil surface, and biological effects due to modified root system formation and soil microbiological activity. Higher organic matter content in the surface near soil layers under conservation tillage is essential for an enhanced infiltration capacity and thereby reduced runoff losses (Zhang *et al*., 2007c) [43]. Mulching is regarded as one of the best ways to reduce soil evaporation. Residues and mulches limit evaporation by reducing soil temperature, preventing vapour diffusion, absorbing water vapour on to mulch tissue, and reducing the wind speed gradient at the soil–atmosphere interface (Steiner, 1989) [36].

Irrigation management

Irrigation management increasingly focuses on more effective and rational uses of limited water supplies with increasing water use efficiency (Marouelli *et al*., 2004) [21]. Improved efficiency can be obtained by reducing drainage, runoff and evaporation losses by using measurement or model assisted irrigation scheduling (Pereira *et al*., 2002) [29]. Also supplemental irrigation at critical growth stages has substantially improved irrigation efficiency (Oweis *et al*., 1999).

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