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Water, Agriculture and Food: Challenges and Issues

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Abstract Population growth, increasing demands for food, ever-growing competition for water, reduced supply reliability, climate change and climate uncertainty and droughts, decline in critical ecosystems services, competition for land use, changing regulatory environments, and less participatory water resources governance are contributing to increasing difficulties and challenges in water resource management for agriculture and food. The need for sustainable food security for our global population and the need for preserving the environment, namely natural and man-made ecosystems and landscapes, have created an increased need for integrated, participative and scalable solutions focusing the various levels of irrigation and nature water management, from the field crop to the catchment and basin scales. Meanwhile, challenges and issues relative to water management for agriculture and food have evolved enormously in the last 30 years and the role of active management of the components of the water cycle is assuming an increased importance since their dynamics are key to assure water use sustainability, mainly agriculture and natural ecosystems sustainability. However, different regions face context-specific challenges associated with water scarcity, climate, governance, and population requirements. The main and first challenge is producing enough food for a growing population, which is intimately related with challenges placed to agricultural water management, mainly irrigation management. This paper revises challenges and progress achieved in the last 30 years focusing on irrigated agriculture, mainly water management, and its contribution to food security and the welfare of rural communities.

Keywords Water management · Energy · Climate change and uncertainty · Water scarcity · Participatory water governance · Reference evapotranspiration · Crop water requirements · Irrigation management

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1 Introduction: Food, Water and Irrigation

The main and first challenge faced by agriculture is producing enough food for a continued increasing population in a complex context of population growth and urbanization, poverty, increased demands for food, ever-growing competition for water and land, climate change, climate uncertainty and droughts, variable supply reliability, decline in critical ecosystems services, changing regulatory environments and less-participatory water resources governance. This challenge and associated issues deeply relate with challenges placed to agricultural water management, mainly irrigation management as analyzed further in this paper. Numerous studies and information are being produced on those various topics, e.g., FAO (2012) and WBCSD (2014), particularly relative to food security and nutrition (FSN). FAO is publishing a series of reports on various facets of FSN, namely relative to climate change impacts on FSN (HLPE 2012) and linkages between water and food (HLPE 2015). Related recommendations include: (a) ensuring sustainable management and conservation of ecosystems for stable availability of water of appropriate quality; (b) integrated approach to water and FSN policies; (c) improved water management in agriculture and adaptation of agricultural systems to enhance water use performance and water productivity, particularly to face water scarcity; (d) fostering an inclusive and effective governance of water for FSN, namely ensuring "the full and effective participation of all actors, including the vulnerable and marginalized", with special attention to gender inclusive processes; (e) promoting a rights-based approach to governance of water (HLPE 2015). Important to note that irrigated agriculture, while representing 16% of cultivated area, is expected to produce 44% of world food by 2050 (FAO 2012; WBCSD 2014).

The CIHEAM adopted a different but complementary approach in supporting development of knowledge required for attaining food security in Mediterranean and considered water issues together with those relative to other natural resources: land, climate (and climate change), biodiversity and energy (Zdruli et al. 2013). Meanwhile, the integrative concept of Water-Energy-Food Nexus is receiving particular attention given that energy resources are paramount in the food chain, from the field to the consumer, which led to its adoption by several institutions, (e.g. FAO 2014; UNU 2016). The factor land use was added by others (Ringler et al. 2013), which brings to the foreground the rational of land use competition with non-agricultural sectors, as well as the need for land preservation and landscape conservation.

This paper revises first a diversity of approaches on water and energy challenges and issues relative to food processes, however aiming at food production. Then, irrigation water use is focused, particularly on challenges placed to water use and consumption and irrigation water management including aiming at reviewing the role of this Journal to innovation in these domains.

2 Water, Energy and Food Nexus

Approaches to consider the role of irrigation in increasing food production are not recent but past approaches were limited in scope, e.g. just considering the impacts of irrigation performance on food production (Jermár 1989). The need of increased food production from irrigation was analyzed by Carruthers et al. (1997) who concluded that not only efficient expansion and intensification of irrigated agriculture are necessary but that there is a need to better explore "the links between water scarcity, food production, food security, and environmental sustainability". In the same line, de Fraiture (2007) referred the need for an integrated and multidisciplinary modelling approach aiming at exploring the linkages between economic trends, agricultural policies and water use and presented the WATERSIM model for those aims. Hanjra and Qureshi (2010) performed a review on factors influencing FSN, particularly those referring to water, by exploring linkages between water supply and food security with focusing on adaptation to climate change, land and water conservation, developing and adopting new crop varieties, modernizing irrigation, and "reforming international food trade". Rosegrant et al. (2009) analyzed impacts of water scarcity on agricultural water use and related consequences on FSN. These authors focused a variety of problems such as "soil degradation, groundwater depletion, increasing water pollution, the degradation of water-related ecosystems, and wasteful use of already developed water supplies", and discussed on policies, institutions, and investments needed to secure access to water for food production. Qadir et al. (2007) focused their review on using non-conventional water for food production in water scarce environments.

A wider approach was used by Pereira et al. (2009) focusing water scarcity and drought impacts, challenges and issues relative to the various economic sectors including food production. That book represents consolidated knowledge which is upgraded with a variety of approaches to better understanding water scarcity (Jaeger et al. 2013), assessing drought impacts in agriculture (Safavi et al. 2014), or decision making relative to coping and mitigating drought impacts in crop production in water scarce areas (Giannikopoulou et al. 2017; Chitsaz and Azarnivand 2017). Water saving measures dictated by the need to cope with water scarcity require, however, proper identification of impacts on yields and farmers' incomes but also on environment, namely on groundwater and soil salinity (Xu et al. 2011).

Analyzing the referred integrative concept of Water-Energy-Food Nexus (Fig. 1) it is evident that complexity is added relative to the sole consideration of water-agriculture-food interactions: on the one hand, it brings to the consideration the challenging questions relative to energy; on the other hand, virtual water comes to the picture. The latter is a difficult concept to handle: it is rational to consider the transfer of water integrated in food products, generally cereals, but it is controversial the way how this transfer may be interpreted. Virtual water may provide for a trade perspective but has little scope as a sound water management issue (Kumar and Singh 2005; Wichelns 2010).

The consideration of energy issues requires various perspectives. The first refers to the current energy requirements of the entire food chain processes, from production to transportation, industrial transformation, preparation, and commercialization. Food crops require enormous quantities of energy and related efficiency in processes is often difficult to achieve (Martinho 2016). The increases in food production since the 1960s is largely related with the direct energy use for food crops cultivation and the indirect energy use relative to fertilizers, agro-chemicals and farming machinery, however, with variable relationship between energy use and yields as reviewed by Woods et al. (2010). Fossil fuels remain the dominant source of energy for agriculture, mainly for traction, so with well-known impacts on production of green-house gases (GHG), while nitrogen fertilizers may represent more than 50% of total energy use in commercial agriculture (Woods et al. 2010), particularly when irrigation water is less used. However, if the trend to replace surface irrigation by pressurized systems largely contributes to increased energy use in agriculture, that trend highly eases adopting precision irrigation. In case of farm systems, solutions refer, on the one hand, to improve systems design, irrigation scheduling and performance (Pereira et al. 2009; Khan et al. 2009) and, on the other hand, to adopt low energy emitters such as for sprinkler lateral moving systems or for small

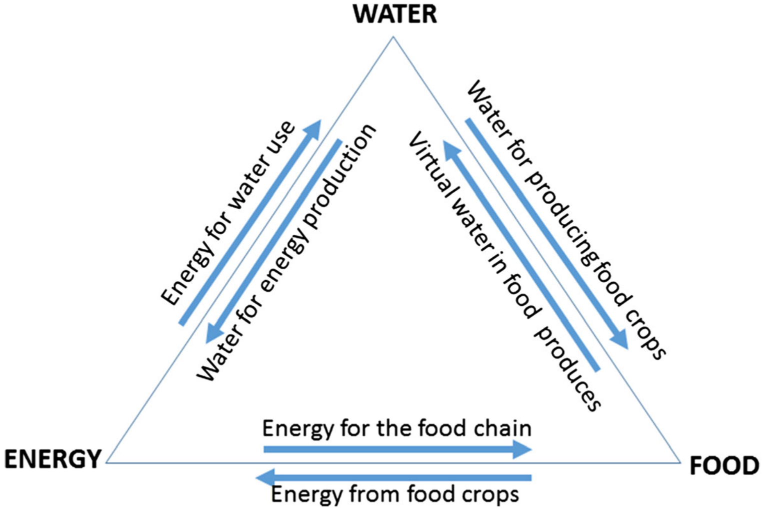

Fig. 1 A schematic representation of the Water Energy Food Nexus (adapted from UNU 2016)

family farms (Singh et al. 2010). In case of pressurized irrigation conveyance and distribution systems, the search for energy saving mainly relates to improved design and operation performance (Córcoles et al. 2015; Khadra et al. 2016).

When keeping dependent of fossil fuels, food production remains a major contributor to anthropogenic GHG emissions. Therefore, trends for using renewable energies is advocated by many and refer to various facets including improving the energy efficiency of food processes, adopting hydrogen energy in transportation and farm tractors (Salvi and Subramanian 2015), extending the use of electricity (Moreda et al. 2016) and adopting an increased use of biofuels (Guo et al. 2015; Matuszewska et al. 2016) including for hydrogen production. However, biofuels bring to the scene the land use competition between food crops and energy crops, which remains a non-solved problem despite some optimism (Rathmann et al. 2010; Valentine et al. 2012).

3 Food, Irrigation, and Cropping Systems Nexus

The last 30 years have shown great innovative solutions in food production, particularly in cultivation techniques, new crop varieties and irrigation. However, innovations are essentially technological, which were not followed by innovations in participation of farmers in water and irrigation systems governance. The gap between small and large farms has increased, with the latter implementing a variety of modern technologies and managerial solutions, with a continued adoption of updated research results, particularly precision agriculture in case of commercial farms. Differently, smallholders face insufficiencies in capital, have difficult access to improved technologies and innovation, lack participation in water governance and often are affected by poverty. As analyzed by Manjunatha et al. (2013) relative to India, land fragmentation is significantly associated with inefficiency and low farm profit, whereas land ownership and crop diversity are associated with farm efficiency. However, small farms are more intensive and may be more efficient in use of inputs than the large ones. Distinctions are detectable due to climate, cropping orientation, access to the property of land, and type of political ruling. Nevertheless, advances in water management are enormous; if they are more easily adopted by large and commercial farms, progresses also contribute to small farms intensification, improved use of resources and enhanced land and water productivities, e.g., drip irrigation (Karlberg et al. 2007).

Fig. 2 presents a scheme of the Food-Irrigation-Cropping Systems Nexus. It intends to illustrate that crop systems vary with the considered food crop and under the influence of local know-how and socio-cultural conditions. Depending on local climate, soils, land conditions and water availability, irrigation may play a main role in the adopted cropping systems to support appropriate water needs of the crop. Finally, irrigation management in terms of control of water deficits and scheduling depends on food produce characteristics, the consumers and market preferences and the requirements of agro-industry. However, Food-Irrigation-Cropping Systems Nexus vary with farm size and orientation, as well as with access to technologies and capital as briefly referred above, and reflect poverty impacts.

Innovations in irrigation and agricultural water management contributed to progresses in FSN since productivity of cereals and legume grains under irrigation is steadily increasing and largely exceeds that obtained in rain-fed conditions (Mueller et al. 2012; Sadras et al. 2015). A spatial analysis study relative to cereals yield gaps show these are large when irrigation is not sufficient (Neumann et al. 2010). However, the importance of the cropping systems must be stressed because its adequateness in terms of production and impacts on the environment are essential. This is well discussed by Foley et al. (2011) who defined a set of challenges faced by agriculture to feed the world: "reducing GHG emissions from agriculture and land use, reducing biodiversity loss, phasing out unsustainable water withdrawals, and curtailing air and water pollution from agriculture". Along these lines, Chen et al. (2014) focused on the needed but possible control of the use of nitrogen fertilizers and related GHG emissions in cereal production in China. The role of plant breeding to search for more productive and more stress resistant varieties has also to be considered relevant to face the referred challenges

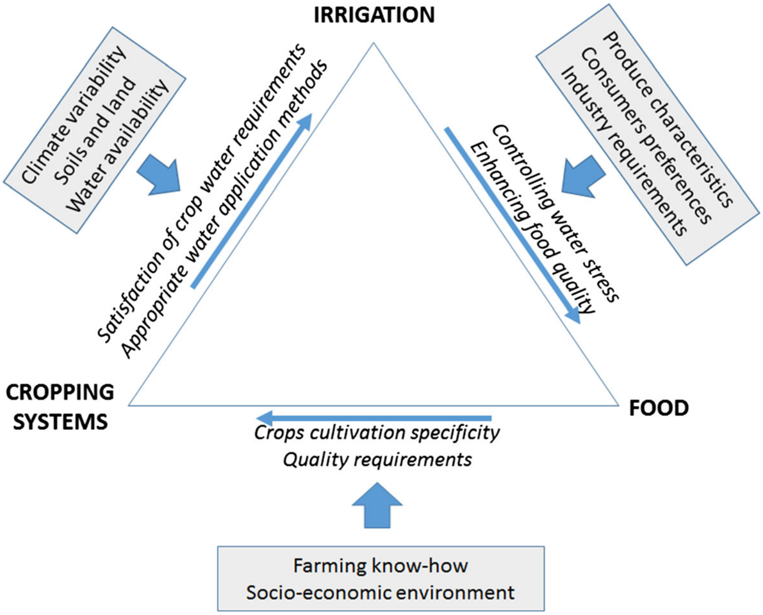

Fig. 2 A schematic representation of the Irrigation-Cropping System-Food Nexus

(Tester and Langridge 2010). Main aspects on irrigation and agricultural water management are reviewed hereafter.

4 Irrigation and Agricultural Water Management Innovation and Challenges

4.1 Reference Crop Evapotranspiration

Doorenbos and Pruitt (1977) introduced, internationally, the two-step crop coefficient – reference evapotranspiration (K_c – ET_{ref}) procedure to estimate crop water requirements in a practical way. ET_{ref} represents the primary weather induced effects on water consumption, and the crop coefficient (K_c) scales the reference ET to account for crop-specific influences on ET and their variation during the crop growing season. Standardized values for K_c at typical crop stages were provided for numerous crops, and four methods were proposed to estimate ET_{ref}, based on data availability. FAO56 proposed only the Penman-Monteith method (Allen et al. 1998).

FAO56 defined ET_{ref} as the rate of evapotranspiration from a hypothetical reference crop with an assumed crop height $h = 0.12$ m, a fixed daily canopy resistance $r_s = 70$ s m^{-1}, and an albedo of 0.23, closely resembling the evapotranspiration from an extensive surface of green grass of uniform height, actively growing, completely shading the ground and not short of water. This definition enabled the parameterization of the Penman-Monteith (PM) equation (Monteith 1965) to produce a standardized grass crop reference (ET_o) equation, the PM-ET_o equation. Particularly in hydrologic studies, ET_o is often referred as potential ET. The computation of parameters in the PM-ET_o equation was also standardized. The philosophy in selecting the PM-ET_o as a globally applicable reference method was that “physics are physics everywhere.” Thus, if the primarily physics-based PM-ET_o method is set up correctly using high quality weather measurement data from a handful of locations, it should sufficiently serve as a basis for crop ET globally. This has largely been demonstrated by comparative studies of PM-ET_o and local ET measurements and regional studies confirming the applicability of the PM-ET_o equation to a large variety of environments as revised by Pereira et al. (2015).

Following the lead of FAO, ASCE standardized the Penman-Monteith equation for both clipped grass and alfalfa surfaces and adopted similar parameterizations resulting ASCE-PM ET_{ref} equation (ASCE-EWRI 2005). Later, a formulation for application to hourly time-steps was adopted (Allen et al. 2006) where a lower $r_s = 50$ s m^{-1} value for the clipped-grass reference was recommended for daytime and $r_s = 200$ s m^{-1} was recommended for night-time.

The application of the PM-ET_o equation has two main requirements: that computation of the parameters follow standardized procedures as proposed in FAO56 guidelines, and that weather data are of good quality and represent weather conditions to be found over a green grass area, consistent with the ET_o definition. Error may result from deviation from standardized methods for computing parameters in the PM-ET_o. The need for strict adherence to the FAO56 recommended parameter computation procedures has been evidenced (Nandagiri and Kovoor 2005; Irmak et al. 2011).

FAO56 encouraged weather data quality assessment and control. The needs for checking the quality of weather data and approaches for their correction were discussed by Allen (1996, 2008) and Estévez et al. (2011) among others. The importance of the weather station location was emphasized in FAO56 because when making calculations of ET_o, weather measurements should reflect the environment that is defined by the grass reference surface. Weather stations supporting the calculation of ET_o should measure temperature, humidity, radiation and wind speed within the dynamic boundary overlying the ground surface (Allen et al. 2011a, 2011b). Properties of this boundary layer characterize the energy balance at the surface and are used to estimate the ET rate. Temperature corrections to overcome problems of local advection and dryness of weather station settings were explored by Allen (1996) and Temesgen et al. (1999). When weather data are not from an agricultural or reference environment and/or are shown to be substantially affected by local advection, the user should be willing to adjust the data using procedures such those from FAO56, ASCE-EWRI (2005) or Allen et al. (2007a), or to abandon the use of the data. Future research can focus on the quality requirements of observation facilities and data control (Allen 1996, 2008; Allen et al. 2011a, 2011b) because of the negative influences that poor data have on estimates of ET_o, particularly in arid and semi-arid regions where local advection and aridity of the weather station may influence ET_o results.

In many countries, measured weather data are not available or accessible without payment, thus leading users to explore computing ET_o using alternative estimation methods, such as using temperature data only. However, FAO56 recommended against adopting a simpler ET_o equation but to estimate missing data and retaining the use of the PM-ET_o method. The latter approach, using maximum and minimum temperature to estimate solar radiation (R_s) and actual vapour pressure (e_a), commonly known as PMT, has been positively tested by many as reviewed recently by Pereira et al. (2015) and Ren et al. (2016a). However, this approach did not receive the preference of most researchers because it requires the calibration of the R_s and e_a estimation equations, mainly the radiation adjustment coefficient k_{Rs} and the correction of minimum temperature to estimate the dew point temperature (Todorovic et al. 2013¸ Ren et al. 2016a). The Hargreaves and Samani (1985) equation, which requires air temperature only, is more often preferred due to its simplicity. Nevertheless, the calibration of that equation is often of statistical nature only, without searching the best value for k_{Rs}, which varies with the aridity of the location as shown by Raziei and Pereira (2013) and Ren et al. (2016a). A large number of publications have reported on the development of a variety of approaches, quite often numerical methods, e.g., ANNs and fuzzy and neuro-fuzzy systems, to replace the PM-ET_o equation. Users of these algorithms need to consider that many trends defined by these approaches remain empirical and may not translate well in time and space and that there is no replacement for basic physics, as represented in the PM-ET_o formulation as noted by Pereira et al. (2015). These aspects need to be considered when performing trend analysis of ET_o because trend results when using full data sets are different from those obtained using temperature only (Ren et al. 2016b).

Recent approaches to estimate ET_o from remotely sensed data include those by de Bruin et al. (2010) and Cammalleri and Ciraolo (2013) which adopted a radiation-temperature equation to estimate daily ET_o using radiation and temperature data from the LANDSAF geostationnary satellite. Another innovative approach refers to using the USGS Global Data Assimilation System (GDAS) daily reference evapotranspiration products (Liu et al. 2011). Of particular interest is the use of reanalysis products for computing with the PM-ET_o equation at various time and space scales (Srivastava et al. 2013; Martins et al. 2016; Paredes et al. 2017). Those issues are expected to further develop in future.

4.2 Crop Water and Irrigation Requirements

Crop water requirements (CWR) referring to the crop season or any period of time are assumed to be the cumulated value of crop ET (ET_c, mm) for that period. Differently, the net irrigation requirements (NIR) consist of the net depth of water required to satisfy CWR in addition to the available soil water in the root zone, precipitation and capillary rise, as well as the depth of water required for leaching of salts in the root zone. Gross irrigation requirements (GIR) result from the inefficiencies of application of irrigation water and consist of the ratio NIR/BWUF, where BWUF is the beneficial water use fraction of the applied water (Pereira et al. 2012). CWR are computed from ET_c, and NIR result from the soil water balance of the crop root zone, which often imply the use of models.

Allen et al. (2011a) revised a variety of methods and related requirements for accuracy when observing or computing crop ET: a) measuring changes in soil water, b) mass balance over large areas providing for watershed scale ET, c) lysimetry, including for measuring soil evaporation, d) Bowen Ratio Energy Balance, e) eddy covariance, f) scintillometers, g) sap flow methods for transpiration estimates, h) remote sensing energy balance, and i) satellite-based ET using vegetation indices.

A consistent and solid estimation of ET of crops or natural vegetation may be obtained using the concept of ET_o and K_c curve, where only three K_c values defining the initial, mid-season and end-season are sufficient to define the curve (Allen et al. 1998). Moreover, it is simple and accurate (Burt et al. 2005; Farahani et al. 2007; Allen et al. 2011a). The $K_c – ET_o$ approach for estimating crop water use and crop ET under various crop growth and management conditions accounts "for the influences of (a) the crop growth stage, amount of vegetation, and cultivar type; (b) the planting date, crop season length, and termination; (c) plant and row spacings, plant density, crop height and canopy architecture; (d) the wetting frequency and its contribution to total ET; (e) soil water availability and associated water stress; (f) soil and water salinity; and (g) non-standard and sub-optimal cropping practices" (Pereira et al. 2015). In addition, the K_c was extended to natural vegetation to support hydrologic applications. The applications of the $K_c – ET_o$ are extremely numerous, particularly in the domain of food crops – cereals, legumes, vegetables, fruit trees and vines – using the common single K_c crop coefficient that incorporates both crop transpiration and soil evaporation processes. Applications of the dual K_c approach, that adopts $K_c = K_{cb} + K_e$, thus the basal K_{cb} representing crop transpiration and the soil evaporation coefficient K_e, hence separating these two processes, are yet limited because of more demanding computational requirements.

FAO56 (Allen et al. 1998) expanded the K_c database provided in FAO24 (Doorenbos and Pruitt 1977). The tabularized values for lengths of crop growth stages are illustrative of general tendencies. Local observation is definitely required to account for variation in crop variety, cultural practices and variation in weather effects. However, many users inappropriately assume tabularized lengths of crop growth stages as universally applicable, hence creating an unnecessary source of error that should not be attributed to insufficiencies in FAO56. A progressively adopted solution is the use of cumulative degree days-based regression equations to estimate crop growth stages when not observed.

The tabularized values for K_c in FAO56 represent ET rates under optimal, well-watered conditions. In the common field practice, crop conditions are often non-optimal due to inadequacies in irrigation, crop density, salinity and soil or agronomic management. It results an actual ET_c ($ET_{c\ act}$) smaller than the ET_c as computed from standardized K_c values, i.e., ET_c

$_{act} < ET_c$ with $K_{c\ act} < K_c$. Therefore, it is common that field observed actual K_c is smaller than tabularized standard K_c, not due to insufficiencies in FAO 56 tables but due to field stresses affecting crop ET, thus $K_{c\ act} = K_s\ K_c$ where K_s is a stress coefficient. The same concept applies to the dual K_c but K_s applies only to K_{cb}, thus with $K_{c\ act} = K_s\ K_{cb} + K_e$. The concepts of potential and actual K_c, K_{cb} and ET_c and related terminology are progressively being accepted and are key to the transferability of K_c and K_{cb} values. Meanwhile, relative to fruit trees and vines, an update and extension of K_c and K_{cb} values was made by Allen and Pereira (2009) to consider crop density and height.

The dual K_c approach requires a soil water balance of the root zone for computing K_s and of the evaporation layer for computing K_e, the latter depending upon the fraction of ground cover by vegetation (Allen et al. 1998, 2005). Therefore it requires modeling. The dual K_c is of great interest for incomplete cover crops - fruit trees and vines -, for other crops during periods where the soil is not fully covered by vegetation, and when the soil fraction wetted by irrigation is reduced as for drip irrigation. It is also of interest to better distinguish the effects of salinity on transpiration and soil evaporation (Rosa et al. 2016). Recently, Kool et al. (2014) reviewed ET partition and discussed about related field techniques for measurement of soil evaporation and plant transpiration in addition to assess various modeling approaches. The Shuttleworth and Wallace (1985) S-W model partitions ET based on two Penman–Monteith equations (Monteith 1965), one for the crop and the second for the soil surface. The S-W model is generally considered accurate but difficult to parameterize, and is used as reference to other models. The FAO dual K_c model (Allen et al. 1998, 2005) is the most commonly used as it requires relatively few parameters and the results are generally accurate (Cammalleri et al. 2013) and compare well with the S-W model (Zhao et al. 2015). The simulation model SIMDualKc (Rosa et al. 2012) applies that approach and has been successfully tested against field observations of soil evaporation (Zhao et al. 2013; Gao et al. 2014; Wei et al. 2015), actual transpiration (Paço et al. 2014; Qiu et al. 2015) and eddy covariance measurements (Zhang et al. 2013; Tian et al. 2016). The HYDRUS model (Šimůnek et al. 2016), that is a soil water flux deterministic model designed for simulation of water, heat and solute transport, and which accuracy depends upon soil parameterization and boundary conditions, was tested together with the dual K_c soil water balance model SIMDualKc for partitioning ET under saline stress. Both models performed similarly well and accurately distinguished the effects of salinity on transpiration and soil evaporation (Rosa et al. 2016).

The use of remote sensing approaches to estimate actual ET of crops is of particular interest and its use will develop in future. One approach is to perform the remote sensing energy balance using models like SEBAL (Bastiaanssen et al. 2005), METRIC (Allen et al. 2007b, 2011c), SEBS (Elhag et al. 2011) and the two-source algorithm (Cammalleri et al. 2012; Neale et al. 2012). These models provide for good accuracy of $ET_{c\ act}$ estimation and their results combine well with a soil water balance for the daily estimation of $ET_{c\ act}$ (Santos et al. 2008; Neale et al. 2012; Paço et al. 2014). An alternative is deriving satellite-based $ET_{c\ act}$ when computing K_c or K_{cb} from vegetation indices, generally NDVI and SAVI (Gontia and Tiwari 2010; Glenn et al. 2011; Mateos et al. 2013; Pôças et al. 2015), which may be easily associated with water balance modeling since the ET estimation accuracy is appropriate for irrigation scheduling.

4.3 Irrigation Scheduling and Management

Appropriate irrigation scheduling (IS) is essential to achieve good yields and profits, efficient water use and controlling environmental impacts of irrigation. Since long (Feinerman and

Falkovitz 1997), it is known that fertilizer scheduling could be associated with IS, so contributing for higher yields and control of nitrates pollution and GHG emissions. The frequency of irrigation may be based on farmers' knowledge or supported by observations of plant water status (Jones 2004) and/or soil water monitoring (Jones 2007), as well as remote sensing plant water status (Pôças et al. 2017). Moreover, farmers advising on IS are often supported by models (Lorite et al. 2012), including in combination with remote sensing information (Vuolo et al. 2015). These approaches require decision on irrigation depths to be applied that is generally provided through models or automated devices. The use of these technologies, which comprise a vast panoply of measuring and wireless transmission devices, is known as precision irrigation and is used by commercial farms, namely tree and vine crops, and with pressurized irrigation, very often automated. IS options depend upon the soil water holding capacity, the type of crops – e.g., vegetables vs. cereals -, the irrigation system – infrequent irrigation with large depth for surface irrigation, which oppose to frequent irrigation and small depths for center-pivots and micro-irrigation as formerly reviewed (Pereira 1999; Pereira et al. 2002, 2009). Moreover, IS options depend upon the quality requirements of food crops, mainly those dictated by the consumers' preferences and industry, as well as water availability, which may dictate the adoption of deficit irrigation (Pereira et al. 2009).

The application of optimized IS depends upon the timing, duration, flow-rate and pressure of water supply or delivery schedule (Pereira 1999). A farmer is free to build the IS more appropriate to his crop, soil and irrigation system when he owns the water source or water rights adequate to his farming. When a farm is supplied by a collective conveyance and distribution system, then IS depends upon the local conditions for delivery scheduling (DS). When the service is through a canal system, DS is often by rotation, thus with restrictions in deliveries frequency, duration and flow-rate; IS is then controlled by the irrigation system managers and only infrequent irrigation may be practiced. Meanwhile, adopting low pressure pipes distribution and modifications in outlets, DS may become more flexible, anyway constrained in terms of duration and flow-rate; then, using private pumps, pressurized farm irrigation - sprinkler or micro-irrigation - can be used. When pressurized distribution systems are adopted DS is generally on-demand and constraints resume to flow-rate and pressure; farmers are then free to select the irrigation system and IS. However, design characteristics impact the functioning of conveyance and distribution systems (Lamaddalena and Pereira 2007; Córcoles et al. 2015; Khadra et al. 2016) and care in management of collective systems is required to avoid impacts on the functioning and performance of farm irrigation systems (Daccache et al. 2010).

5 Conclusion

The role of water and irrigation to support food security was discussed while considering both the food-water-energy nexus and the food-cropping systems-irrigation nexus. It was evidenced that irrigation may play a dominant role in the FSN contexts despite it varies in space and with the socio-economic and environmental conditions of the populations. It has been clear that increased food crop yields, namely cereals, were much influenced by fertilizers usage, improved crop cultivation practices, energy used in direct and indirect forms, but it was also clear that water and irrigation are paramount for successfully attaining food security and feed the continued growth of the world population. However, it must be stressed that environmental sustainability has to be strongly searched in association with food security.

Progresses observed in irrigation, particularly of food crops, show that there are the base conditions to achieve appropriate FSN: crop evapotranspiration processes are progressively well known with consequent advances in estimating crop water and irrigation requirements; irrigation scheduling has enormously advanced because crops water use is better known and computer modelling may base advice to farmers; remote sensing has great potential to identify the vegetation water conditions and support irrigation management; there are progresses in irrigation methods and in canal and pipe conveyance and distribution systems contributing to improve irrigation and delivery schedules; and the joint water and fertilizers management are providing for controlled impacts of irrigation and to reduce GHG emissions. WARM is contributing to diffuse knowledge on these issues mainly relative to drought and water scarcity challenges and issues, and off farm pressurized systems design, management and energy control. However, a few other challenges require better solutions relative to controlling the increased competition for water between sectors, making fair and transparent the water allocation mechanisms, improving the participation of water actors in water governance, and recognizing and protecting the interests and rights of all users, especially the most vulnerable and marginalized, so developing a new gender paradigm in water use and irrigation and contributing to the welfare of rural communities.

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