Agricultural Water Management 227 (2020) 105832

Contents lists available at ScienceDirect

Agricultural Water Management

journal homepage: www.elsevier.com/locate/agwat

Review

Coping with salinity in irrigated agriculture: Crop evapotranspiration and water management issues

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ARTICLE INFO

Keywords:
FAO56
Correcting Kc for salinity
Leaching requirement
Salinity modeling
Salinity management
Irrigation to cope with salinity
Water and salinity stress coefficient (K_s)

ABSTRACT

Soil and water salinity and associated problems are a major challenge for global food production. Strategies to cope with salinity include a better understanding of the impacts of temporal and spatial dynamics of salinity on soil water balances vis-à-vis evapotranspiration (ET) and devising optimal irrigation schedules and efficient methods. Both steady state and transient models are now available for predicting salinity effects on reduction of crop growth and means for its optimization. This paper presents a brief review on the different approaches available, focusing on the FAO56 framework for coping with the effects of soil salinity on crop ET and yields. The FAO56 approach, applied widely in soil water balance models, is commonly used to compute water requirements, including leaching needs. It adopts a daily stress coefficient (K_s) representing both water and salt stresses to adjust the crop coefficient (K_c) when it is multiplied by the grass reference ET_o to obtain the actual crop ET values for saline environments ($ET_{c\ act} = K_s\ K_c\ ET_o$). The same concept is also applied to the dual K_c approach, with K_s used to adjust the basal crop coefficient (K_{cb}). A review on applications of K_s is presented showing that the FAO56 approach may play an interesting role in water balance computations aimed at supporting irrigation scheduling. Transient state models, through alternative formulations, provide additional solutions for quantification of the salinity build-up in the root zone. These include irrigation-induced salinity, upward movement of salts from saline ground water-table, and sodification processes. Regardless of the approach, these models are now very much capable of supporting irrigation water management in saline stress conditions. For maintaining crop growth under salinity environments, soil-crop-water management interventions consistent with site-specific conditions are then discussed. Adequateness of irrigation methods, cyclic uses of multi-salinity waters and proper irrigation scheduling are further analyzed as examples of efficient means to obviate the effects of salinity.

1. Introduction

Soil and water salinity and associated problems constitute one of the major abiotic constraints in global food production and are particularly critical in semi-arid and arid regions. In regions faced with water scarcity, it is common practice to utilize saline groundwater in irrigated agriculture (Rhoades et al., 1992; Minhas and Gupta, 1992; Hoffman and Shalhevet, 2007; Pereira et al., 2009), and drainage-and waste-waters are increasingly recycled and used for irrigation as well (Tanji and Kielen, 2002; Qadir et al., 2010). However, about 830 million ha of land area are estimated to be afflicted by salinity and sodicity (FAO, 2015), which are increasing every year (Qadir et al., 2014).Thus, there is an increased need for further raising awareness on this issue and for improving management of salt affected soils and of poor quality waters.

The impacts of salinity on crop production and concerns regarding its management have been the focus of several prior comprehensive reviews (Rhoades et al., 1992; Minhas, 1996; Tanji and Kielen, 2002; Hoffman and Shalhevet, 2007; Grattan et al., 2012; Pereira et al., 2014). Strategies for handling salinity usually aim at preventing the build-up of salts in the root zone to levels that limit the root water uptake, controlling the salt balances in the soil–water system by preventing endless accumulation in the root zone, and minimizing the damaging effects of salinity on crop transpiration and soil evaporation for optimal crop growth. Improved understanding of the precise effects of temporal and spatial dynamics of soil salinity is essential for calculating soil water balances (SWB) including evapotranspiration (ET) and

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https://doi.org/10.1016/j.agwat.2019.105832
Received 16 May 2019; Received in revised form 11 September 2019; Accepted 27 September 2019

thereby, devising optimal irrigation schedules and avoiding build-up of soil salinity as proposed in FAO56 (Allen et al., 1998). Of course, factors like ionic chemistry of soil solutions/irrigation waters, soil texture and clay mineralogy, cropping systems and climate require due consideration (Ayers and Westcot, 1985; Minhas and Gupta, 1992). Solutions for estimation/calculation of salt dynamics include different levels of empirical models. Simple steady-state models (Letey et al., 1985; Letey and Feng, 2007; Corwin et al., 2012) assume that salt concentrations vary little with time and space along a field, therefore not affecting SWB calculations, and transient-state models (Wagenet and Hutson, 1987; Šimůnek and Suarez, 1994; Verburg et al., 1996; Pang and Letey, 1998; Ragab, 2002; van Dam et al., 2008; Šimůnek et al., 2016), which are able to account for time-varying field conditions, including soil water dynamics and salinity build-up. Each of the approaches have advantages and disadvantages regarding their applicability to predict long-and short-term impacts of salinity on crop performance and soil properties and to be used as tools in water management decision making. Approaches like that proposed in FAO56 (Allen et al., 1998) play an important role in managing irrigation in saline/sodic environments because, despite using a steady state approach for salinity, these compute the soil water dynamics using transient information as the soil water balance is computed daily (Pereira et al., 2007; Rosa et al., 2016).

The principles to produce crops in saline environments are now well understood and advocate the adoption of special crop-soil-water management practices. Irrigation practices at the field level include methods and frequency of irrigation (Hanson et al., 2006; Pereira et al., 2002, 2009), meeting leaching requirements, and judicious use of multi-quality waters (Rhoades et al., 1992; Minhas, 2012; Pereira et al., 2014). Nevertheless, profit margins tend to be low for agriculture under saline conditions, and saline soils always present a risk for crop failure.

The objectives of this paper consist of reviewing issues referred above, mainly: (i) salinity impacts on soils, crops and the environment, (ii) modelling salinity and leaching requirements, (iii) the FAO56 approach to assess crop ET and its partition when affected by salinity, and (iv) appropriate water and irrigation management issues to cope with salinity in agriculture. The article is divided into six sections: the first is the current introduction; the second refers to reviewing critical issues and impacts of salinity in irrigated agriculture; the third concerns the dynamics of salts in irrigated agriculture and leaching requirements; the fourth focuses onpredicting ET in salt affected agriculture, mainly using the FAO56 approach; the fifth reviews irrigation methods and management to cope with salinity; and conclusions and recommendations are presented in the last section.

2. Critical issues and impacts of salinity in irrigated agriculture

2.1. Edaphic changes affecting crop growth and yield under saline conditions

In agricultural lands, the direct effects of high levels of soluble salts on plant growth and productivity include increased osmotic stress affecting water uptake and ion toxicities or imbalanced accumulation of specific ions, e.g. Cl, Na, etc., in plants. Reduced soil water availability at high salinity causes water deficits in plants, and plant growth becomes inhibited when soil solution concentration reaches a critical level, referred to as the threshold salinity (Maas and Hoffman, 1977). Under field situations, the first reaction of plants when exposed to high salinity is reduced germination, but the most conspicuous effect is the growth retardation of crops. Generally, the detrimental effects of salinity include reduced initial water uptake and growth resulting in smaller plants. These salt-affected smaller plants with less leaf area and even root growth, in turn are able to transpire less water and therefore produce fewer assimilates for productive growth. Though the translocation of once developed assimilates may remain unaffected by salinity, their lower synthesis can lead to impairment of crop yields and yield contributing attributes.

In addition to ionic composition of soil solutions and ion specific affects, the complex interaction of soil solution-exchange phases can also change root zone chemistry and alter hydro-physical and biological behaviour. The soil physical properties and processes that play important roles in crop growth under sodic conditions include soil-water relations and structural stability. High sodium saturation of the exchange complex; often monitored in terms of exchangeable sodium percentage (ESP) and pH leads to dispersion of soil colloids that affects the movement of water and air. Generally soils having natric horizons with ESP $>$ 15% are rated as sodic. However, for heavy textured soils with shrinking-swelling clays the critical ESP is lower, ranging between 6 and 14%, and soils are classified as strongly sodic when having an ESP of 15% or more (Minhas, 2010; Rengasamy, 2016). Sodic soils become prone to formation of surface crusts, which impact the emergence of seedlings, favour water stagnation, reduce infiltration and cause anoxic conditions. Root growth in such "hard setting" soils is impaired and roots fail to proliferate in to deeper soil layers. Dispersion and swelling of clays reduces pore sizes, which not only affects water storage capacity but also reduces unsaturated hydraulic conductivity and restricts root water extraction. With deterioration of soil structure and restricted movement of water, more salts are retained in the surface soil which can cause difficulties in tillage and sowing operations (Oster and Jaywardane, 1998; Minhas et al., 2004). Additionally, sodicity causing pH $>$ 9 is expected to increase toxicities of microelements including Fe, Al, Mn, etc. (Setter et al., 2009). In saline-sodic soils, osmotic effects are prevalent along with ion toxicities dominated by bicarbonate and carbonate. Soil structural problems induce water-logging once the surface salts are leached, e.g. with low electrolyte rainwater. The moved-in clays in plow-sole become a sort of permanent throttle for downward movement of water in saline-sodic soils especially under irrigation with high soil adsorption ratio (SAR) or residual alkalinity waters (Minhas et al., 2019).

All the above conditions and potential salinity/sodicity impacts in the soil environment have implications on irrigation and drainage management. Under saline conditions, irrigation should aim at maintenance of sufficiently high soil water potential and cause salt leaching in the soil profile. For this, frequent irrigation events and regimes providing leaching requirements (as discussed in Sections 2 and 5) are usually advocated. When salinity is associated with shallow and saline groundwater, provisions for surface/sub-surface drainage systems further help in aeration, lateral water flows for salt removal and trafficability. Possibilities of sub-irrigation have emerged where water-table can be controlled such to promote upward movement of water to the root zone where it can be taken up (Ayars, 2012).

Clay dispersion and associated decline in aeration porosity and water infiltration in high ESP and pH soils also result in temporary water-logging during irrigation events. Such conditions especially prevail during monsoon/Mediterranean rains when infiltration of low electrolytic rainwater is prevalent. The replacement of Na with favourable cations like Ca improves soil-water relations. However, during initial years of reclamation, sub-soil sodicity may continue to restrict root growth and therefore smaller but frequent irrigation events are usually recommended. In saline-sodic soils, salts held back by the blockage of water conducting pores due to dispersion of soil particles increase the water required for leaching (Minhas, 2010). Since these soils are also characterised with lower intake rates of water and reduced profile-water storage, smaller but frequent irrigation inputs are recommended for meeting crop water requirements and salt leaching may be effective when restricted to non-crop periods.

2.2. Leaching requirements

The traditional salinity management approach (Richards, 1954) assumed the existence of long-term steady state conditions and indicated that the economical way to control soil salinity is to ensure net downward flow of water through the root zone. Assuming salt uptake by crops to be negligible, ET as a distillation process, and no chemical reactions, leaching requirement was computed (Ayers and Westcot, 1985) as:

$$LR = \frac{EC_{iw}}{5\,EC_e - EC_{iw}} \tag{1}$$

where EC_{iw} and EC_e are the electrical conductivity of the irrigation water and saturated extract of the soil, respectively. For Eq. (1), the water extraction patterns of 40-30-20-10 percent are typically assumed from the upper to lower quarters of the root zone. The EC_e values are for acceptable yields (70–90%) and not for the potential (100%) yield.

The concept of a leaching requirement is logical for cases of seasons without rainfall, like in Mediterranean summers or fairly arid regions where the assumption of steady state conditions is reasonable. However, under field conditions where rainfall can be significant immediately prior to or during the crop season, e.g. under monsoonal conditions, the concentration of rains within 2–3 months (July–September) is the main uncontrolled factor causing non-steady state salinity. The rains mobilize and move salts downwards as infiltration through the soil occurs and rainwater is stored in the soil profile until it either gets mixed with additional applied irrigation water or consumed by crops. This implies that, when rainfall distribution does not favour steady state conditions, the use of the LR Eq. (1) may not be practicable and suggests the need for additional approaches.

The fraction of salt leached depends on soil texture; e.g. for the removal of 80% of the salts, 1.85,0.95 and 0.76 cm rain water per cm soil depth were required in fine, medium-and coarse-textured soils respectively (Minhas and Gupta, 1992). In addition to rainfall taking care of a part of leaching, surface irrigation systems are often quite inefficient. Farm irrigation efficiency typically reaches only 60–70% and thus inadvertently provides for the leaching requirements, albeit not necessarily uniformly across a field. Moreover, the leaching requirement concept may also not work where shallow and saline water-tables exist unless drainage is provided to export the salts and to avoid additional root zone salt content from upward flux from ground water. Leaching should be synchronized with the salt tolerance of crops such that salinity damage is minimized at sensitive crop stages.

Another strategy is to practice leaching just before the onset of rains for increasing antecedent moisture contents and to reduce salinity levels in soils even with saline waters where $EC_e > EC_{iw}$, so as to increase the salt leaching with rain (Minhas and Gupta, 1992). Similarly, Forkutsa et al. (2009) supported that pre-season leaching should be preferred to mid-season leaching under shallow water-table conditions. In North China, a irrigation is commonly applied in autumn, before soil freezing, mainly to leach salts and, in addition, to improve soil structure and store water for crop use in early spring (Feng et al., 2005; Pereira et al., 2007). Even when irrigation waters have residual alkalinity, the sodification of soils increases when large leaching fractions (LF) are maintained. For example, Minhas and Sharma (2006) reported that very high quantities of irrigation water (LF 0.6 – 0.8) applied to rice-wheat cropping system resulted in faster and higher (1.8 fold) sodification, especially of surface soil, when compared with upland crops such as cotton, maize, and pearl millet in rotation with wheat.

2.3. Salt-tolerance of agricultural crops and modifying factors

Salt tolerance refers to the ability of a plant to withstand a concentration of soluble salts in the soil solution without hampering its normal growth. This level, known as the threshold salinity of the soil, is crop specific (Maas and Hoffman, 1977). Usually, the concentration of soluble salts (salinity) in the soil is highly dynamic and requires frequent monitoring, and therefore is complex to relate with plant growth throughout the crop cycle. The salinity of root zone soil, measured as EC_e, has been commonly accepted as a representative and comparable measure of spatio-temporal root zone salinity. Tolerance of different plants to salinity varies a great deal, almost 10 fold, amongst crop species and, to a lesser extent, amongst their genotypes. Salinity response functions (Fig. 1) were traditionally and are still commonly computed by a piecewise linear response equation (Maas and Hoffman, 1977) as:

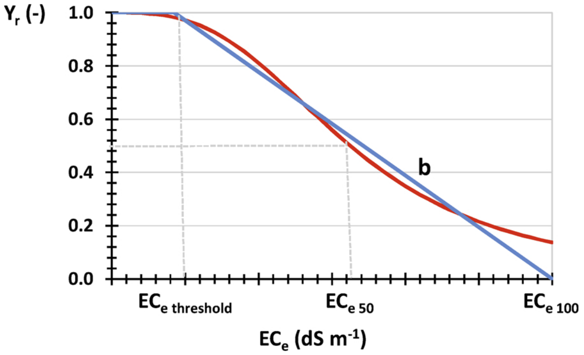

Fig. 1. Most common response functions (Maas and Hoffman, 1977; van Genuchten and Hoffman, 1984) used to describe crop tolerance to soil salinity (Y_r, relative yield; EC_e, electrical conductivity of the soil saturation extract; $EC_{e\ threshold}$, EC_e value above which yield begins to decrease; $EC_{e\ 50}$ and $EC_{e\ 100}$, EC_e value at which crop yield is reduced by 50 and 100%, respectively; b, rate of reduction of yield per unit increase in EC_e).

$$Y_r = 100 - b(EC_e - EC_{e\,threshold}) \tag{2}$$

where Y_r is relative yield i.e. ratio of the actual to the maximum yield (Y_a and Y_m, kg ha^{-1}), $EC_{e\ threshold}$ is the threshold salinity (dS m^{-1}), and b is the rate reduction in yield per unit increase in EC_e (% per dS m^{-1}). The EC_e in this case is the time and root zone averaged saturated paste EC. Threshold and slope values relative to Eq.2 are presented in several publications (Ayers and Westcot, 1985; Maas and Hoffman, 1977; Maas, 1990; Allen et al., 1998; Maas and Grattan, 1999; Katerji et al., 2000; Hoffman and Shalhevet, 2007; Grieve et al., 2012). These are included in Table 1. Besides this piecewise linear function, various non-linear models have been proposed to relate crop yield to salinity (van Genuchten and Hoffman, 1984):

$$Y_r = \frac{100}{1 + \left(\frac{EC_e}{EC_{e50}}\right)^{P_{Yr}}} \tag{3}$$

$$Y_r = \exp(\alpha\, EC_e - \beta\, EC_e^2) \tag{4}$$

Eqs. (3) and (4) represent sigmoid and exponential functions where P_{Yr}, α and β are empirical parameters and EC_{e50} is the EC_e at which the yield is reduced by 50%, which is also given in Table 1 for several crops. Later, Steppuhn et al. (2005) introduced a salinity tolerance index (ST_{Index}) as an indicator for crop's inherent tolerance defined as:

$$ST_{Index} = EC_{e50} + P_{Yr} EC_{e50} \tag{5}$$

Data sets utilized for developing salt tolerance parameters were often generated under steady-state conditions where different salinities were created either by varying the salt inputs, or growing the crops in non-saline conditions until their establishment, and then rapidly exposing them to a specified salinity that was kept almost uniform with depth by maintaining about 50% leaching fraction (LF) at each irrigation event. Because of frequent irrigation, fluctuations in osmotic and matric potentials were minimized. Therefore, the salt tolerances are usually defined in relative rather absolute terms, which do provide for general guidelines for selecting crops under particular salinity conditions. Under field conditions, distribution of salts is neither uniform with soil depth nor constant with time. The non-uniformity of salinity distribution is usually affected by both irrigation and leaching practices designed to control salt gradients in the root zone, and by the amount and patterns of rainfall. For example, concentration of rainfall events in short period under both monsoonal (summer) and Mediterranean (winter) climates leads to seasonal displacement of surface accumulated

Table 1
Salt tolerance of common agricultural crops.
Source: Adapted from Allen et al. (1998); Ayers and Westcot (1985) and Grieve et al. (2012).

Crop		$EC_{e\ \text{threshold}}$ (dS m^{-1})	$EC_{e\ 50}$ (dS m^{-1})	b (% / dS m^{-1})	Rating
a. Small vegetables					
Broccoli	*Brassica oleracea* L. (Botrytis group)	1.3-2.8	8.2	9.2-15.8	MS
Brussels sprouts	*Brassica oleracea* L. (Gemmifera group)	1.8	–	9.7	MS
Cabbage	*Brassica oleracea* L. (Capitata group)	1.0-1.8	7.0	9.8-14.0	MS
Cauliflower	*Brassica oleracea* L. (Botrytis group)	1.5-1.8	–	6.2-14.4	MS
Celery	*Apium graveolens* L.	1.8-2.5	9.9	6.2-13.0	MS
Lettuce	*Lactuca sativa* L.	1.3-1.7	5.1	12.0-13.0	MS
Onion	*Allium cepa* L.	1.2	4.3	16.0	S
Purslane	*Portulaca oleracea* L.	6.3	–	9.6	MT
Spinach	*Spinacia oleracea* L.	2.0-3.2	8.6	7.6-16.0	MS
Swiss chard	*Beta vulgaris* L. (Cicla group)	7.0	–	5.7	T
Radish	*Raphanus sativus* L.	1.2-2.0	5.0	7.6-13.0	MS
b. Vegetables - Solanum Family (*Solanaceae*)					
Egg Plant	*Solanum melongena* L.	1.1	–	6.9	MS
Pepper	*Capsicum annuum* L.	1.5-1.7	5.1	12.0-14.0	MS
Tomato	*Lycopersicon esculentum* L.	0.9-2.5	7.6	9.0-9.9	MS
c. Vegetables Cucumber Family (*Cucurbitaceae*)					
Cucumber	*Cucumis sativus* L.	1.1-2.5	6.3	7.0-13.0	MS
Melon	*Cucumis melo* L.	1.0	–	8.4	MS
Pumpkin, winter squash	*Cucurbita moschata* Poir	1.2	–	13.0	MS
Squash, Zucchini	*Cucurbita pepo* L.var *melopepo* (L.) Alef.	4.7-4.9	10.0	10.0-10.5	MT
Squash (scallop)	*Cucurbita pepo* L.var *melopepo* (L.) Alef.	3.2	6.3	16.0	MS
Watermelon	*Citrullus lanatus* (Thunb.) Matsum. & Nakai	–	–	–	MS
d. Roots and Tubers					
Artichoke, Jerusalem	*Helianthus tuberosus* L.	0.4	–	9.6	MS
Beetroot	*Beta vulgaris* L. (Conditiva group)	4.0	–	9.0	MT
Carrot	*Daucus carota* L.	1.0	4.6	14.0	S
Garlic	*Allium sativum* L.	3.9	–	14.3	MS
Parsnip	*Pastinaca sativa* L.	–	–	–	S
Potato	*Solanum tuberosum* L.	1.7	5.9	12.0	MS
Sweet potato	*Ipomoea batatas* (L.) Lam.	1.5-2.5	6.0	10.0-11.0	MS
Turnip	*Brassica rapa* L.	0.9	6.5	9.0	MS
Sugarbeet	*Beta vulgaris* L. (Altissima group)	7.0	15.0	5.9	T
e. Legumes (*Leguminosae*)					
Bean	*Phaseolus vulgaris* L.	1.0	3.6	19.0	S
Bean, mung	*Vigna radiata* (L.) R. Wilcz.	1.8	–	20.7	S
Broadbean (faba bean)	*Vicia faba* L.	1.5-1.6	6.8	9.6	MS
Cowpea	*Vigna unguiculata* (L.) Walp.	4.9	9.1	12.0	MT
Groundnut (Peanut)	*Arachis hypogaea* L.	3.2	4.9	29.0	MS
Pea	*Pisum sativum* L.	1.5-3.4	–	10.6-14.0	S/MS
Soybean	*Glycine max* (L.) Merrill	5.0	7.5	20.0	MT
f. Perennial Vegetables (with winter dormancy and initially bare or mulched soil)					
Artichokes	*Cynara scolymus* L.	6.1	–	11.5	MT
Asparagus	*Asparagus officinalis* L.	4.1	–	2.0	T
Mint	*Mentha spicata* L.	–	–	–	–
Strawberry	*Fragaria sp.* L.	0.75-1.5	2.5	11.0-33.0	S
g. Fibre crops					
Cotton	*Gossypium hirsutum* L.	7.7	17.0	5.2	T
Flax	*Linum usitatissimum* L.	1.7	5.9	12.0	MS
Kenaf	*Hibiscus cannabinus* L.	8.1	–	11.6	T
h. Oil crops					
Castorbean	*Ricinus communis*L.	–	–	–	MS
Crambe	*Crambe abyssinica* Hochst. ex R.E. Fries	2.0	–	6.5	MS
Lesquerella	*Lesquerella fenderli* (Gray) S. Wats.	6.1	–	19	MT
Rapeseed	*Brassica sp.*L.	9.7-11.0	–	13-14	T
Safflower	*Carthamus tinctorius* L.	–	–	–	MT
Sunflower	*Helianthus annuus* L.	4.8	–	5.0	MT
i. Cereals					
Barley	*Hordeum vulgare* L.	8.0	18.0	5.0	T
Oats	*Avena sativa* L.	–	–	–	MT
Maize	*Zea mays* L.	1.7	5.9	12.0	MS
Maize, sweet	*Zea mays* L.	1.7	5.9	12.0	MS
Millet	*Setaria italica* (L.) Beauvois	–	–	–	MS
Rice	*Oryza sativa* L.	3.0	7.2	12.0	S
Rye	*Secale cereale* L.	11.4	–	10.8	T
Sorghum	*Sorghum bicolor* (L.) Moench	6.8	9.9	16.0	MT
Triticale	*X Triticosecale* Wittmack	6.1	–	2.5	T
Wheat	*Triticum aestivum* L.	6.0	13.0	7.1	MT
Wheat, semidwarf	*Triticum aestivum* L.	8.6	–	3.0	T
Wheat, durum	*Triticum turgidum L. var. durum Desf.*	5.7-5.9	15.0	3.8-5.5	T
j. Forages					
Alfalfa	*Medicago sativa* L.	2.0	8.8	7.3	MS
Barley (forage)	*Hordeum vulgare* L.	6.0	13.0	7.1	MT

(*continued on next page*)

Table 1 (*continued*)

Crop		$EC_{e\ threshold}$ (dS m^{-1})	$EC_{e\ 50}$ (dS m^{-1})	b (% / dS m^{-1})	Rating
Bermuda	*Cynodon dactylon* (L.) Pers.	6.9	15.0	6.4	T
Clover, Berseem	*Trifolium alexandrinum* L.	1.5	10.0	5.7	MS
Clover	*Trifolium sp.* L.	1.5	5.7	12.0	MS
Cowpea (forage)	*Vigna unguiculata* (L.) Walp.	2.5	7.1	11.0	MS
Fescue, tall	*Festuca elatior* L.	3.9	12.0	5.3-6.2	MT
Foxtail	*Alopecurus pratensis* L.	1.5	6.7	9.6	MS
Hardinggrass	*Phalaris tuberosa* L. var. *stenoptera* (Hack) A. S. Hitchc.	4.6	11.0	7.6	MT
Lovegrass	*Eragrostissp.* N. M. Wolf	2.0	8.0	8.4	MS
Maize (forage)	*Zea mays* L.	1.8	8.6	7.4	MS
Orchardgrass	*Dactylis glomerata* L.	1.5	9.6	6.2	MS
Rye (forage)	*Secale cereale* L.	7.6	–	4.9	T
Rye-grass (perennial)	*Lolium perenne* L.	5.6	12.0	7.6	MT
Sesbania	*Sesbania exaltata* (Raf.) V.L. Cory	2.3	9.4	7.0	MS
Sphaerophysa	*Sphaerophysa salsula* (Pall.) DC	2.2	9.3	7.0	MS
Sudangrass	*Sorghum sudanense* (Piper) Stapf	2.8	14.0	4.3	MT
Trefoil, narrow leaf birdsfoot	*Lotus corniculatus* var tenuifolium L.	5.0	10.0	10.0	MT
Trefoil, big	*Lotus pedunculatus* Cav.	2.3	–	19.0	MS
Vetch, common	*Vicia angustifolia* L.	3.0	7.6	11.0	MS
Wheat (forage)	*Triticum aestivum* L.	4.5	–	2.6	MT
Wheat, Durum (forage)	*Triticum turgidum L. var. durum Desf.*	2.1	–	2.5	MT
Wheatgrass, tall	*Agropyronelongatum* (Hort) Beauvois	7.5	19.0	4.2	T
Wheatgrass, fairway crested	*Agropyroncristatum* (L.) Gaertn.	7.5	15.0	6.9	T
Wheatgrass, standard crested	*Agropyronsibiricum* (Willd.) Beauvois	3.5	16.0	4.0	MT
Wildrye, beardless	*Elymus triticoides* Buckl.	2.7	11.0	6.0	MT
k. Sugar cane	*Saccharum officinarum* L.	1.7	10.0	5.9	MS
l. Tropical Fruits and Trees					
Banana	*Musa acuminata* Colla	–	–	–	MS
Coconut	*Cocos nucifera* L.	–	–	–	MT
Coffee	*Coffea sp.*L.	–	–	–	–
Date Palm	*Phoenix dactylifera* L.	4.0	18.0	3.6	T
Pineapple	*Ananas comosus* (L.) Merrill	–	–	–	MT
Tea	*Camellia sinensis* (L.) Kuntze	–	–	–	–
m. Grapes and berries					
Blackberry	*Rubus macropetalus* Doug. ex Hook	1.5	3.8	22.0	S
Boysenberry	*Rubus ursinus* Cham. and Schlechtend	1.5	3.8	22.0	S
Grape	*Vitis vinifera* L	1.5	6.7	9.6	MS
Hops	*Humulus lupulus*L.	–		–	–
n. Fruit trees					
Almond	*Prunus duclis* (Mill.) D.A. Webb	1.5	4.1	19.0	S
Avocado	*Persea americana* Mill.	–	–	–	S
Citrus (Grapefruit)	*Citrus x paradisi* Macfady	1.2-1.8	4.9	13.5-16.0	S
Citrus (Orange)	*Citrus sinensis* (L.) Osbeck	1.3-1.7	4.8	13.1-16.0	S
Citrus (Lemon)	*Citrus limon* (L.) Burm. f.	1.5	–	12.8	S
Citrus (Lime)	*Citrus aurantiifolia* (Christm.) Swingle	–	–	–	S
Citrus (Pummelo)	*Citrus maxima* (Burm.)	–	–	–	S
Citrus (Tangerine)	*Citrus reticulata* Blanco	–	–	–	S
Deciduous orchard					
Apple	*Malus sylvestris* Mill.	–	–	–	S
Peach	*Prunus persica* (L.) Batsch	1.7	4.1	21.0	S
Cherries	*Prunus spp.*	–	–	–	S
Pear	*Pyrus communis* L.	–	–	–	S
Apricot	*Prunus armeniaca* L.	1.6	–	24.0	S
Plum, prune	*Prunus domestica* L.	1.5-2.6	4.3	18.0-31.0	S/MS
Pomegranate	*Punica granatum* L.	–	–	–	MT
Guava	*Psidium guajava* L.	4.7	–	9.8	MT
Olive	*Olea europaea* L.	–	–	–	MT

$EC_{e\ threshold}$, EC_e value above which yield begins to decrease; $EC_{e\ 50}$, EC_e value at which crop yield is reduced by 50%; b, rate of reduction is yield per unit increase in EC_e;S, sensitive; MS, moderately sensitive; T, tolerant; MT, moderately tolerant.

salts to deeper soil depths, and thereby reduced salinity in the seeding zone benefitting establishment of following crops in well-drained soils. However, inverted salinity profiles develop with the movement of salts toward the surface during rainless periods, especially in high water table areas or in cases where deficit irrigation is practiced. Similar processes were observed when pre-freezing autumn irrigation is practiced (Feng et al., 2005). Again, the rate of salinization during irrigation of crops and final salinity build-up vary depending upon the salt loads of irrigation waters, conjunctive use modes of fresh and saline waters, precipitation, irrigation needs and methods, leaching fractions, root water extraction patterns of crops, and even with soil structural changes due to sodic conditions.

Plants are also known to exercise control over root growth and adjust to meet water requirements consistent with water availability vis-à-vis salinity distribution in different soil zones. To explain the complexities of soil-water-salt interactions under spatial and temporal variations in salinities in the root-zone, the concepts put forward include: i) growth responds to the mean salinity of the root-zone (Shalhevet and Bernstein, 1968; Bower et al., 1969; Ingvalson et al., 1976; Meiri, 1984; Shalhevet, 1994), ii) growth responds to a weighted-mean salinity of the root-zone (either water uptake-weighted mean or root (dry matter, DM)-weighted mean salinity (Bernstein and Francois, 1973; Dirksen, 1985; Minhas and Gupta, 1993a), and iii) the most saline part of root zone controls growth (Ayars et al., 2012). Paradigms of mean root zone salinity have been mainly based upon analysis of experiments in pots, lysimeters, and fields for steady state conditions (Meiri and Plaut, 1985). However, plants usually have control mechanisms for adjusting their root growth to site-specific conditions and their ability to extract water according to local conditions. If there is enough water available locally in non-saline conditions, it will be compensatively taken up, in spite of the presence of potentially stress-causing conditions in other locations in the same root zone (Jarvis, 1989; Šimůnek and Hopmans, 2009; Peters, 2016). For situations representing non-steady state conditions, Minhas and Gupta (1993a) evaluated responses of wheat to vertically variable salinity at planting which were superimposed by different patterns and rates of salinization. Although the total salt with which the wheat roots interacted during the growth period was kept constant, there were three-fold variations in wheat yield. Grain yield was best related to weighted mean salinity, calculated in proportion to the root mass or water uptake in each soil zone rather than the simple mean. Independent estimates of response to salinity that existed down to rooting depth at different stages of wheat showed EC_{e50} to increase from 9.1 dS m^{-1} until crown rooting to 13.2 dS m^{-1} at dough stage indicating that wheat became progressively more tolerant as it grew older. It is thus implied that for non-steady state conditions, as commonly exist under field conditions, both the initial distribution of salinity in soil profiles along with the modes of salinization need to be considered for effective description of crop response to salinity. Nevertheless, proper protocols for predicting plant responses are still awaited in order to apply them to cases of heterogeneous, both vertical and horizontal, and temporal salinity.

Table 2
Modifications in salinity tolerance with management and other factors.
Source: Adapted from Minhas (1996).

Modifying factor	Crop	Salinity considered	$EC_{e\ 50}$ (dS m^{-1})
Growth stages	Wheat	Time averaged	16.0
		Sowing time	9.7
		Mid season	11.9
		Harvest time	16.7
	Mustard	Time averaged	9.7
		Sowing time	8.0
		Mid season	9.4
		Harvest time	17.1
	Maize	Constant salinity	10.5
		Increased after tesseling	14.7
Irrigation method	Potato	Sprinkler	5.4
		Drip	10.5
Agro-climate	Wheat	Subtropical (Colder)	16.0
		Tropical (Warmer)	11.0
Soil texture	Wheat	Loamy sand	17.5
		Sandy loam	16.8
		Silty clay loam	12.9
	Mustard	Loamy sand	24.9
		Sandy loam	14.7
		Silty clay loam	12.3
Ionic constituents/applied nutrients			**EC_{iw90}**
EC_{iw} and SAR_{iw}	Wheat	$SAR_{iw} = 5$	7.8
		$=10$	7.6
		$=20$	5.2
		$=30$	3.6
		$=40$	2.2
Anionic ratio and applied P (kg ha^{-1})	Wheat		
	26	$Cl:SO_4 = 0.3$	7.7
		$=3.0$	6.8
		$=5.0$	2.1
	39	$=0.3$	8.9
		$=3.0$	8.8
		$=5.0$	6.7

$EC_{e50}$is the EC_e value at which crop yield is reduced by 50% and EC_{iw90} is the irrigation water salinity for 90% relative yield.

The accumulation of salts *vis-à-vis* their osmotic effects is further modified as a function of soil texture, agro-climatic conditions, ionic constituents of salinity, and soil-irrigation-crop management strategies (Table 2; Minhas, 1996). The impacts of these factors on salt tolerance limits are summarized here:

- Environmental factors like temperature, humidity, etc. that govern evaporative demands also affect salt content of the soil closely adhering to the roots and thus under low ET demands crops show higher tolerance to bulk soil salinity (Sinha and Singh, 1976; Groenveld et al., 2013).
- With increased water retention capacity and decreased rainwater infiltration, the salt concentration factor (EC_e/EC_{iw}) increases with clay content. With further reduction in dilution factor (i.e. lower ratio θ_s/θ_{FC} between soil water content at saturation, θ_s and at field capacity, θ_{FC}), salinity tolerance limits of crops defined in terms of EC_e are usually low in clayey soils (Minhas and Gupta, 1992).
- The constituent cations and anions of salinity modify the crop tolerance by: i) control over precipitation/dissolution reactions and salt leaching through structural changes in soils etc. which ultimately govern the actual salinity of soil solution with which the plant roots interact and ii) cause nutritional imbalances and direct toxicities in the plant tissues. High sodium on exchange complex, pH and dominance of chloride are typical examples of chemical processes essentially affecting salinity tolerance (Chauhan et al., 1991; Singh et al., 1992; Sharma et al., 1993; Minhas, 1996).
- Seedling establishment being the most critical, salinity will prove more deleterious at initial stages and this is followed by the phase changes from vegetative to reproductive, i.e. heading and flowering to seed setting (Minhas and Gupta, 1992; Grieve et al., 2012). Thus, careful irrigation management is required to minimize salinity impacts at these stages.
- Wide variations exist in the inherent salt tolerance of crop cultivars (Minhas and Gupta, 1992). Crop varieties with high yield potential, as well as higher salt tolerances, have been developed following conventional and molecular breeding approaches (Minhas et al., 2019).
- The amount and frequency of rain govern salt dynamics, and ET demands are reduced with increased humidity and reduced radiation during rainfall events (Minhas and Gupta, 1992, 1993a; Allen et al., 1998; Grieve et al., 2012). Therefore, with short-term compensation in water uptake, crops get a boost to offset the effects of salinity.
- The modes of irrigation that obviate salinity in seeding zone for crop establishment e.g. pre-plant irrigation with good quality water help in increased salt tolerance in later stages of crop growth (Minhas and Gupta, 1992; Rhoades et al., 1992; Minhas, 1996).
- With modifications in the patterns of salt distribution and maintenance of constantly higher matric potentials, drip irrigation system enhances crop threshold limits of salt tolerance (Meiri and Plaut, 1985; Grieve et al., 2012).

2.4. Environmental impacts

Salinity affected soils, in addition to their profound impacts on long-term sustainability of agriculture, also lead to a number of environmental quality concerns like anthropogenic impacts of soil, water and air that can negatively affect human and ecological health. For utilisation of these soils for crop production, the first requisite is to lower the salinity to within acceptable levels, which is accomplished through either the displacement of salts below the root zone or laterally with provision for removal with drainage in soils with a shallow water-table. The salts removed ultimately make their way into either or both subsurface and surface water resources; often degrading water resources utilized for agriculture downstream. A major problem related to salt leaching in arid zones, where large quantities of water are introduced,

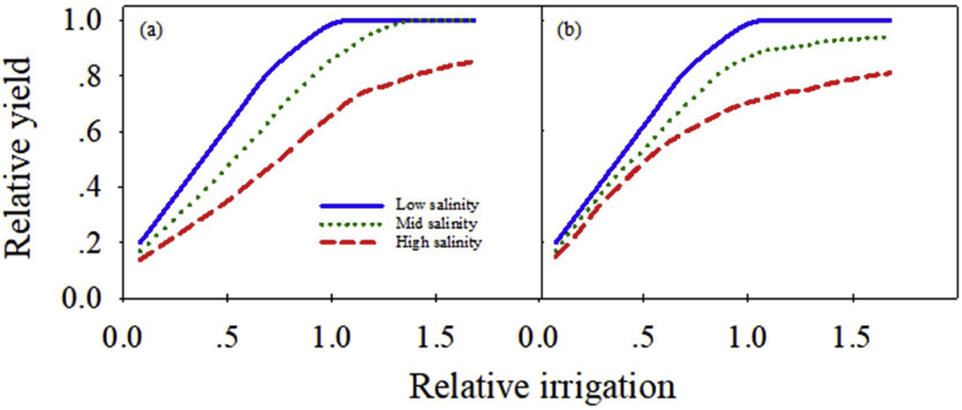

Fig. 2. Schematic illustration of water production functions (relative yield response to combined water availability and salinity) for varied irrigation water salinities according to (a) additive-compensative, and (b) multiplicative-compensative approaches. Based on Shani et al. (2005).

involves the accumulation of salts in the groundwater. Eventually (sometimes very quickly), the saline water table rises, intruding into the root zone (Beltrán, 1999). Even when aquifers are deep or rivers are distant, the salts in arid zones eventually may make their way to water resources and become problematic. When salts are associated with sodicity, the soils become dispersive to generate colloidal suspensions, which become mobilised in the environment, posing a major threat to water quality in streams and drainage waters (Rengasamy, 2016). Additionally, colloidal particles can transport adsorbed heavy metal ions including selenium and cadmium, pesticides and other anthropogenic organic compounds that may be present.

A more modern enigma, particularly when irrigating with recycled wastewater containing nutrients, but also relevant whenever fertilization is combined with saline water, is the paradox between nutrients, especially nitrogen, and salinity control. In their study under Mediterranean conditions, Libutti and Monteleone (2017) pointed out that since soil salinity control is bound to increase nitrogen leaching, operational criteria should optimize the volumes needed to reduce salinity and those necessary to protect groundwater from nitrate contamination. They suggested a "decoupling" strategy where nitrogen is applied only when needed and when leaching due to rainfall is unlikely, and where salt leaching is concentrated in less sensitive seasons, maximizing the utilization of natural precipitation. It is obvious that such coupled nutrient-salt management to minimize the salinity-nitrogen leaching paradox will be specific to location, crop, and particularity of salinity.

Irrigated agriculture in dry regions often employs drainage water collection systems to facilitate long-term leaching. While drainage collection may facilitate field-scale salinity management, disposal of the collected saline water remains an issue. Leachate contains unwanted salts, excess agricultural additives (including toxic ions, nutrients, herbicides and pesticides) and naturally occurring contaminants that, without irrigation, would not have been mobilized. Proper design of drainage systems, including shallow placement of laterals, have been shown to cause lower drainage volumes and salt loading (Ayars et al., 2006).

2.5. Implications on coping with climate change

Climate change (CC) is expected to impact various sectors of the economy (IPCC, 2014), with agriculture particularly sensitive because crops are profoundly influenced by weather conditions during their life cycles (Phogat et al., 2018; Saadi et al., 2015). Major effects of CC will be on crop water availability due to variation in rainfall amounts, changes in dry spell frequency and intensity and in drought regimes, and expected decrease in rainfall infiltration. In addition, changes in salinity are expected to increase agricultural vulnerability to climate change. Increased temperatures coupled with reduced frequency of rainfall may lead to an increase of salt accumulation in upper soil layers of areas affected by aridity and dryness, and hence affect plant growth (Cullen et al., 2009). Increased risk of intense droughts will induce uncertainty for water availability, thus impacting the sustainability of irrigated agriculture. In addition, CC can variably increase the seasonal irrigation requirement and impact the resultant salinity in the soils. For example, Phogat et al. (2018) predicted a 14–17% increase in irrigation requirement for wine grapes due to changing rainfall and ET dynamics and that salinity could increase by almost three times ($6.04\,\mathrm{dS\,m^{-1}}$) by the turn of 21st century compared to the corresponding baseline salinity during 2000-2015.

3. Dynamics of salts in irrigated agriculture: modeling approaches

3.1. Steady-state models

Steady-state models are based on the assumption that salt concentration and soil-water content are nearly constant for a given place and time period, thus allowing simple representations of soil salinity and crop growth conditions. While in many irrigated systems that assumption can only be valid over sufficiently long time periods (sometimes needing a season or more), in arid regions with no or little rainfall or under protected cultivation, steady-state models have shown to provide reasonable predictions of the crop-water-salinity status in irrigation water management applications.

Any method for evaluating irrigation water amount – salinity – leaching– crop response interactions, ultimately provides salinity-specific water production functions. These functions are useful to visualize agronomic effects of irrigation water salinity, including costs and benefits of leaching. Examples of salinity-specific water production functions, which can be empirical or mechanistic model-based (Hanks et al., 1978; Letey et al., 1985; Letey and Dinar, 1986; Tripler et al., 2012), are shown in Fig. 2 (Shani et al., 2005). While assumptions regarding the character of combined stress-causing factors influence the nature of the curves, they all demonstrate benefit from water applied to remove salts. For example, Fig. 2a follows an additive, compensative approach as in the uptake model of van Genuchten (1987), while Fig. 2b follows a potential flow model where stress-causing reductions to uptake are multiplied (Dudley and Shani, 2003). Their predicted yields differ due to the basic principles and assumptions they are based on but, clearly in both, leaching increases yields when irrigation water is saline.

Model-derived production functions like those in Fig. 2, together with experimentally generated data, can be used to determine leaching requirements (LR) and leaching fractions (LF) for irrigation management. The models, and therefore the water production functions they provide, respond to input parameters including meteorological conditions, soil hydraulics, and crop sensitivity. Examples of analysis of LFs and LRs using such functions are found in Ben-Gal et al. (2008) and Dudley et al. (2008a). Both studies show the importance of considering the effect of salinity on plant transpiration and consequential feed-back between plant water uptake and soil water content and salinity on calculations of LRs. Such solutions, even with their inherent issues of exactness related to the steady state and representative root zone conditions assumptions offer an improved method for calculating LRs compared to traditional equations like that of FAO29 (Eq. 1) (Ayers and Westcot, 1985).

Steady state models may be afflicted by the overestimation of LR (Corwin et al., 2007; Letey et al., 2011; Corwin and Grattan, 2018). They provide also less opportunity to be applied confidently for micro-irrigation systems such as surface or subsurface drip where irrigation water is applied at specific location with high frequency. Under drip irrigation, soil salinity, soil water content, and root density all vary around the drip line, thus resulting uncertainty in calculating the average root zone salinity and thus, the LF (Hanson et al., 2008).These authors used HYDRUS-2D to predict LFs that ranged between 7.7 to 30.9% for applied water (EC_{iw} 0.3 dS m^{-1}) as applied water amounts increased from 60 to 115% of the potential crop evapotranspiration (ET_c) for the EC_{iw} of 0.3 dS m^{-1} irrigation water, even though the water balance method showed no leaching for applied water amounts equal to or smaller than ET_c. This example indicates that appropriate estimation of leaching requires accurate soil water balance and the ability of the used model to adequately estimate deep percolation.

3.2. Transient-state models

Transient state models simulate changes in soil–water content and salinity in the root zone caused by irrigation, rainfall, soil heterogeneity and management options. These changes may refer to timing and amount of irrigation, variable soil salinity conditions, variable crops and crop salinity tolerances, and variable irrigation water quality including rainfall (Cardon and Letey, 1992; Minhas and Gupta, 1993b; Corwin et al., 2007; Letey and Feng, 2007; Oster et al., 2012). This group of models includes, for example, LEACHM (Wagenet and Hutson, 1987), WAVE (Vanclooster et al., 1995), UNSATCHEM (Šimůnek and Suarez, 1994), SWIM (Verburg et al., 1996), ENVIRO-GRO (Pang and Letey, 1998), SALTMED (Ragab, 2002), SWAP (van Dam et al., 2008), and HYDRUS (Šimůnek et al., 2016). Most of these models are based on the numerical solution of the Richards equation for variably-saturated water flow, and on analytical or numerical solutions of the Fickian-based convection–dispersion equation for solute transport. In their simplest one-dimensional forms, these equations are respectively given as follows:

$$\frac{\partial\theta}{\partial t} = \frac{\partial}{\partial z}\left(K(h)\frac{\partial h}{\partial z} - K(h)\right) - S \tag{6}$$

$$\frac{\partial(\theta Rc)}{\partial t} = \frac{\partial}{\partial z}\left(\theta D\frac{\partial c}{\partial z} - qc\right) - Sc \tag{7}$$

where θ is the volumetric soil water content (L^3L^{-3}), h is the soil matric potential (L), t is the time (T), z is the soil depth (L), K is the hydraulic conductivity (LT^{-1}), R is a retardation factor accounting for sorption or exchange (−), c is the solute concentration of the liquid phase (ML^{-3}), D is the solute dispersion coefficient (L^2T^{-1}), q is the Darcy volumetric water flux (LT^{-1}), and S is the sink term accounting for water uptake by plant roots ($L^3L^{-3}T^{-1}$).

The sink term included in both equations is commonly computed using the macroscopic approach introduced by Feddes et al. (1978), wherein crop transpiration (T_c) is distributed over the root zone and may be diminished by the presence of depth-varying root zone stressors, namely water and osmotic stresses (Feddes and Raats, 2004; Skaggs et al., 2006; Šimůnek and Hopmans, 2009):

$$S(h,h_\varnothing, z,t) = \alpha(h,h_\varnothing, z,t)S_p(z, t) = \alpha(h,h_\varnothing, z,t)\,\beta(z, t)T_c(t) \tag{8}$$

where $S_p(z, t)$ and $S(h, h_\phi, z, t)$ are the potential and actual volumes of water removed from the unit volume of soil per unit of time ($L^3L^{-3}T^{-1}$), respectively, β(z, t) is the normalized root density distribution function (L^{-1}), and $\alpha(h, h_\phi, z, t)$ is a prescribed dimensionless function of the soil water (h) and osmotic (h_ϕ) pressure heads ($0 \le \alpha \le 1$). The actual transpiration rate, $T_{c\ act}$ (LT^{-1}), is then obtained by integrating the previous equation over the root domain L_R (L) as follows:

$$T_{c\ act}(t) = \int_{L_R}^{0} S(h,\ h_\varnothing,\ z,\ t)\ \partial z = T_p\int_{L_R}^{0} \alpha(h,\ h_\varnothing,\ z,\ t)\ \beta(z,\ t)\ \partial z \tag{9}$$

Root water uptake reductions due to salinity stress, $\alpha(h_\phi)$, can be computed by considering, for example, the piecewise linear response equation proposed by Maas and Hoffman (1977) or the non-linear functions of van Genuchten and Hoffman (1984), van Genuchten (1987), or Homaee et al. (2002).

Transient-state models are process based, complex, especially 2D and 3D versions, and sophisticated compared to steady state models, and they therefore require more soil, crop and climate parameters for their use to solve water and solute problems in the vadose zone. As an example, in terms of soils characterization, transient-state models require a complete description of soil hydraulic functions, i.e. the soil water retention and soil hydraulic conductivity curves from soil water content at saturation to oven dryness. The determination of these parameters is known to be costly and time-consuming, with issues related to size sampling and representativeness of laboratory measurements often raised when describing actual flow conditions, transport, and reaction processes occurring at the field scale due to limitations in the porous medium continuum. As such, and because these models are based on the solution of non-linear partial differential equations, it is essential to calibrate and validate them for field conditions in order to drive logical outcomes. When run in 2 and 3 dimensions, these models are especially well suited for micro-irrigation systems, which frequently and partially wet the soil surface for precise and localized application of water and fertilizers. Increased adoption of drip irrigation systems, especially in horticulture, vegetables and widely spaced crops, has led to more robust transient models in order to advance understanding of root water uptake and solute dynamics in soil. However, transient state models also apply well to other irrigation systems, namely tosurface irrigation.

3.3. Integrated approaches

Shani et al. (2007, 2009) and Skaggs et al. (2014a) published intermediate models between the above described steady-state and transient-state solutions. These offer mechanism-based, steady-state solutions for water uptake and leaching, capturing essential factors of the soil-plant-atmospheric system as closed form analytical solutions. Differing in some of the soil hydraulic models driving water balance and uptake by roots, both approaches rely on an assumption of steady-state. The Shani et al. (2007, 2009) solution, later named ANSWER (Analytical Salt Water) consists of a water balance, a salt balance, a soil hydraulic model for calculating water content and water movement (Brooks and Corey, 1966), a root water uptake response model (Nimah and Hanks, 1973), and a salinity driven uptake reduction function (van Genuchten and Hoffman, 1984). Skaggs et al. (2014a) presented an alternative pair of steady-state analytical solutions, one for each of the different functional forms of the uptake reduction due to salinity function, based on mass balance and root water uptake from pre-defined density profiles (Hoffman and van Genuchten, 1983; Raats, 1975), with macroscopic potential uptake (transpiration) reduced by the presence of depth-varying stressors (Feddes et al., 1978; Skaggs et al., 2006). The Skaggs et al. (2014a) solutions are explicit, needing no iterations to be solved. Both the Shani et al. (2007, 2009) and Skaggs et al. (2014a) approaches allow the consideration of management (irrigation water quantity and quality), biological (plant response), and physical (soil, water and weather) variables in closed form equations and can therefore be used to evaluate plant response to water and salinity (Skaggs et al., 2014b; Ben-Gal et al., 2008, 2017), determine LRs and LFs (Ben-Gal et al., 2009, 2017), and be coupled to economic models and decision support tools (Ben-Gal et al., 2013; Kaner et al., 2017, 2019). The Shani et al. (2007, 2009) and Skaggs et al. (2014a) models are further consistent with one another and with numerical solutions, as long as the assumption of steady-state conditions remains reasonable. Steady-state conditions have shown to be a reasonable approximation, especially in frequently irrigated systems where irrigation is given at a constant ratio to potential crop ET. Tripler et al. (2012) showed that date palms irrigated according to constant or slowly changing crop factors and ET_o had root zones with quasi-steady state conditions regarding water content and salinity. The advantages of the analytical models are clear; they are much more accessible, requiring modest input data and relatively simple representations of soils and crops, compared to transient-state numerical models.

4. Predicting crop evapotranspiration under saline environments

4.1. The FAO56 approach to crop evapotranspiration as affected by salinity

The FAO56 approach (Allen et al., 1998) consists of the estimation of crop ET as $ET_c = K_c\, ET_o$, i.e., as the product of the crop coefficient (K_c) specific of the crop and of its stage of development by the grass reference ET (ET_o), that is solely a function of the local climate (Pereira et al., 1999). The approach is commonly used in soil water balance models with transient state models usually adopting it for defining the atmospheric boundary conditions. Potential transpiration and soil evaporation can well be estimated with the FAO56 dual K_c approach (Allen et al., 2005). There are different approaches for adjusting the potential values to the actual ones through the computation of the soil water balance (considering the sink term). Models that adopt the $ET_c = K_c ET_o$ approach include, for example, BUDGET (Raes, 2002), ISAREG (Pereira et al., 2003), MOPECO (Domínguez et al., 2011), AQUACROP (Vanuytrecht et al., 2014), and SIMDualKc (Rosa et al., 2012). These models may compute actual ET ($ET_{c\ act}$) by reducing the potential ET_c using a stress coefficient that is function of the soil salinity and of the salinity tolerance of the crop as detailed hereafter. These models are not aimed at describing the salinity dynamics of cropped soils but just at supporting irrigation planning and management while assessing impacts of salinity on crop ET or crop transpiration using the FAO56 salinity stress coefficient described below (Allen et al., 1998). The LF is considered in these models only to adjust irrigation depths to cope with both crop water requirements and the salinity stress; generally, the LF is an input to modeling.

The FAO56 approach computes the soil water balance at the field scale (Fig. 3a) on a daily time step (Allen et al., 1998, 2005):

$$D_{r,i} = D_{r,i-1} - (P - RO)_i - I_i - CR_i + ET_{c\,act,i} + DP_i \tag{10}$$

where D_r is the root zone depletion at the end of day i and day i−1 (mm), P is the precipitation (mm), RO is the runoff (mm), I is the net irrigation depth (mm), CR is the capillary rise from the groundwater table (mm), $ET_{c\ act}$ is the actual crop evapotranspiration (mm), and DP is the deep percolation through the bottom of the root zone (mm), all referring to day i.

The soil water balance is performed for a soil of depth z_r (m) and total available water (TAW, mm). The latter is defined as the water storage in the root zone between the soil water content at field capacity (θ_{FC}, $m^3\,m^{-3}$) and at the wilting point (θ_{WP}, $m^3\,m^{-3}$), thus (Fig. 3a):

$$TAW = 1000\,(\theta_{FC} - \theta_{WP})\,z_r \tag{11}$$

The fraction of TAW that a crop can extract from the root zone without causing water stress is the readily available water (RAW, mm). It is defined as RAW = p TAW (Fig. 3a) where p (−) is the depletion fraction for no stress (p). RAW is the threshold value bellow that the soil water is no longer transported fast enough towards the roots to respond to the transpiration demand; thus, when depletion exceeds the fraction p the crop begins to experience stress. Designating θ_p as the soil water content when the depletion fraction is p, that value may be used as threshold for water stress corresponding to the water storage RAW.

$ET_{c\ act}$ equals the potential ET_c when the soil water storage is above RAW. Differently, under water stress conditions $ET_{c\ act} < ET_c$ and K_c is reduced with a stress coefficient (K_s, dimensionless) to give

$$ET_{c\,act} = K_s K_c ET_o = K_{c\,act} ET_o = K_s\, ET_c \tag{12}$$

where ET_c is the potential (non-stressed) crop ET (mm), $ET_{c\ act}$ is actual crop ET as affected by water and/or salinity stress (mm), ET_o is the grass reference ET (mm), K_s is the stress coefficient due to soil water deficit and/or to the increase of osmotic potential due to soil and water salinity (not considering other crop stresses that may affect crop water use), K_c is the single crop coefficient (−) relating the evapotranspiration of the crop with that of the reference crop ($K_c = ET_c/ET_o$).

When adopting the dual K_c approach for partitioning ET into transpiration and soil evaporation (Allen et al., 1998, 2005). K_c is the sum of a basal crop coefficient, K_{cb}, that refers to crop transpiration, and a coefficient of evaporation, K_e, relative to soil evaporation ($K_c = K_{cb} + K_e$). Under stress conditions K_s applies to K_{cb} only, thus:

$$ET_{c\,act} = T_{c\,act} + E_s = (K_s K_{cb} + K_e) ET_o = (K_{cb\,act} + K_e) ET_o \tag{13}$$

where K_{cb} is the potential basal crop coefficient (−) referring primarily to crop transpiration although some diffusive soil evaporation may also be included particularly during the initial crop stage, K_e is the evaporation coefficient (−) that describes direct evaporation from the soil surface, $T_{c\ act}$ is the actual crop transpiration (mm), and E_s is the soil evaporation (mm). $T_{c\ act}$ and E_s may therefore be defined as:

$$T_{c\,act} = K_s T_c = K_s K_{cb} ET_o \tag{14}$$

$$E_s = K_e ET_o \tag{15}$$

Where T_c and $T_{c\ act}$ are the potential and actual crop transpiration values (mm). Updates on K_c and K_{cb} tabulated values for most crops are dealt in various papers of this Special Issue.

Soil evaporation (Eq. (15)) is not directly affected by salinity but is indirectly influenced because the fraction of the soil that is both exposed to radiation and wetted by rain and/or irrigation is larger when the crop is stressed. In fact, crops grown under saline conditions are less developed compared to non-stressed crops and have less dense canopies, thus having a smaller fraction of ground shaded by the crop.

The water stress coeficient K_s is expressed as a linear function of root zone depletion (D_r, Eq. (10)) and is calculatedviaa daily soil water balance applied to the entire root zone (Fig. 4) as:

$$K_{s,i} = \frac{TAW - D_{r,i}}{TAW - RAW} = \frac{TAW - D_{r,i}}{(1-p)\,TAW} \tag{16a}$$

$$K_{s,i} = 1 \text{ for } D_{r,i} \le RAW \tag{16b}$$

Under soil salinity conditions, ET fluxes start to be affected when the crop specific soil salinity threshold is attained. Thus, the stress coefficient K_s needs to also consider salinity stress. The FAO56 approach (Allen et al., 1998) defines Ks considering both the yield impacts of water and salinity as:

$$K_{s,i} = \left(\frac{TAW - D_{r,i}}{TAW - RAW}\right)\left(1 - \frac{b}{K_y\,100}(EC_e - EC_{e\,threshold})\right) \tag{17}$$

where K_y is the yield response factor (−) that describes the relationship between the relative yield decrease with the relative evapotranspiration

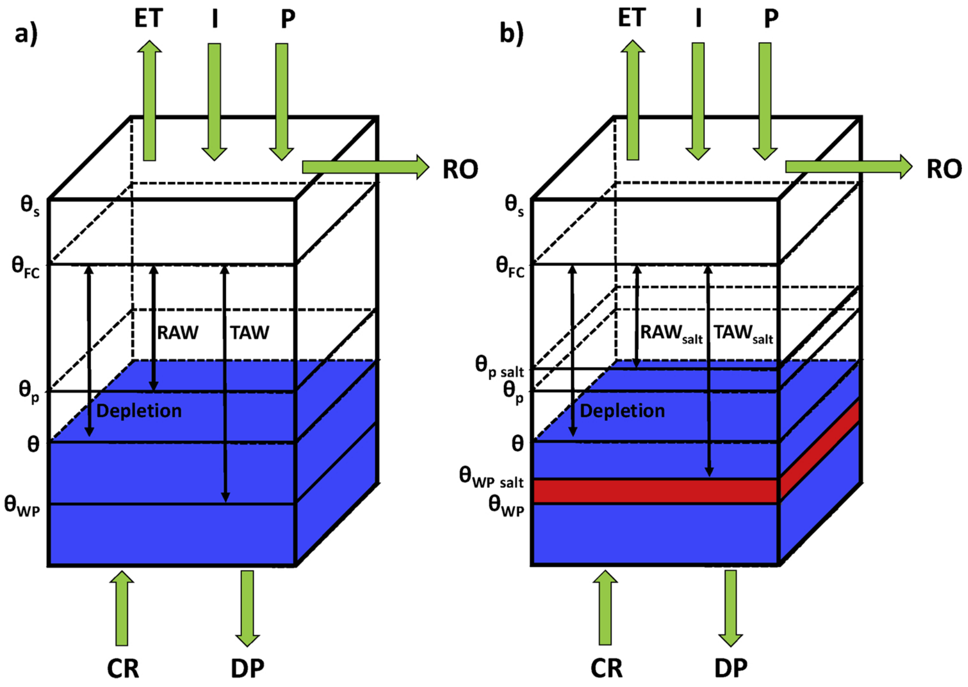

Fig. 3. Water balance of the root zone in: (a) a non- or low-saline environment, and (b) a saline environment (ET, evapotranspiration; I, irrigation; P, precipitation; RO, runoff; CR, capillary rise; DP, deep percolation, θ, soil water content; θ_s, θ_{FC}, θ_p and θ_{WP}, soil water content at saturation, at field capacity, corresponding to the depletion fraction for no stress (p), and at the permanent wilting point, respectively; TAW and RAW, total and readily available water, respectively; the subscript salt is used when variables are adjusted to saline conditions). Based on FAO56 (Allen et al., 1998).

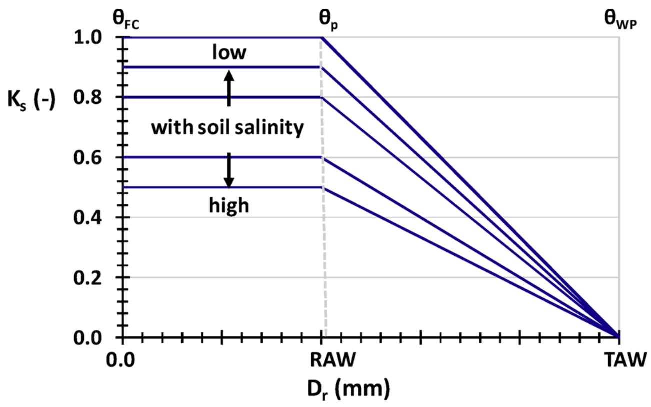

Fig. 4. The effect of soil salinity on the water stress coefficient K_s as described by Allen et al. (1998), where θ_{FC}, θ_p and θ_{WP} are soil water content at field capacity, corresponding to the depletion fraction for no stress p, and at the permanent wilting point, respectively; TAW and RAW, are total and readily available water, respectively; D_r is cumulative depth of water depletion from the root zone.

deficit (Stewart et al., 1977; Doorenbos and Kassam, 1979), $EC_{e\ threshold}$ ($dS\ m^{-1}$) is the soil EC_e value from where crop production starts to be affected by salinity, and b is the percent rate of yield decrease relative to the EC_e excess relative to $EC_{e\ threshold}$ ($\%/(dS\ m^{-1})$). TAW, RAW and $D_{r,i}$ were defined previously. The parameters K_y, $EC_{e\ threshold}$ and b are crop specific but may vary with the crop variety and crop and irrigation practices, i.e., the salinity stress due to the condition $EC_e > EC_{e\ threshold}$ is only approximately computed using the described linear approximation. The uncertainties of the referred parameters are larger when yield reduction reaches 50%. It is therefore, advisable not to perform water balance computations for large K_s during long periods during the season, roughly for $K_s > 0.50$ for around one month. For this high level of stress it is also not likely that production could be economically satisfactory.

The dynamics of K_s are described in Fig. 4 which shows that there is no stress when the soil water content in the root zone at any day i (θ_i) is above the soil water threshold corresponding to the p depletion fraction for no water stress (θ_p), i.e., when storage is larger than RAW and $EC_e < EC_{e\ threshold}$. Contrarily, water stress occurs when the cumulative depletion $D_{r,i}$ increases to exceed RAW resulting $K_s < 1.0$ (Eq. (16a)) and $\theta_i < \theta_p$. The water deficit ($\theta_p - \theta_i$) increases linearly with the reduction of θ_i and the linear decrease of K_s. When $EC_e > EC_{e\ threshold}$, the crop yield is affected and ET is reduced ($K_s < 1.0$). If $\theta_i > \theta_p$, then K_s (Eq. (17)) depends only upon $EC_e > EC_{e\ threshold}$ and is defined by a horizontal line lower than the non-stressed upper line (Fig. 4). The larger the difference $EC_e - EC_{e\ threshold}$, the smaller is K_s. If both water and salinity stress occur simultaneously, then K_s also decreases linearly with θ_i as suggested in Fig. 4.

The parameters p, $EC_{e\ threshold}$, b and K_y are tabulated for a variety of crops (Tables 1 and 3). Values for p are tabulated in FAO56 (Allen et al., 1998) and in various papers of this Special Issue. In general, p values are as small as 0.30 or 0.40 for vegetable short rooted crops, average around 0.50 for most field crops and may exceed 0.60 in case of crops resistant to dryness. The adjustment of p to climate was proposed by Allen et al. (1998). However, their values should be used carefully, particularly due to the uncertainty of the simplified assumed linear nature of crop response to salinity. In addition, tolerance or sensitivity to salinity may vary between crop varieties and with crop and irrigation management. Values for K_y tabulated in Table 3 reflect uncertainty related to crop variety and crop and irrigation management. Despite uncertainties, the proposed values are based on best available sources and should be useful until more accurate information becomes available from new research. Nevertheless, it is advisable to limit the use of $ET_{c\ act}$ computations when these would correspond to yield losses greater than 50%.

4.2. *A modification of the FAO56 approach to crop evapotranspiration under salinity*

Under salinity, crop roots have to overcome an increased retention of water due to increased effects of osmotic potential. This condition recognizes that the soil water content at the wilting point is higher than for non-saline soils (Beltrão and Ben Asher, 1997) and thus the available soil water is reduced for saline soils. Considering this condition, Pereira et al. (2007) corrected soil water content at wilting point as a function of actual soil salinity relative to the specific crop salinity tolerance, thus:

Table 3
Seasonal yield response factor (K_y) for field and vegetable crops.
Source: FAO33 (Doorenbos and Kassam, 1979) and updates referenced in the Table.

Crop	K_y	Sources
Alfalfa	1.10-1.30	FAO33, Kuslu et al. (2010)
Apple	1.20	Ucar et al. (2016)
Banana	1.20-1.35	FAO33
Barley, malt	1.25	Pereira et al. (2015)
Beans	1.15	FAO33
Cabbage	0.95	FAO33
Citrus	1.10-1.30	FAO33
Cotton	0.85-1.25	FAO33, Yazar et al. (2002) and DeTar (2008)
Cucumber	0.95	Wang et al. (2019)
Eggplant	0.70-1.35	Lovelli et al. (2007) and Çolak et al. (2018)
Grape	0.85	FAO33
Groundnut	0.70	FAO33
Maize	1.25-1.32	FAO33, Popova and Pereira (2011) and Paredes et al. (2014)
Olive	0.70-0.80	Fleskens et al. (2005)
Onion	1.10-1.25	FAO33, Kipkorir et al. (2002)
Peach	1.20	Gunduz et al. (2011)
Peas	1.15	FAO33, Paredes et al. (2017)
Pepper	1.10	FAO33
Potato	1.10	FAO33, Paredes et al. (2018)
Rapeseed	0.90	Istanbulluoglu et al. (2010)
Safflower	0.80-0.93	FAO33, Lovelli et al. (2007) and Istanbulluoglu (2009)
Sorghum	0.90	FAO33
Soybean	0.85-1.30	FAO33, Wei et al. (2015)
Spring wheat	1.00-1.15	FAO33, Rao et al. (2013)
Sugarbeet	1.00-1.10	FAO33, Shrestha et al. (2010)
Sugarcane	1.20	FAO33
Sunflower	0.95	FAO33
Tomato	1.05-1.35	FAO33, Cantore et al. (2016)
Watermelon	1.10-1.25	FAO33, Erdem and Yuksel (2003) and Kirnak and Dogan (2009)
Winter wheat	0.95-1.05	FAO33, Sezen and Yazar (2006)

$$\theta_{WP\,salt} = \theta_{WP} + \frac{b}{100}\left(\frac{EC_e - EC_{e\,threshold}}{10}\right)(\theta_{FC} - \theta_{WP}) \tag{18}$$

where $\theta_{WP\ salt}$ is the corrected value of θ_{WP} for a soil of actual salinity EC_e. Crop sensitivity to salinity is defined by given values of $EC_{e\ threshold}$ and percent yield reduction b. Therefore, TAW (Eq. 16) is reduced (Fig. 3b) to

$$TAW_{salt} = 1000\ (\theta_{FC} - \beta\ \theta_{WP\ salt})\ z_r \tag{19}$$

where TAW_{salt} (mm)is the corrected value of TAW for the considered soil and crop.

The depletion fraction for no water stress should also be corrected because under saline conditions crops may be stressed for a depletion fraction smaller than p. Therefore, Pereira et al. (2007) decreased p when $EC_e > EC_{e\ threshold}$ as a function of the percent yield reduction b resulting:

$$p_{salt} = p - b(EC_e - EC_{threshold})\ p \tag{20}$$

where p_{salt} is the adjusted value of p for the considered crop when cultivated in a soil with a salinity EC_e. The soil water threshold for no stress refers now to p_{salt} ($\theta_{p\ salt}$).

Adjusting p implies also decreasing RAW (Fig. 3b), thus:

$$RAW_{salt} = p_{salt} TAW_{salt} \tag{21}$$

Where RAW_{salt} (mm) is the corrected value of RAW for the considered crop and soil. The adjustment of TAW and RAW to saline cropping conditions require modifications of stress coefficient in order to consider the impacts of salinity, resulting in:

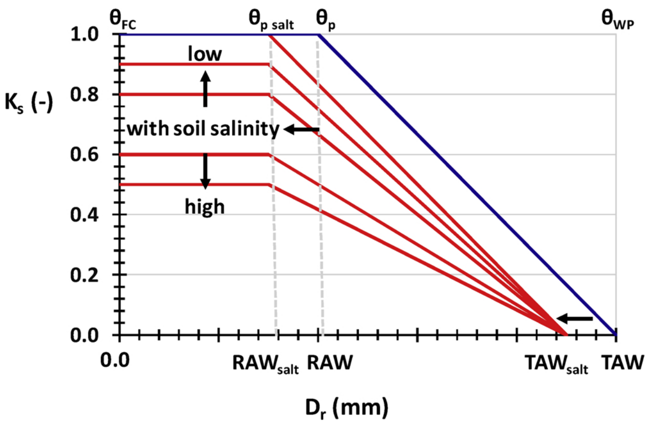

Fig. 5. comparison between the original (Allen et al., 1998; —) and modified (Pereira et al., 2007; —) approaches to compute the stress coefficient K_s(θ_{FC}, θ_p and $\theta_{WP}$are soil water content at field capacity, corresponding to the depletion fraction for no stress, and at the permanent wilting point, respectively; TAW and RAW, are total and readily available water, respectively; D_r is cumulative depth of water depletion from the root zone; the subscript salt is used when variables are adjusted for salinity).

$$K_{s,i} = \left(\frac{TAW_{salt} - D_{r,i}}{TAW_{salt} - RAW_{salt}}\right)\left(1 - \frac{b}{K_y\,100}(EC_e - EC_{e\,threshold})\right) \tag{22}$$

Eq. (22) is applicable to the considered crop when the cumulative depletion $D_{r,I}$ exceeds RAW_{salt}, and where TAW_{salt} and RAW_{salt} are the total and readily available water (mm) as defined above for saline conditions. The scheme of Fig. 5 illustrates the changes resulting from assuming TAW_{salt}, RAW_{salt} and $\theta_{p\ salt}$. This adjustment of the soil water balance to salinity is likely not important when soil salinity is low and the crop is tolerant, but will likely be relevant for less tolerant crops and more saline soils.

4.3. Modeling applications of the FAO56 approach using single and dual crop coefficients

Although the FAO56 approach is limited to the representation of general impacts of soil salinity on crop ET over extended time periods, the methodology has been applied for improving irrigation water use in saline stress environments over the years. For example, Pereira et al. (2007) assessed various irrigation management issues for wheat, maize and surface irrigation improvements aimed at water saving and salinity control in the upper Yellow River Basin, China. They used the model ISAREG (Pereira et al., 2003), which incorporates the above described water balance procedure for dealing with saline conditions, to develop and evaluate alternative irrigation schedules for wheat and maize adopting precise land leveling for improved distribution uniformity in basin irrigation and, thus better controlling the leaching fraction. Hassanli and Ebrahimian (2016) and Hassanli et al. (2016) determined the crop water requirements of forage maize (*Zea mays* L.) irrigated with different EC_{iw} (0.4–5.7 dS m^{-1}) in Iran. These authors reported K_s values of 0.8 and 0.6 when attaining 25 and 50% reduction in yield production, respectively. Hassanli and Ebrahimian (2016) focused on the impacts of cyclic and constant use of saline and non-saline waters on yield and irrigation water productivity, while Hassanli et al. (2016) tested a series of modeling approaches for reproducing field observations in different experimental plots. Nassah et al. (2018) considered the FAO56 approach to control both crop water stress and leaching of mandarin (*Citrus reticulate* Blanco) orchards grown in saline (EC_e of 4 dS m^{-1}) and non-saline (EC_e of 2 dS m^{-1}) soils in Morocco, with estimated water saving of up to 30–47% due to the optimized irrigation schedules when compared with farmers' practices.

In terms of crop response to salinity, Ould Ahmed et al. (2007) used the Ks Eq. (16) to assess the impacts of two irrigation amounts and frequencies considering three salinity levels (up to 12.50 dS m^{-1}) on the ET response of sorghum (*Sorghum bicolor* (L.) Moench) grown in a plastic greenhouse. Bhantana and Lazarovitch (2010) analyzed the response of ET, crop coefficient and growth of two young pomegranate (*Punica granatum* L.) varieties grown in Israel to varying levels of EC_{iw} (0.8–8.0 dS m^{-1}) and found that the percent yield reduction b was not constant but decreased throughout the crop cycle. Mahjoor et al. (2016) followed the FAO56 approach to study the interaction effects of water salinity stress using different hydroponic media on the qualitative and quantitative characteristics of eggplant (*Solanum melongena* L.), namely on yield, water-use efficiency, and ET. These authors reported an $EC_{ethreshold}$ for eggplant in hydroponic cultivation of 2.5 dS m^{-1}, which is higher than the one presented in Table 1. The crop salinity stress coefficients were found to depend upon the hydroponic media, with coco-peat having a greater water-holding capacity that was able to better counteract the salinity stress. Ünlükara et al. (2017) investigated spinach (*Spinacia oleracea* L. Matador) response to different levels of EC_{iw} (0.65–7.0 dS m^{-1}) using the FAO56 approach and reported that the spinach response to salinity was different when grown inside or outside a greenhouse due to outdoor effects of weather on salinity tolerance.

The FAO56 approach served also as framework for several modeling developments aimed at improving irrigation management with saline waters. Jorenush and Sepaskhah (2003) adapted the TSAM model for computing the soil water balance under saline stress conditions using the FAO56 approach. An empirical formulation was embedded to consider capillary rise and salt transport from the shallow groundwater table. The model was applied to wheat (*Triticum aestivum* L.) and to irrigated and non-irrigated pistachio seedlings (*Pistacia vera* L.) grown in micro-lysimeters. Varied water table depths (0.3–1.2 m) and EC of the groundwater table (0.5–13 dS m^{-1}) were used, with the model accurately reproducing micro-lysimeter data except for higher saline water table conditions (13.0 dS m^{-1}) and shallower water table depths (< 0.6 m). Domínguez et al. (2011) added a salinity module to the MOPECO model following the FAO56 approach. The model was used to predict onion (*Allium cepa* L.) and potato (*Solanum tuberosum* L.) response to salinity in Spain (Eastern Mancha) and Lebanon (Bekaa Valley), respectively. The model helped to assess the sustainability of irrigation strategies including relative to the need for applying a LF or whether rainfall would be able to washout the soluble salts accumulated in the root zone. Domínguez et al. (2012) further evaluated the robustness of the FAO56 approach for simulating the yield versus total water relationships in maize irrigated with low saline waters (0.85 dS m^{-1}) in Castilla La Mancha, Spain. Shabani et al. (2015) also developed a model following the FAO56 approach for estimating ET reductions of rapeseed (*Brassica napus* L.) due to water and salinity stress, providing empirical functions for computing the root zone salt budget. Finally, Reca et al. (2018) implemented a decision support system (DSS) for helping farmers optimizing the combined use of saline and desalinated seawater for greenhouse irrigation while providing maximum economic profit. The DSS followed the FAO56 framework for computing the effect of salinity stress on crop ET and yields and was tested for watermelon (*Citrullus* spp.) with salinity ranging from 2.5 to 4.0 dS m^{-1}.

Some model developments included modifying the FAO56 approach to better account for the salinity effect on crop ET and growth. Sepaskhah et al. (2006) modified the FAO56 approach for computing the soil water balance and salt effects on yield with the modified K_s-($K_{s\ Sep}$) computed as:

$$K_{s-Sep} = \left(\frac{TAW - D_{r,i}}{TAW - RAW}\right)\left(1 + \frac{(a-1)}{K_y} - \frac{b(EC_e - EC_{e\,threshold})}{K_y}\right) \tag{23}$$

where a is reduction factor (−). The model was applied to sugarbeet (*Beta vulgaris* L.), winter wheat, and sweet maize in a semi-arid region in Iran using irrigation water of different EC_{iw} levels (2.55–11.5 dS m^{-1}) and various leaching fractions (10%–50% of yield reduction), and irrigation amounts. At a larger scale, Xiong et al. (2019) modified the SWAT model by further introducing a soil salinity stress coefficient ($K_{s\text{-}sal}$) to limit crop transpiration and growth based on a modification of the FAO56 approach follows:

$$K_{s-sal} = 1 - \frac{b}{100\,K_y}\left(\frac{C_{rz}\theta_{rz}}{0.64\,\theta_{rz,s}} - EC_{e\,threshold}\right) \tag{24}$$

where b is the percent yield reduction per unit increase in EC_e (%/dS m^{-1}), K_y is yield response factor (−), c_{rz} is the average soil salt content of the root zone (g L^{-1}), θ_{rz} is the soil water content of the root zone at saturation ($m^3\ m^{-3}$), $EC_{e\ threshold}$ is the crop specific value of EC_e for crop stress (dS m^{-1}), and 0.64 is a global conversion factor. K_s were then multiplied by the water stress reduction factor (W_{str}) of SWAT when predicting the actual T_c affected by salinity:

$$T_{c\,act-sal} = K_s W_{str}\,T_c \tag{25}$$

The Pereira et al. (2007) approach (Section 4.2 above) was adopted by Xue et al. (2018), who coupled a water and salt balance model to compute irrigation water productivity in crops grown under the influence of shallow-saline groundwater conditions. That approach was used by Rosa et al. (2016) as an extension of the SIMDualKc model (Rosa et al., 2012) for estimating actual $T_c$as affected by salinity. The model was applied to maize and sweet sorghum crops irrigated with saline waters adopting Eq. (22). Results for the SIMDualKc simulation of the soil water balance of maize using the approach described in Section 4.2 are presented in Fig. 6 for 3 years of observation comparing the use of saline and non-saline irrigation water. These results show the ability of the model to simulate the soil water content after adjusting the soil water parameters to saline conditions to better estimate $ET_{c\ act}$.

Results in Fig. 7 demonstrate the impact of saline irrigation waters on the actual K_{cb} ($K_{cb\ act}$) and K_e values during the three maize growing seasons. The $K_{cb\ act}$ values differed considerably under non-saline and saline irrigation conditions, becoming increasingly lower in the latter due to the salinity build-up over the years. EC_e values were measured at different stages of the crop season and were used as model inputs. For the saline plots, the decrease of $K_{cb\ act}$ values with time were associated with smaller plants due to salt stress and, thus, with a reduction of ground cover by vegetation and an increase of solar energy available for soil water evaporation. Therefore, soil evaporation and the respective coefficient K_e progressively increased during the mid-season stage under saline conditions. For sweet sorghum, Rosa et al. (2016) also reported reductions in $T_{c\ act}$ due to the cumulative use of saline irrigation waters however less important due to the higher tolerance of sorghum to soil salinity.

4.4. *Comparative case studies*

The FAO56 approach for computing Ks for saline stress (Eq. (22)) needs to be implemented with a soil water balance model. The soil domain may be defined simplistically, just referring to the soil water storage between field capacity and the wilting point (Fig. 3), with the water dynamics being computed as described with Eq. (10). However, the other terms of the soil water balance need to be estimated accurately, even while empirical or semi-empirical equations are used to compute deep percolation, capillary rise and runoff (Raes, 2002; Liu et al., 2006; Allen et al., 2007; Vanuytrecht et al., 2014). The simplicity of these models allows their easy global implementation, but they require appropriate calibration and validation, which may be performed by minimizing the differences between observed and simulated soil water content through the crop season.

Once the models are calibrated, they can be used to search the best crop and irrigation management practices that allow as close as possible matching actual to potential ET_c or, preferably, when the dual K_c approach is used, provide for $T_{c\ act}$ to be close to potential T_c and to,

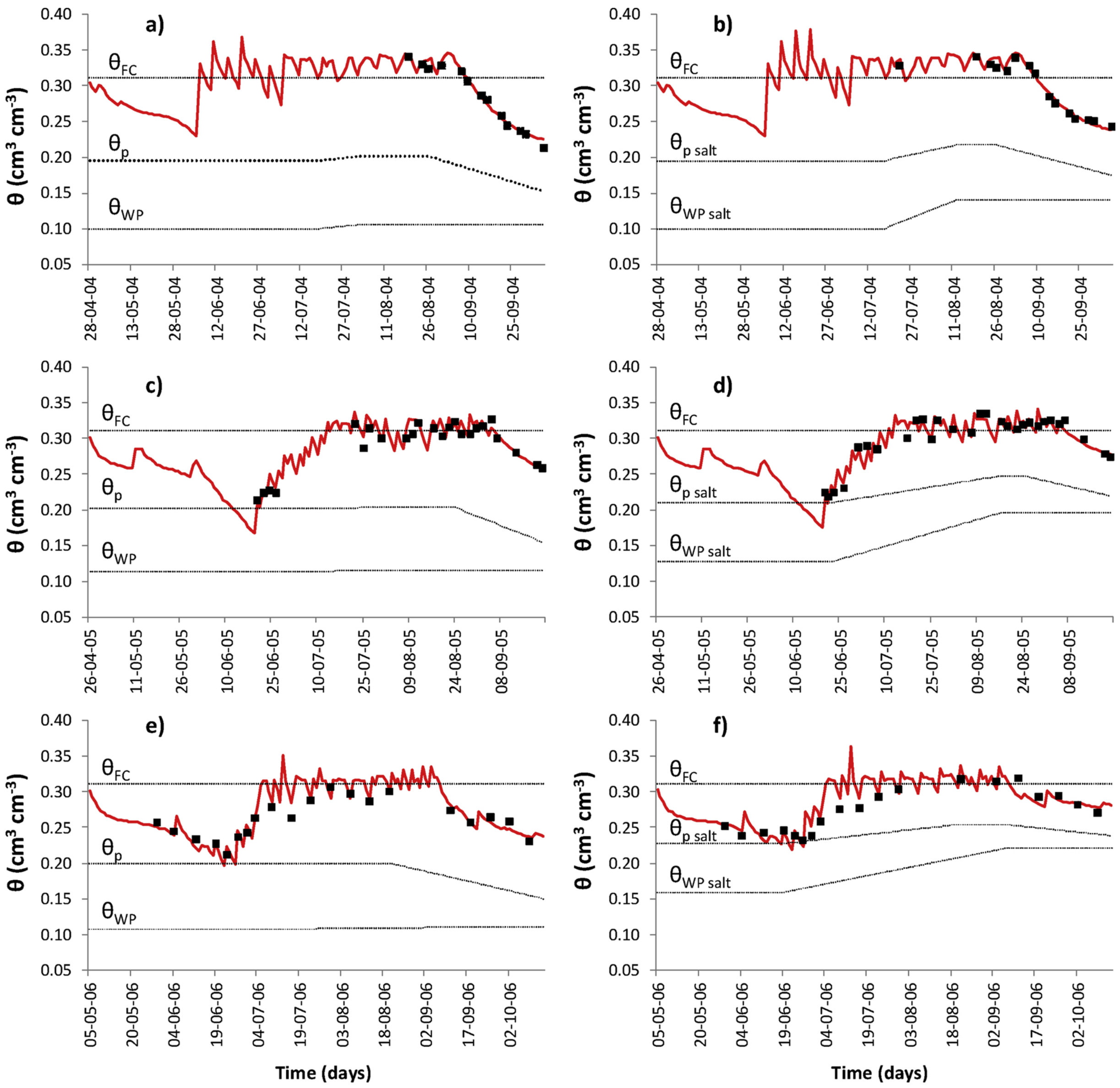

Fig. 6. Observed (■) and simulated soil water contents (θ) computed with the SIMDualKc (——) model under non-saline (a, c, e) and saline (b, d, f) conditions along the maize growing seasons of 2004–2006 (θ_{FC}, θ_p and θ_{WP} refer, respectively, to field capacity, to the depletion fraction for no stress and to the permanent wilting point. The subscript salt is used when variables are adjusted for salinity).
Source: Rosa et al. (2016).

thereby, enable yield to be maximized. To assess the impact on yields, one can use the classical Stewart et al. (1977) model relating relative yield with relative ET using the yield response factor K_y, as has been established for a large number of crops (Table 3). The adoption of a LF may then be tested using data regarding crop tolerance to salinity, as found in Table 1 (e.g., Pereira et al., 2007).

Transient-state models, whose consideration of the FAO56 approach is restricted to defining of surface boundary conditions, may be preferable tools for irrigation water management in saline environments despite their greater complexity. This is the case for the quantification of salinity build-up in the root zone because of irrigation-induced salinity or the upward migration of salts from saline ground waters (Xu et al., 2013; Karandish and Šimůnek, 2019) or when aimed at the further analysis of soil sodification processes (Gonçalves et al., 2006; Rasouli et al., 2013; Raij et al., 2016; Ramos et al., 2019). Transient-state models have a clear advantage for research purposes but their inherent complexity does not favour their use when searching for simple solutions relative to crop water requirements and irrigation scheduling, which should be more accessible when solved with water balance models adopting the FAO56 approach as referred to above.

Comparative studies on the performance of the described FAO56 and other approaches are limited. Domínguez et al. (2011) compared the FAO56 approach, including the modifications introduced by Pereira et al. (2007), with other methodologies and reported that results did not differ substantially among the different approaches. Mosaffa and Sepaskhah (2019) studied the effects of different irrigation regimes (full irrigation, FI, and 65% and 35% of FI), salinity levels (0.6–10.0 dS m^{-1}) and cropping techniques on yield, yield quality and water productivity of winter wheat (*Triticum aestivum* L.) in Iran. They reported that the FAO56 approach was able to estimate yield reductions with high accuracy (R^2 of 0.88) relative to estimates provided by other methodologies commonly used in transient-state models. Rosa et al. (2016) used results from the HYDRUS-1D model (Šimůnek et al., 2016) to validate crop ET reductions due to the salinity stress in maize and sweet sorghum crops using the FAO56 approach with the SIMDualKc water balance model. The approach used in SIMDualKc was based upon the

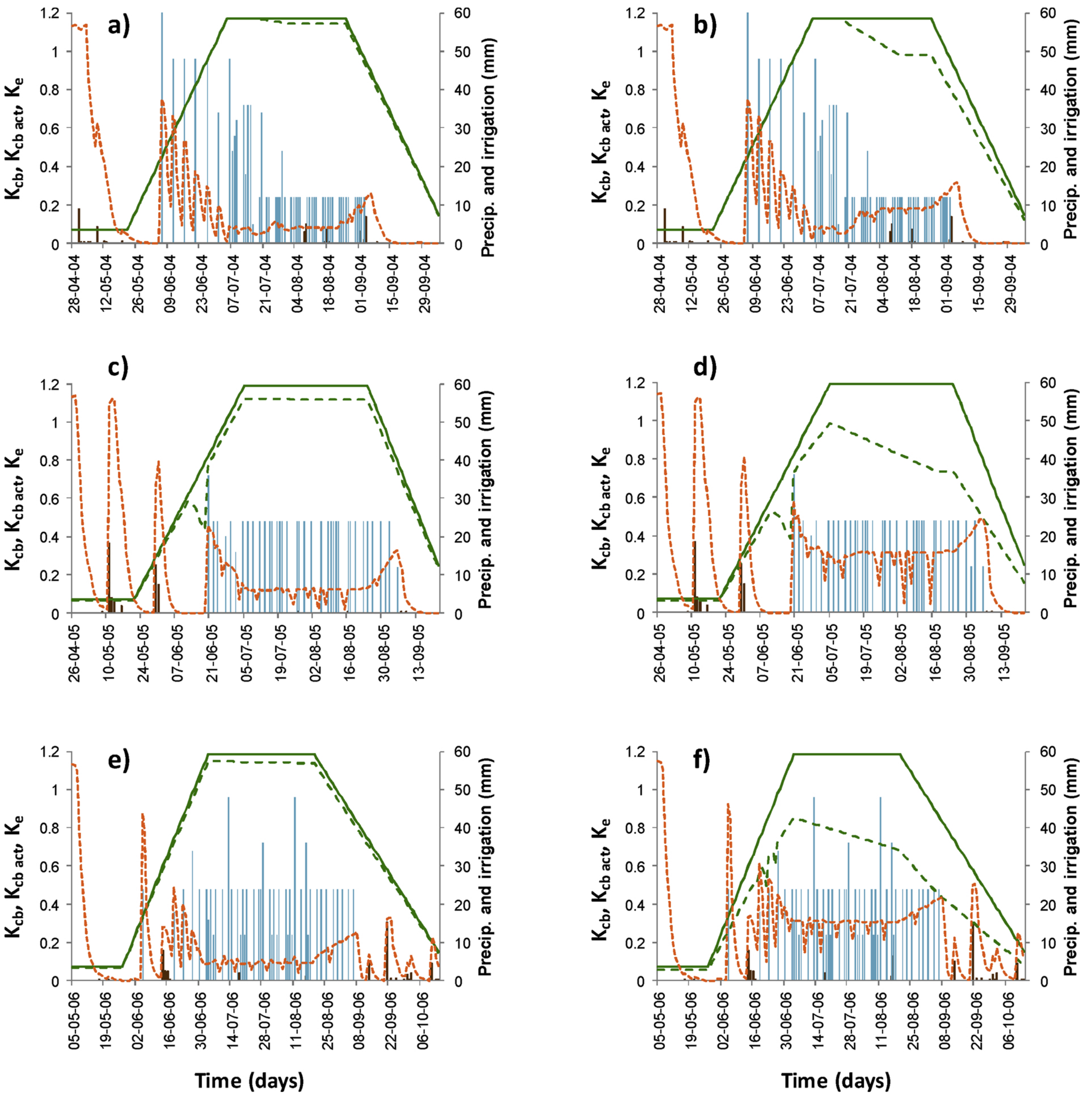

Fig. 7. Seasonal variation of K_{cb} (—), $K_{cb\ act}$ (- - - -), K_e (········), precipitation (▬), and irrigation (▬) in non-saline (a, c, e) and saline (b, d, f) plots during 2004–2006 maize growing seasons.
Source: Rosa et al. (2016).

dual K_c approach with refinements described in Section 4.2 while the HYDRUS-1D model considered a multiplicative approach combining the van Genuchten (1987) model for water stress and the Maas and Hoffman (1977) model for the salinity stress. Rosa et al. (2016) showed that both SIMDualKc and HYDRUS-1D models estimated similar ET_c and T_c reductions for maize and sorghum due to the increased soil salinity build-up observed along the growing seasons (Fig. 8). The departure between potential and actual ET_c and T_c values became progressively greater along each crop season and along the years due to the increase of EC_e values. At the same time, soil evaporation was increased over the years (Fig. 8c) because the fraction of ground cover decreased with the decrease of plant size due to salt stress, thus somewhat compensating $T_{c\ act}$ reductions in terms of the total amount of water consumption ($ET_{c\ act}$). For sweet sorghum, the results were similar (Rosa et al., 2016) although the gap between potential and actual ET and T was found to be smaller due to the crop's higher tolerance to soil salinity. SIMDualKc estimates ended up showing the same trends as those in HYDRUS-1D, with the latter computing slightly larger reductions of $ET_{c\ act}/ET_c$ and $T_{c\ act}/T_c$ over the years.

5. Irrigation methods and management to cope with salinity

5.1. Requirements for irrigation methods

Proper water and crop management are vital to minimise accumulation of salts in the active root zone, to ease the application of a leaching fraction with irrigation, and to eliminate salt stress, especially during the critical growing stages of the plants. These include (Pereira et al., 2002, 2009; Qadir and Oster, 2004; Hoffman and Shalhevet, 2007):

- Selecting the proper method of irrigation and schedules to suit the method;
- Efficient salt leaching management and disposal of drainage water;

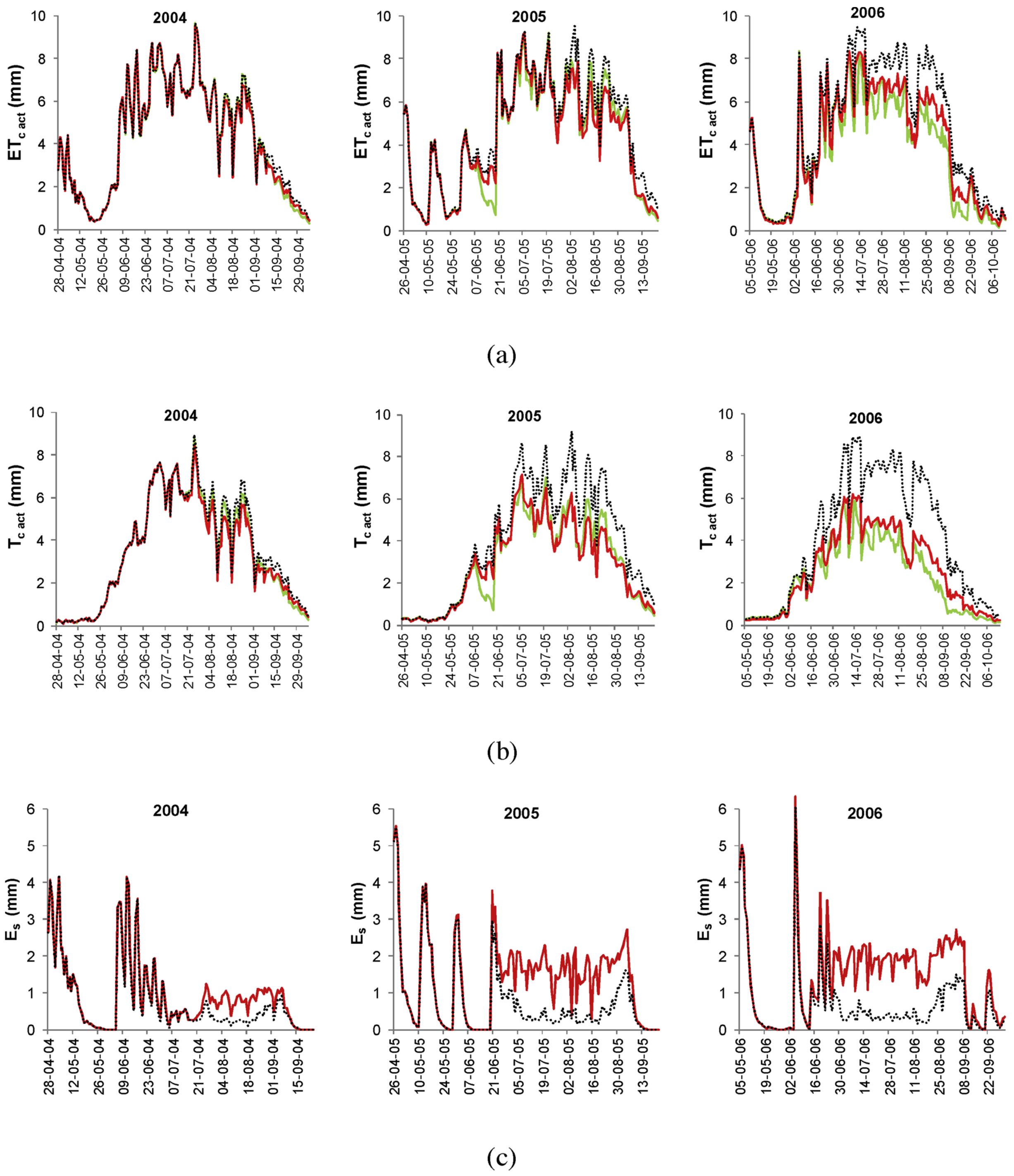

Fig. 8. Non-saline (⋯⋯) vs. saline stressed simulations using the models SIMDualKc (——) and HYDRUS-1D (——): (a) actual crop evapotranspiration ($ET_{c\ act}$), (b) actual crop transpiration ($T_{c\ act}$), and (c) soil evaporation (E_s) for maize during the crop seasons of 2004–2006.
Source: Rosa et al. (2016).

- Suitable cropping systems based upon quality and quantities of irrigation water, soil and agro-climatic conditions.

The distribution of water and salts in soils varies with the method of irrigation. Irrigation methods should create and maintain favourable salt and water regimes in the root zone such that water is readily available to plants for their growth and without any damage to yield. Surface irrigation methods, including border strips, check basins and furrows are the oldest and most commonly practiced in most parts of the world. These irrigation methods, when traditionally practiced, typically result in excessive irrigation and non-uniformity in water application (Pereira et al., 2007; Miao et al., 2015). However, properly designed and operated, surface irrigation methods can maintain the salt balance and minimize salinity hazards (Pereira et al., 2009, 2014). To meet the objectives of optimised water and salt management, land needs to be precise levelled to ensure uniform distribution of water. Parameters such as the length of the water run, stream size, slope of the soil and cut off ratio, which influence the uniformity and the depth of water application for a given soil type, should be as per the desired specifications.

Table 4
Evaluation of the irrigation methods for use with saline water.
Source: Adapted from Pereira et al. (2009).

Irrigation method	Flat basin Irrigation	Corrugated basin irrigation	Border irrigation	Furrow irrigation	Sprinkler irrigation	Drip and subsurface drip irrigation	Micro-sprinkling and microspray
Salt accumulation in the root zone	Not likely to occur in modernized upgraded systems. Problems occur ifdistribution uniformity and water application control are poor. The leaching fraction is then difficult to control as in traditional systems	Salts tend to accumulate on the tops of the ridges. Leaching prior to seeding/planting may be required for germination and crop establishment. Other limitations as for flat basins	As for flat basin irrigation. However, due to slope, uniformity is more difficult to achieve, as well as the control of the leaching fraction, mainly in traditional systems	As for corrugated basins. Uniformity is more difficult to achieve due to slope.	Not likely to occur when set systems are used except when low distribution uniformity occurs. Using light and frequent irrigation as for center-pivots does not favour leaching	Not likely to occur except for poorly designed systems with low uniformity and when irrigation is not managed to keep salts out of the wetted bulb. The application of leaching is easier when well designed	Not likely to occur if design is aimed at saline environments. Otherwise, leaching is difficult and the application of a LF may be useless.
Foliar contact, avoiding toxicity	It is possible only for bottom leaves in low crops and fodder crops, or during the first stage of growth of annual crops	Unlikely because crops are grown on ridges.	As for flat basins	Unlikely because crops are grown on ridges	Severe leaf damage can occur affecting yields. Damage greater with more frequent irrigation.	Not likely to occur	Leaf damage can occur, affecting yields of annual crops. Less damage for tree crops
Ability to infiltrate water and refill the root zone	Adequate because large volumes of water are generally applied at each irrigation and water remains in the basin until infiltration is complete	As for flat basins,	Less favourable than flat basins. Due to slope, infiltration occurs while water flows on the soil surface and runoff losses increase	Salinity reduced infiltration may increase slope runoff losses	Salinity induced infiltration problems, including soil crusting, may cause high runoff losses	Problems generally do not occur except for poorly designed cases, with not enough number of emitters	Problems are similar to those for set sprinklers
Control of crop stress and yield reduction	Adequate since toxicity is mostly avoided, salts are moved down through the root zone, infiltration is easily controlled as well as irrigation schedules to avoid crop stress	As for flat basins but requires avoiding salt stress at plant emergence and crop establishment	Crop stress may occur when runoff reduces infiltration andinduces yield reduction	As for borders when high runoff is induced	Crop stress is likely to occur due to toxicity by contact of water with the leaves and fruits, and due to reduced infiltration, thus yield losses are likely to occur	These systems are able to provide for crop stress and toxicity control, so yield losses are minimised	Toxicity due to direct contact with the leaves in case of vegetable and field crops. Yield losses likely to occur

Drip irrigation is regarded as superior in improving crop production under saline and saline-sodic soils (Pasternak and De Malach, 1995; Hanson et al., 2008), but surface irrigation may also be very efficient if land is precisely levelled and water is applied uniformly (Pereira et al., 2002; Darouich et al., 2014).

The selection of irrigation method must be based on irrigation water quality and associated potential hazards. Relevant considerations are included Table 4 and these refer to their potential to cause:

- Soil salinity hazards due to the build-up of salts in the root zone;
- Toxicity hazards caused by direct contact of toxic ions with plant leaves and fruits;
- Soil structural deterioration and the resultant aeration and waterlogging problems caused by poor water infiltration, mainly due to increased sodicity;
- Loss of productivity with lack of control over frequency and quantities of irrigation water to be applied.

The irrigation methods referred in Table 4 are described in various irrigation manuals (e.g., Hoffman et al., 2007; Stetson and Mecham, 2011) and their adaptability for using saline and wastewater is discussed in numerous papers. Modernized surface irrigation methods, particularly flat basins and borders are appropriate to apply saline waters and for salt leaching. However, they require appropriate management (e.g. Devkota et al., 2015) and they do not allow application of small irrigation depths. When water is delivered to farms through surface canal systems, delivery schedules generally rotate between sections and users, and are often rigid, delivering large irrigation volumes at long intervals. These systems are well adapted for leaching, but are less appropriate for irrigation of less tolerant crops that require small and frequent applications, e.g. vegetable crops.

Micro (drip) irrigation systems are the most advanced, allowing precise application of water and fertilizers, and, as such, improved efficiency and potential benefits under saline conditions. The nature of drip irrigation, where water application is by definition non-uniform in micro-spatial, but often is very uniform in macro-spatial and temporal terms, raises some interesting possibilities regarding its specific appropriateness with saline water (Burt and Isbell, 2005). Since small and frequent irrigation depths are possible, it is appropriate for salt sensitive crops. However, the possibilities of salts returning into the wetted bulb should be minimised. Moreover, emitters need careful selection, i.e., these should not have too small orifices, and filtration must be efficient. Drip irrigation systems must be properly maintained and cleaned to avoid clogging of emitters with precipitation of salts.

Actual salt distribution is dependent on soil type, irrigation/rainfall quantity, irrigation salinity, root distribution and plant uptake as well as on the irrigation method and on drying and wetting cycles associated with frequency regimes (Mmoloawa and Or, 2000). Drip irrigation can essentially reduce salt load in drainage as salts are stored in the upper root zone but beyond the plant's zone of active uptake. For a specific case tested by Dudley et al. (2008b), drip methodology and increased frequency of irrigation events both reduced drainage water salt load without affecting transpiration.

5.2. Crop irrigation management with leaching fraction

Irrigation under saline conditions must aim at meeting both water (ET) needs as well as leaching requirements to maintain a favorable salt balance in the root zone. Salts in the water and the soil decrease the osmotic potential of the soil water, which combines with effects of matric potential changes to cause stress between irrigations and to make water uptake by crop roots more difficult. For irrigation scheduling purposes, it is possible to consider total available soil water less than that for non-saline soils by correcting the soil water content at the wilting point (Eqs. (16) and (17)). Thus, frequent irrigation regimes should eliminate both the matric potential effect and minimize the osmotic (Hillel, 2000).

On-farm irrigation management under saline situations should be specific of irrigation method and system (Pereira et al., 2002, 2009). For surface irrigation, scheduling should be practiced with large depths and a reduced number of irrigation events with controlled discharges and excellent land levelling, thus to eliminate salinity build-up and assure optimal crop production as described by Pereira et al. (2007). For drip irrigation, frequent events can maintain maximum leaching of the root zone. This has lead researchers to probe the methods and frequency of irrigation, the total amount of irrigation water to be applied for meeting leaching requirements and making judicious use of multi-quality waters.

The issue of irrigation frequency and salinity is controversial. On one hand, irrigation events in saline soils should logically be more frequent because they reduce the cumulative water deficits (both matric and osmotic) between the irrigation cycles. On the other hand, small irrigation intervals would be expected to induce water uptake from shallow soil layers, increase unproductive evaporative losses from soil surface and increase the salt load of soils. Moreover, the nonsaline soil water carried over from the monsoon rains may also be displaced beyond the reach of plant roots by the frequently added saline irrigations (Minhas and Gupta, 1992). Extended irrigation intervals usually result in deeper roots and larger proportions of water extractions from deeper zones. Since, under saline conditions, water uptake and thus ET is reduced, higher salinity soils will retain more water than low salinity ones between irrigation events. Thus, overall water stress is moderated and the inhibitory effect of increased solution concentration on growth is reduced. The net results of above counteracting processes still awaits further experimentation, but based upon model predictions Minhas and Gupta (1993b) have shown that depth of applied water should be simultaneously reduced if higher benefits from small intervals are to be accrued. However, it is difficult, nearly impossible, to apply below 40 mm water with surface methods even while using appropriate flow rates and precisely levelled land. The small frequent irrigation events enabled by drip irrigation not only allow efficient salt leaching but would also reduce deep percolation (Hanson and Ayars, 2002). The use of straw mulch to control soil evaporation also helps to control upward transport of salts to the root zone (Bezborodov et al., 2010; Pang et al., 2010).

For highly frequent drip irrigation, a low salinity zone around and below drippers promotes high yields while allowing controlling and minimizing of the LF (Phene, 1986; Hillel, 2000; Dudley et al., 2008b). A number of studies support this theory. Assouline et al. (2006) monitored identical yield and less salt removal when comparing pulsed to daily irrigation of bell pepper with saline water. Five pulses a day of saline (EC 6.2 $dS\,m^{-1}$) water reduced midday salt concentration in the rhizosphere and were able to overcome the detrimental effects of salinity as observed in daily irrigation (Pasternak and De Malach, 1995). Dehghanisanij et al. (2006) also observed that timing the drip irrigation with saline water to match maximum ET demand maintained favourable moisture and salinity regimes in the immediate vicinity of roots.

5.3. Combined use of multi-salinity waters

Under most saline situations, fresh water supplies are either unsure or inadequate such that farmers are forced to pump saline ground/drainage waters to meet crop water requirements. Waters from dual sources can be applied either separately, in cyclic or sequential fashion or mixed/blended together. Mixing of waters to acceptable quality for crops also results in improving stream size and thus enhances the uniformity in irrigation, especially for the surface method. Blending involves the mixing of two or more water sources to reach a targeted salinity for a particular crop. The goal is to increase the total irrigation water supply or to reuse water having a salinity that would otherwise not be allowed to drain into a receiving water body. The permissible salinity of a blend depends on the salt tolerance of the crop(s) to be irrigated, the soil type and climate, and the long-term management plan for irrigation and crop production (Minhas and Gupta, 1992; Rhoades et al., 1992; Grattan et al., 2012; Minhas, 2012). There is a practical upper limit to the saline component of the blend above which it has little or no contribution to the total usable water supply. According to Grattan and Oster (2003), if the saline portion of the blend cannot contribute at least 25% of the total portion of the blend, then the potential costs and risks of crop damage outweigh the potential benefits of using the saline water in the blend. However, growers with little or total lack of accessibility to better quality supplemental irrigation water available may be willing to accept a substantial yield reduction in the crop grown and will therefore blend using greater proportions of the saline water. Examples of blending have been reported, e.g. for pearl millet/cotton/paddy-wheat rotations in India (Naresh et al., 1993a, 1993b; Minhas et al., 2007), tomato in Egypt and Syria (Malash et al., 2002; Flowers et al., 2005), sweet bell pepper in Israel (Ben-Gal et al., 2009) and cotton in Uzbekistan (Bezborodov et al., 2010). Not surprisingly, all of the studies reported intermediate yields, less than with non-saline water and greater than with only brackish water, when blending was applied. Blending does require additional infrastructure to allow for controlled mixing of the two water sources, either as network dilution where the water sources are blended in the irrigation conveyance system, or by diverting water of different sources into a storage reservoir where supplies blend to suitable quality and then later pumped to the fields as needed. Recently mixes of desalinated and brackish water in Israel have been practiced, not only to control salinity levels and increase irrigation water volume, but to re-introduce Ca, Mg and SO_4 into the irrigation water when desalinated water is used in significant amounts (Ben-Gal et al., 2008, 2009; Yermiyahu et al., 2007).

The options for allocation of different salinity waters also exist in terms of their application at different crop growth stages, to crops grown in separate fields or seasons such that minimum salinity exist at sensitive stages or during the growth of salt sensitive crops (Minhas and Gupta, 1992). Since germination and seedling establishment are the most sensitive stages in most crops, it is advisable to apply low salinity waters for pre-sowing irrigation and early stages of crop growth, then switch over to higher salinity waters at later stages when the crops can tolerate higher salinity. Rhoades et al. (1992) also advocated seasonal cyclic strategy, where non-saline water is used for salt sensitive crops/initial stages of tolerant crops to leach out the accumulated salts from irrigation with salty waters to previously grown tolerant crops. However, such a management strategy may work better for arid climates with very low rainfall, as it tends to occur naturally under the Monsoonal and Mediterranean climates where crop seasons start with rainfall leached surface soils. Thus, the options of utilising multi-quality waters have to be either mixing or cyclic use, mainly during the growth of dry season crops. Presuming that the prerequisite facilities for blending exist and different qualities of waters are simultaneously available on demand, then the question arises as to which option should be followed. Analysis of a large number of experiments (Minhas and Gupta, 1992; Minhas, 2012) showed that, at the same level of EC_w (weighted average salinity), the yields for various cyclic use modes were higher than those estimated for mixing. For example, when relative yield (Y_r) with blended water was 0.50, that obtained with cyclic irrigation modes of 2FW:1SW, 1FW:1SW and 1FW:2SW (canal: saline water irrigations) were estimated to be 0.67, 0.59 and 0.56, while for Y_r of 0.75 with blending, the respective Y_r with cyclic modes were 0.84, 0.79 and 0.77. This indicated the benefits of cyclic strategies as mean EC_{iw} increases. Moreover, this analysis provided useful evidence that multi-salinity waters should be used cyclically where better quality water is applied at early stages and the use of saline waters should be delayed to later stages. Similar results were obtained with combined irrigation with waters having residual alkalinity where fresh waters were used initially to better obviate the impact of sodicity in soils (Chauhan et al., 2007; Minhas et al., 2007, 2019). More recent numerical studies have suggested that sensor-based triggered alternate irrigation of fresh and higher salinity treated wastewater within crop growing seasons can minimize negative effects on crops and reduce contamination of deep soils and groundwater (Russo et al., 2015; Russo, 2016). In addition to better performance of crops, the cyclic uses have operational advantages over mixing since they do not require the creation of infrastructure for mixing the two supplies in desired proportions.

6. Conclusions and recommendations

Among the edaphic constraints hindering crop growth, development of salinity is considered an adjunct to irrigated agriculture for the reason that the most saline soils exist in irrigated areas of arid and semi-arid regions. Agronomic interventions and innovative techniques are now available for overcoming salinity constraints and providing resilience to agriculture on the affected soils. Efficient leaching management, proper irrigation methods and schedules, appropriate conjunctive use of saline and fresh water modes, and the micro-irrigation systems like drip, modernized precise leveled and flow rate regulated surface irrigation systems, are all effective means to obviate the salinity impacts.

For predicting salt balance and optimizing crop growth in saline environments, both steady and transient state models have been developed which are becoming increasingly user friendly. Simplified approaches for crop ET computation are available when adopting the FAO56 framework, which are designed to assess crop water requirements, supporting irrigation scheduling and planning irrigation management under salinity stress conditions. Actual crop ET as affected by salinity and water stress may be computed by adopting single and dual K_c approaches though using a stress coefficient that considers those two stresses (Eqs. (17) and (22)). Reviewing various applications, the advantage in using the FAO56 framework for computing ET_c act under salinity conditions was demonstrated, mainly when partitioning ET when adopting the dual K_c approach, and evidencing the simplicity of approaches.

Considering some of the recent advances on crops responses to salinity it was possible to identify research issues that may contribute for refinements in using the FAO56 approach, which include:

- In FAO56 approach, computations of the daily values of the stress coefficient (K_s) are based upon the responses of the crops to water and salinity stresses. For the latter, the unified linear salt response function of the crop is parameterized adopting the crop-specific constants $EC_{e\ threshold}$ and slope 'b'. However, it is progressively known that tolerances to salinity stress may vary along the crop season. Since K_s is computed daily, it is advisable that the salinity response parameters used to compute K_s (Eqs. (17) and (22)), mainly the factor b, can change dynamically throughout the season when there is enough information for establishing their dependence on time. There is no difficulty in adopting time dependent parameters in the daily computed K_s function but this is dependent on availability of reliable information regarding the dependence of the parameters over time. It is therefore recommended that research investigate and provide improved approaches to the parameterization of b and $EC_{e\ threshold}$, as well as of K_y yield response factors.
- The Maas and Hoffman (1977) linear crop salinity response function tends to be replaced with a sigmoid function based on the crop specific values of EC_{e50} and the exponent P_{Yr}, (e.g., Eq. (3)) since these functions better represent inherent salt tolerance behavior. On the one hand, research is required to extend the availability of EC_{e50} and P_{Yr} valuesto ease the use of that sigmoid function (Eq. (3)); on the other hand, research is required to find linear approximations of those curves to be usable for computation of K_s with the FAO56 approach. In addition, it is required that such approximations be evaluated against field observations and/or other well-calibrated

transient state model.

- Concentrations of salts in the soil are a function of ion pair formation and precipitation of salts occurring during root water uptake, and osmotic effects may be lower than expected. Computation of K_s and, therefore, the predictive ability of the FAO56 approach would thereby benefit from related adjustments of the parameters $EC_{e\ threshold}$ and slope b using effective salinity based upon ionic constituents of salinity. Research is required to provide means for adjusting those parameters values when osmotic effects may be lower than commonly predicted.
- Applications using the dual K_c approach in saline stress environments are still very scarce and are totally absent for woody fruit/forestry tree crops. With their deep and extensive root systems, trees can better adjust to both spatial and temporal heterogeneous salinity. Thus, there is the need to extend research to these crops to better assess anyneed for introduction of refinements in the methodology and, mainly, for validation through the comparison of $ET_{c\ act}$ values with measured data and/or well-calibrated transient state model estimates.
- The current FAO56 approach is mainly for ET predictions under saline conditions while more than half the global salt-affected soils are afflicted by various levels of sodicity. Sodicity response functions of crops are now available. When applied with predictions on soil solute composition as a result of chemical interactions and the impact of these changes on water transmission characteristics of soils vis-à-vis root water uptake, simplistic formulations should be possible for FAO56 assessments under sodic soil conditions. Related research is required that provides for appropriate parameters to be used in K_s calculations, thus for the water balance and $ET_{c\ act}$ computation.

Declaration of Competing Interest

There is no conflict of Interest.

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