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Key Points:

- Advanced models are key to managing the risks and benefits of irrigating with saline waters
- We examine leading models for studying the effects of salinity and sodicity on plant health and soil structure
- We focus on dynamical models, which can be used to analyze how climate and irrigation affect plants and soils over time

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Review: Modeling the Effects of Salinity and Sodicity in Agricultural Systems

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Abstract Soil salinity and sodicity are major concerns in agricultural systems, threatening plant growth in the short term and soil health in the long term. Despite these risks, use of marginal quality water with high salt concentrations is often essential to maintaining food production, especially in arid and semi-arid regions. Leveraging our understanding of basic soil processes and feedbacks is essential for ensuring sustainable use of marginal quality water and land. Models are an important component in effective management, since they allow us to investigate large numbers of potential future scenarios, augmenting our ability to predict the consequences of agricultural practices. In this review, we examine the most advanced models for studying the effects of salinity and sodicity on plant health and soil structure. We place special emphasis on the integration of these frameworks into dynamical models, which can be used to examine how changing climate and irrigation conditions lead to evolving plant and soil responses over time. We highlight important differences in existing modeling frameworks, especially with regard to their relative complexity and suitability for integration into larger climate models. We overview important applications of these models, including studies of localized leaching of salts, complex ion chemistry, the dynamics in layered profiles, and the risk of long-term soil degradation as a result of particular irrigation practices.

1. Introduction

In the face of rising water scarcity, spurred by growing human populations and climate change, policy makers and farmers are increasingly reliant on treated wastewater and brackish water as critical sources for irrigation (Assouline et al., 2015; Bixio et al., 2006; Levy, 2011; Oster, 1994). While integration of these and other marginal quality water sources can help maintain food production under conditions of growing demand, it also introduces its own set of environmental hazards. Marginal quality water resources often have higher salinity concentrations than freshwater (Assouline & Narkis, 2013; Levy, 2011; Schacht & Marschner, 2015). When not managed properly, salinity can lead to declining plant yields and irreversible damage to soils (Assouline & Narkis, 2011, 2013; Bardhan et al., 2016; Hillel, 2000; Läuchli & Grattan, 2011; Levy, 2011; Mandal et al., 2008; Schacht & Marschner, 2015; Shainberg & Singer, 2011). Because of this, salinity and sodicity are considered major drivers of land degradation—affecting as much as 50% of irrigated land, leading to billions of dollars in economic losses, and threatening global food security (Daliakopoulos et al., 2016; FAO & ITPS, 2015; Ghassemi et al., 1995; Howitt et al., 2009; Prăvălie et al., 2021; Qadir et al., 2014; Wallender & Tanji, 2011; Wicke et al., 2011). The extent of global salinity is presented in Figure 1, which relies on data compiled by the FAO's Global Map of Salt-Affected Soils (FAO, 2023), an ongoing initiative to survey salinity distribution across all countries. Although the data are incomplete, it is clear that arid regions are amongst the most affected by soil salinity. Many of these areas are key to world agricultural productivity and also home to rapidly growing populations.

Compounding the dangers posed by salinity and sodicity is the fact that over the long term, unaddressed land degradation can lead to a net increase in carbon emissions, and therefore a negative feedback on climate (Olsson et al., 2019). Given the potential benefits and dangers of dependence on saline waters, effective models are essential to facilitate sustainable management (Assouline et al., 2015; Hopmans et al., 2021; Oster, 1994; Vereecken et al., 2016). Such models can be used to analyze the complex interactions between soil and plant systems, and the main drivers of their dynamics, namely climate and irrigation. As pressures on global food supplies rise under growing populations, efficient management of marginal quality land and water resources will become increasingly important to ensuring reliable and secure agricultural output.

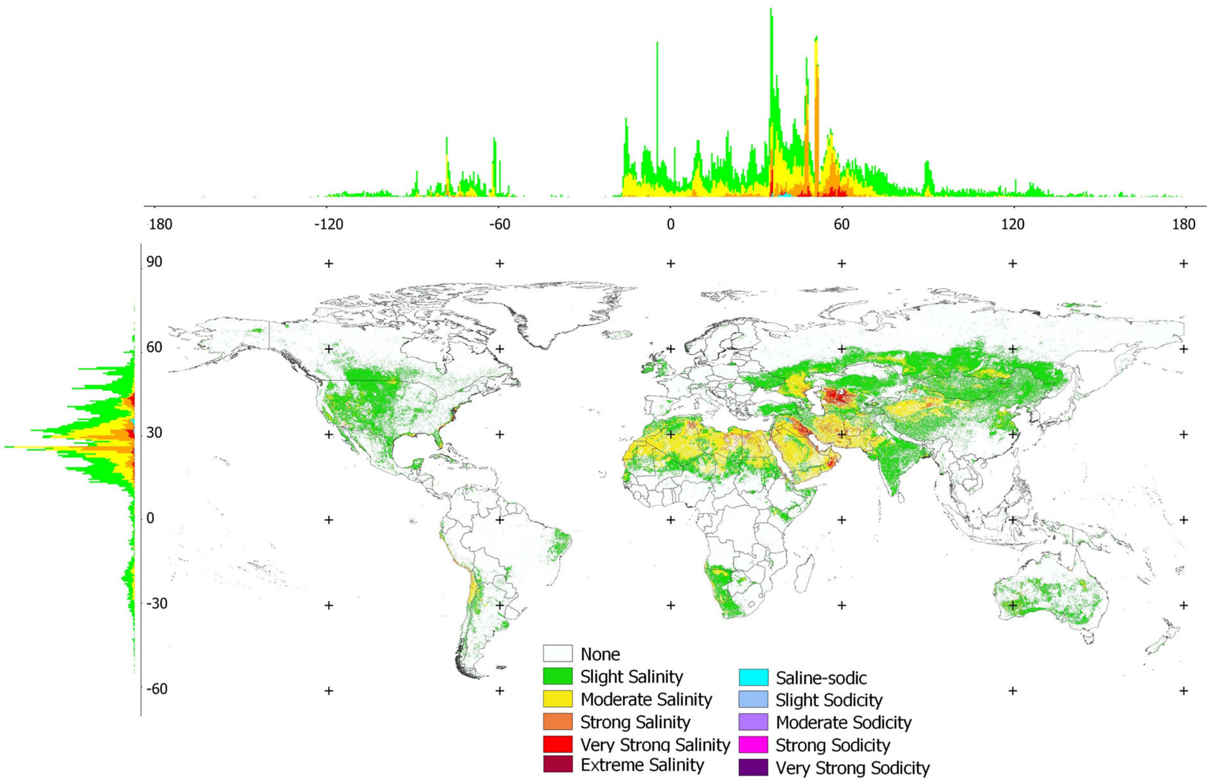

Figure 1. Major agricultural producing regions across the world are the most affected by surface level salinity, according to FAO effort to map salinity issues among UN member states. Data collection from members states is ongoing and regularly updated on the FAO's website (FAO, 2023). Figure reprinted with permission from FAO and Christian Omuto (Global Salt-Affected Soils Map, v2.0, 2023).

The aim of this review is to compare the most important modeling frameworks developed for studying salinity and sodicity in agricultural systems. We begin by briefly outlining how salinity and sodicity affect agricultural systems (Section 2) and then discuss models that have been developed for the study of their effects on soil structure (Section 3) and plant functioning (Section 4). In Section 5, we examine dynamical models, which facilitate the study of how soil salinity and sodicity conditions evolve over time, and how these changes affect soil structure and plant output. We then overview some of the most significant applications of these models—studies that simulate expected plant yields in conditions of changing salinity, soil degradation risk over time, and the effectiveness of specific rehabilitation methodologies (Section 7). Finally, we discuss the most pressing gaps in present modeling capabilities and priorities for future research (Section 8).

2. Effects of Salinity and Sodicity on Plants and Soils

2.1. Soil Salinity

Soil salinity refers to the concentration of various electrolytic mineral solutes—most commonly sodium, calcium, magnesium, chloride, and sulfate ions; less commonly nitrate and potassium—in the soil solution (Bernstein, 1975; McGeorge, 1954). Salinity can be measured as the electrolyte concentration in the soil solution ($\mathrm{mmol_c\,L^{-1}}$). It is more common, however, to use electrical conductivity ($\mathrm{dS\,m^{-1}}$) as a proxy for salinity, due to its ease of measurement, with the rule-of-thumb conversion: $1\ \mathrm{mmol_c\,L^{-1}} \approx 10\ \mathrm{dS\,m^{-1}}$ (McGeorge, 1954).

As the osmotic pressure of the soil solution rises, it becomes increasingly difficult for plants to extract water from the root zone (Bernstein, 1975; Maas & Grattan, 1999; Munns, 2002; Tanji & Kielen, 2002). Plants in highly saline conditions, therefore, often experience stresses similar to those of plants facing drought (Bernstein, 1975; Maas & Grattan, 1999; Munns, 2002; Tanji & Kielen, 2002). Certain crops, for example, corn and potatoes, are extremely sensitive to saline conditions, with yields beginning to decline at concentrations as low as 20 $\mathrm{mmol_c\,L^{-1}}$ (Maas & Grattan, 1999). Other species, including barley and cotton, are comparatively resilient, with yields declining only when concentrations approach 80 $\mathrm{mmol_c\,L^{-1}}$ (Maas & Grattan, 1999).

The input of salts to soils can occur from both primary (erosion of rocks with high salinity content, ocean spray, or seawater intrusion) and secondary (human) sources. This review focuses on models used to study secondary salinity in agricultural systems, most commonly resulting from irrigation with marginal quality waters that are high in salt content, or irrigation practices and land-use changes that cause a rise in saline groundwater.

2.2. Soil Sodicity

Soil sodicity refers specifically to the relative concentration of sodium bonded to exchange sites on the surface of clay and organic matter, called the exchange complex. As water of varying chemical composition enters and exits the root zone, exchange between the soil water and soil surface affects the distribution of cations adsorbed to the exchange complex. The relative fraction of sodium ions in the exchange complex is important because high concentrations of monovalent cations are known to cause the breakdown of bonds between soil particles, resulting in the dissolution of soil aggregates (Bardhan et al., 2016; Levy, 2011; McGeorge, 1954). Damage to soil aggregates inhibits the easy movement of water and air in a soil's root zone, thereby threatening plant growth (Bardhan et al., 2016; Levy, 2011; Mandal et al., 2008; McGeorge, 1954).

The relative fraction of sodium ions in the exchange complex is typically referred to as the Exchangeable Sodium Percentage (ESP). When the exchange complex is in chemical equilibrium with soil water, the Sodium Adsorption Ratio (SAR) is a useful measure of sodicity (McGeorge, 1954). The commonly used Gapon Equation is based on exchange isotherm considerations, and it relates the SAR and ESP (Sposito, 1981). Most experimental and modeling studies have focused on the role of sodium in causing aggregate breakdowns, since it is the most common monovalent cation in soils. Recent works, however, have attempted to integrate the effects of less common monovalent cations. Notably, the CROSS ratio considers the effects of both Na and K cations on clay dispersion and Ca and Mg cations on clay flocculation (Bennett et al., 2016; Rengasamy & Marchuk, 2011).

2.3. Saturated Hydraulic Conductivity

The effect of changing chemical conditions on soil structure can be analyzed through changes in saturated hydraulic conductivity, K_s (mm/day). Abundant field and laboratory experiments have demonstrated that while moderately sodic conditions may cause small declines in K_s via the temporary swelling of clay particles, more extreme inputs can cause an actual breakdown of the bonds between soil particles, leading to irreversible dispersal of clay particles and long-term destruction of soil aggregates (Bhardwaj et al., 2008; Dang et al., 2018, 2018a, 2018b; Levy et al., 2005; McNeal et al., 1968; Menezes et al., 2014; Oster & Schroer, 1979; Shabtai et al., 2014). The exact thresholds at which this transition from reversible to irreversible damage occurs is highly soil specific, dependent on clay mineralogy, and other factors (Bennett et al., 2019; Dang et al., 2018, 2018a, 2018b; Frenkel et al., 1978; Levy et al., 2005; McNeal et al., 1968; Menezes et al., 2014; Quirk & Schofield, 1955; Y. Zhu et al., 2019). The USDA initially identified ESPs above 15 as dangerous for soils (McGeorge, 1954), while other experimental work has demonstrated that ESPs as low as five can cause serious soil damage (McIntyre, 1979; Oster & Schroer, 1979).

3. Modeling the Effect of Soil Salinity and Sodicity on Soil Structure

Given the threat of damage to K_s, models that can offer insight into how soil structure will respond to changing chemical conditions are critical. Declines in K_s are most likely to occur when there is a precipitous drop in overall salinity concentration, but the relative fraction of sodium ions bonded to the soil's surface remains high (Adeyemo et al., 2022; McNeal & Coleman, 1966; Shainberg & Letey, 1984; Shainberg & Singer, 2011). In arid and semi-arid regions, these conditions are common when irrigation with saline water is followed by rainfall-induced leaching. Intense precipitation events can lead to large declines in the salinity concentration of the soil solution, while the ESP remains high, since changes to the soil exchange complex occur on a slower time scale (Kramer & Mau, 2020; Mau & Porporato, 2015; Shainberg & Shalhevet, 1984; van der Zee et al., 2014). In what follows, we overview models for the effect of salinity and sodicity on K_s that were developed based on data from soil column experiments that replicate this change in chemical conditions. Additionally, several mechanistic models have been developed by incorporating theoretical knowledge of the soil electric double layer.

3.1. Empirical Models

The framework developed by McNeal (1968) exemplifies the empirical approach to modeling the effect of chemical composition on K_s. The model itself is based on the results of experiments (McNeal & Coleman, 1966) in which declines in K_s were measured as water of progressively lower EC was applied to soil columns, while SAR was held constant. The experiments were repeated for several SAR values and the collected data was used to fit a model (an algebraic equation) for the fractional reduction in K_s, given two inputs: salinity concentration and soil ESP. While the McNeal model includes soil-specific parameters, such as the fraction of montmorillonite clay and the ESP at which declines in relative K_s first begin, applications have nearly always relied on the original values assumed by McNeal. This simplification eliminates the possibility of comparing between soils, but it has arguably been a major factor in the wide incorporation of the McNeal model into dynamical models (Section 5).

An incremental improvement on McNeal, presented by Ezlit et al. (2013), addresses some of the former's limitations with regards to soil-specific differences. Beginning with the same experimental framework used by McNeal, Ezlit et al. seeks to clarify the soil-specific boundary between clay flocculation (largely reversible) and the disaggregation of soil aggregates (irreversible). In effect, Ezlit's model reparametrizes McNeal's model so that it can be used to calculate relative K_s for given salinity and sodicity values on a soil-specific basis.

The McNeal and Ezlit models share an important assumption: they are based on experiments in which EC only declines, despite the fact that EC and SAR regularly increase *and* decrease in agricultural systems, in response to changes in root zone inputs and outputs. Fluctuations in salinity and sodicity have been shown to cause hysteresis in relative K_s (Adeyemo et al., 2022; Dane & Klute, 1977), but neither Ezlit nor McNeal can capture this phenomenon. Instead, both models implicitly predict increases in relative K_s will occur as if any prior decline was completely reversible in nature. When integrated into dynamic models (Section 5), this can produce misleading results, wherein relative K_s rapidly jumps when the chemical composition of the input water improves, despite ample field evidence that declines in relative K_s following the application of high-SAR water are often irreversible (Assouline & Narkis, 2011; Bhardwaj et al., 2008; Schacht & Marschner, 2015).

Kramer et al. (2021) targets the issue of hysteresis, presenting a model for the effect of salinity and sodicity on relative K_s that explicitly accounts for irreversible declines in relative K_s. The Kramer model considers soil-specific differences in hysteresis patterns, both with respect to susceptibility to degradation and propensity to rehabilitation. The Kramer model achieves this flexibility by adapting the Preisach model for hysteresis (Mayergoyz, 1986). Parameterizing the Kramer model requires a set of experiments that begins similarly to those utilized by McNeal and Ezlit. In contrast, Kramer requires that K_s also be measured as water of increasing quality is applied to the soil, following its initial decline (Adeyemo et al., 2022; Kramer et al., 2021). While validation has shown that the Kramer model can successfully capture observed hysteresis trends in soils (Adeyemo et al., 2022), the experiments required to parameterize it are significantly more demanding than those needed for the Ezlit or McNeal models, both with respect to time and labor. Their difficulty is a limiting factor in the wide-scale application and validation of the Kramer model. Likewise, the computational and programming requirements to implement the Kramer model are significantly higher than those of the McNeal or Ezlit models. In situations with limited computer capacity or expertise, users are likely to find the Ezlit or McNeal models more accessible.

3.2. Theoretical (Mechanistic) Models

Another set of models for the effect of salinity and sodicity on K_s are theoretical models, notably those developed by Russo (Russo, 1988; Russo & Bresler, 1977) and Lagerwerff et al. (1969). These models are based on diffuse double layer theory and incorporate earlier works linking water flow rates to soil porosity (Childs et al., 1950; Marshall, 1958; Millington & Quirk, 1959). A significant advantage of these models is that they capture the state of knowledge around the relationship with actual soil properties. This frees them from the constraints of soil-specific experiments, and allows users to efficiently explore the models' sensitivity to various parameters. In other respects, however, these models are less flexible than their empirical counterparts. In particular, the mechanistic models are dependent on imperfect double layer theory and ionic functions to explain the swelling processes in soils (Ezlit et al., 2013; Lagerwerff et al., 1969). In focusing on explaining swelling processes, these models do not take into account changes in K_s that might result from dispersion of clay particles. Dispersion of clay particles is a key element in the breakdown of soil aggregates, which can cause the type of irreversible declines in K_s discussed in Section 2.3 (Russo & Bresler, 1977). Finally, while parameterization of these models is not dependent on experimental work, it does still require extensive knowledge of soil properties. The Russo model, for instance, requires measurements of the specific surface area of the soil and water content-pressure relationships, and should be used only when montmorillonite is the dominant clay (Russo & Bresler, 1977). It is also sensitive to accurate estimation of the number of platelets per clay particle (Russo & Bresler, 1977).

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4. Modeling the Effects of Salinity on Plant Functioning

Models for the effects of salinity on plant functioning are used to predict how varying salinity concentrations will affect transpiration and, ultimately, yield. Such models have been extensively reviewed (Minhas et al., 2020), and so we present only a short summary here.

For the most part, models for plant response to salinity consider steady-state conditions in which salinity concentration and soil water content remain constant. The most basic steady-state models use simple linear functions in which declines in yield are based on a particular plant's sensitivity thresholds (Ayers & Westcot, 1985; Maas & Hoffman, 1977). The FAO's guidelines for computing crop water requirements adopt this approach, linking salinity concentrations to changes in expected evapotranspiration (Allan et al., 1998). The FAO model considers the threshold EC at which a specific crop begins to experience decreases in yield and the rate of decline thereafter (Allan et al., 1998). This approach is implemented in the AquaCrop model (Salman et al., 2021), which is designed to study the effects of water shortages on crop productivity.

More complex mechanistic models include Shani et al. (2007) and Skaggs et al. (2014). Shani et al. develop a mechanistic model that can be used to analytically solve for the effect of root zone salinity and water status on plant transpiration, which serves as a proxy for total yield. The model is capable of considering various plant species, climates conditions, soil characteristics, and irrigation practices. The Skaggs et al. model takes a similar approach, but uses explicit equations that do not require an iterative approximation to solve (Minhas et al., 2020; Skaggs et al., 2014). The Skaggs et al. model also considers two alternative mechanisms for reduced plant water uptake (Skaggs et al., 2014). Numerous experimental works have supported the overall effectiveness of the Skaggs and Shani models (Karlberg et al., 2006; Shani et al., 2007; Skaggs et al., 2014).

Perri, Entekhabi, and Molini (2018) and Perri et al. (2019) developed plant osmoregulation models that explain the different transpiration profiles of glycophytes and halophytes as a function of soil salinity. These models assume a storage compartment in the plant, that helps regulate water fluxes and internal salt concentration. This storage module is then coupled with other modules for stomatal regulation, xylem vulnerability curve, root filtration, and carbohydrates production and transport, into a coherent soil-plant-atmosphere continuum (SPAC) model. Perri assumes short time scales of minutes to hours, where salt-stress is mostly due to osmotic effects, while longer ionic stress (toxicity) effects are neglected. Nevertheless, the models offer an elegant minimalistic account of the emergent behavior of salt tolerance.

5. Dynamical Models

In regions where annual precipitation is above 500 mm, rainfall is generally a sufficient control on the ill effects of irrigating with high salinity water (Lado et al., 2012). In arid and semi-arid regions, however, active management is often necessary to prevent dangerous salinity and sodicity buildup. Historically, the primary mechanism for lowering salinity levels in agricultural systems has been through leaching, that is, the application of more water than required for plant and evaporative demands. Leaching stimulates the downward movement of water, and with it suspended solutes, out of the soil's root zone. The simplest models for calculating a soil's leaching requirements are based on steady-state systems, with constant input conditions. Such models have been reviewed extensively (Corwin et al., 2007; Corwin & Grattan, 2018; Hoffman, 1985; Letey et al., 2011; Oster, 1994; Rhoades, 1968; Van Hoorn, 1981; Visconti et al., 2012).

Here, we focus on more sophisticated models, which allow for the study of how salinity and sodicity dynamics evolve over time, as driven by irrigation, climate conditions, and soil properties. At a minimum, these models feature equations for water flow through the root zone and transport of solutes under conditions of variable saturation. They differ with regards to their treatment of water infiltration and drainage, feedback on K_s, and methods for determining rainfall inputs, among other features. Such models have a number of advantages over basic models for calculating leaching requirements. Leaching, by definition, leads to wasted resources. When leached water contains salts and other solutes, it can also constitute a significant source of pollution, endangering the quality of groundwater, streams, rivers, or other bodies to which the drainage flows (Assouline & Shavit, 2004; Schoups et al., 2005). Likewise, leaching focuses primarily on salinity hazards, while ignoring the equally important risk of soil degradation posed by high sodicity. Dynamical models can effectively address each of these issues.

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5.1. Soil, Plant, and Atmospheric Dynamics Using the Richards Equation

The most common method for modeling salinity in soils has been to combine the Richards equation for unsaturated water flow and some form of the advection-diffusion equations for solute transport. Models that rely on this approach include Hydrus (Šimůnek et al., 2013; Šimůnek & Suarez, 1994), SWAP (Kroes et al., 2017), RZWQM2 (Ma et al., 2012), WAVES (L. Zhang et al., 1999a), LEACHC (Hutson & Wagenet, 1995), SALTMED (Ragab, 2002), SWS (Suarez, 2011), and the Russo model (Russo, 1984, 1988, 2013; Russo et al., 2004).

A major advantage of the Richards and advection-diffusion approach is that together the equations can accurately model solute and water dynamics at both high spatial and temporal resolutions. This makes it possible to use these models to study questions related to the localized leaching of salts, the effects of a single irrigation event, complex ion chemistry, or the dynamics in layered profiles, where soil physical and chemical properties are spatially variable (Section 7). Less advantageous, it has been argued that the Richards equation can be computationally expensive for simulations with small time steps (Kramer & Mau, 2020; Mau & Porporato, 2015; van der Zee et al., 2014). The Richards Equation has also been shown to fail under certain conditions, such as a fast wetting rate (Farthing & Ogden, 2017; Short et al., 1995; Tocci et al., 1997) and preferential flow (Brindt & Wallach, 2017, 2020), which is common in saline conditions (Brindt et al., 2019). This can be an obstacle to the study of questions related to climate, for example, where a user might want to examine thousands of different parameters at once, on sub-daily time scales (Kramer & Mau, 2020; Mau & Porporato, 2015).

Hydrus, SWAP, and RZWQM2 are the most widely used models of this category, and the only ones for which regularly maintained software is available. All three are extensive applications, which can be used to study a range of processes in the vadose zone—not just those related to salinity dynamics. Hydrus, in particular, has been widely applied to the study of salinity and sodicity in one-, two-, and three-dimensional environments (Section 7). Chemical exchange in Hydrus is determined using the UNSATCHEM module, which can account for equilibrium chemical reactions, including cation exchange and precipitation-dissolution (Šimůnek et al., 1996). (The SWS model also uses a modified version of UNSATCHEM).

SWAP (Soil, Water, Atmosphere, Plant) and RZWQM2 (Root Zone Water Quality Model) likewise, focus on the transport and exchange of salts and other solutes, albeit for 1D profiles only. While the extensive nature of SWAP, RZWQM2, and Hydrus can allow for the simultaneous study of several complex environmental processes, it is worth noting that they require users to have a minimal understanding of an entire suite of soil processes before operating the software, thus imposing an entry barrier for novice users interested in studying a single process. Earlier reviews cover some of the primary differences in software requirements, relative strengths, and weaknesses of these models (Corp., 2003; Ditthakit, 2011; Goel & Tiwari, 2013; Nolan et al., 2005).

5.2. Other Richards Equation-Based Models

The model developed by Russo likewise relies on the Richards and advection-diffusion equations, focusing exclusively on the movement and exchange of calcium and sodium cations in 1D or 3D soil profiles. Focusing on Ca^{2+} and Na^{+} is common when the user wants to study salinity apart from other soil chemical processes, since it emphasizes the contrasting effect of monovalent and divalent cations on soil structure, and because sodium is far more common than other monovalent cations (Bernstein, 1975; McGeorge, 1954). The most distinctive aspect of the Russo model is its consideration of a spatially heterogeneous soil profile, achieved through stochastic distributions of soil parameters. While similar examinations of heterogeneous soil profiles can be handled by many of the modeling frameworks discussed here, doing so requires pre-programming of inputs and post-processing of results.

WAVES, SALTMED, and LEACHC offer the most narrow applications of the Richards and advection-diffusion equations approach. LEACHC, part of the LEACHM suite of models, focuses on the movement of water and solutes in a 1D layered soil profile, with modules for crop growth and solute exchange. WAVES and SALTMED take simplified approaches to solute transport, leaving aside exchange between the solution and soil matrix, which is crucial for understanding the effects of soil sodicity.

Friedman and Gamliel (2021) applies the DIDAS model (Friedman et al., 2016) to study salinity management for systems using drip irrigation. The model can account for seasonal salt accumulation under changing climate and irrigation conditions, with an evolving root-zone and under differently arranged driplines and drippers. The

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DIDAS model, it is important to note, focuses only on changes in salt mass balance and does not consider chemical exchange or precipitation.

5.3. Non-Richards Equation-Based Models

An alternative approach, which eschews reliance on the Richards and advection dispersion equations altogether, is offered by SOTE (Kramer et al., 2022; Kramer & Mau, 2020) and its earlier versions (Mau & Porporato, 2015, 2016), and a series of models developed by van der Zee et al. (S. H. Shah et al., 2011; van der Zee et al., 2010, 2014). These models favor mathematical and computational simplicity over precision, and focus exclusively on salinity and sodicity dynamics. While this limits users interested in the additional soil processes included in Hydrus and SWAP, for instance, it reduces the processing power and time needed to run these programs, making them more amenable, for example, to coupling with climate models. The simplicity of these models is also, arguably, an advantage in terms of analysis, allowing for more accessible insights into the connection between input conditions and simulation results.

SOTE and the van der Zee models are similar in structure, with each featuring three differential equations, one each for water, salinity, and sodicity dynamics. In both models, drainage and evaporation are determined using well-known ecohydrological and pedotransfer functions (Laio et al., 2001; Rodríguez-Iturbe & Porporato, 2005), thus forgoing the complexity of the Richards equation. Most importantly, neither of these models have a spatial component, averaging the variables in the root zone using a bucket-model approach. As in the Russo model, chemical exchange is restricted to Ca^{2+} and Na^{+}, to emphasize the difference between monovalent and divalent cations, which is critical to understanding degradation risk. Both models also use the Gapon equation for chemical exchange between the soil solution and soil surface. A major area of difference between the two models is their focus on the source of salts. The van der Zee models prioritizes input of salts from groundwater. While SOTE can accommodate groundwater inputs, it has mainly been used to study the input of salts from irrigation.

Shah et al. modify the well-known DNDC model to include the effects of salinity on soil water (Hussain Shah et al., 2021, 2022; S. H. H. Shah et al., 2022). Originally developed to predict carbon and nitrogen dynamics in agricultural systems, the DNDC model (C. Li et al., 1992) connects soil water dynamics with plant growth, nutrient cycles, and carbon and nitrogen emissions. Shah et al. adapt this framework so that it includes salt transport equations, which allow for the study of the effects of salinity on soil water movement and vegetation growth on a daily time scale. The Shah et al. model does not explicitly consider sodicity changes.

Finally, SaltMod (Mao et al., 2017; Oosterbaan, 2001) is another program that strives to be a simple tool for salinity management. Like SOTE and van der Zee, SaltMod avoids the Richards equation in favor of a simpler description of water flow dynamics. SaltMod, however, is designed to analyze salinity levels on a seasonal basis, and cannot accommodate the analysis of input or output on smaller time resolutions. SahysMod expands upon the Saltmod framework for analysis of larger spaces (Inam, Adamowski, Prasher, & Albano, 2017; Inam, Adamowski, Prasher, Halbe, et al., 2017; Singh & Panda, 2012).

5.4. Hydraulic Conductivity Feedback

A major area of difference between the discussed models is their consideration of how changing chemical conditions affect K_s. Hydrus (Šimůnek et al., 2013) and van der Zee (van der Zee et al., 2014) implement versions of the McNeal (1968) model to calculate relative K_s at particular salinity and sodicity levels, with Hydrus also considering pH. Likewise, the dynamical Russo model integrates Russo's mechanistic framework for declines in K_s (Russo & Bresler, 1977). As discussed in Section 3, neither the McNeal nor the Russo frameworks include the effects of hysteresis on K_s. Furthermore, the McNeal model, as implemented by Hydrus, does not consider soil-specific differences in susceptibility to degradation. Dynamical models that integrate the McNeal and Russo frameworks are therefore limited in their ability to quantify realistic changes in K_s as chemical conditions evolve. When used to forecast the risk of longterm soil degradation they are likely to provide unrealistically low probabilities of declines in K_s (Kramer et al., 2022).

SOTE (Kramer et al., 2022), by contrast, incorporates the Preisach-based framework developed by Kramer (Kramer et al., 2021). SOTE's hysteresis-based K_s function can be computationally demanding if the user runs thousands of stochastic simulations (Kramer et al., 2022). Running a smaller number of simulations, however, is unlikely to significantly affect the model's run time and enables users to study how soils with varying susceptibilities to degradation and propensities to rehabilitation will respond to evolving input-water conditions. Aside from the models discussed in this subsection, all other dynamical models ignore any effect of changing chemical conditions on K_s, precluding their use as tools to study sodicity as a cause of soil degradation.

5.5. Feedbacks on Plant Growth

Several of the models introduced in Section 5 can model the effects of changing salinity on plant output, in various capacities. In Hydrus, root water uptake can be limited by osmotic stress, with changes in crop yield represented through actual and potential crop evapotranspiration (Karandish & Šimůnek, 2019). Likewise, SALTMED also connects root water uptake to salt concentrations, but can simulate actual crop yields during the growing cycles (Karandish & Šimůnek, 2019). Invidual studies have attempted to couple the dynamic models with crop growth modules, including the pairing of the EPIC model and Hydrus (Feng et al., 2021). SWAP simulates plant growth through the integration of the WOFOST cropping model (de Wit et al., 2019; Kroes et al., 2017; Kroes & Supit, 2011). WOFOST does not, however, explicitly consider the effects of salinity as a limitation on plant growth, thereby limiting the integrated models ability to predict the effects of changing salinity on plant health (J. Zhu et al., 2018). Likewise, RZWQM2 integrates the DSSAT model for plant growth, but the version of DSSAT used by RZWQM2 does not include the effects of salinity (Jones et al., 2003). WAVES considers the effects of salinity on carbon assimilation by plants and water availability, and has been shown to effectively model declines in yield due to severe salinity stress (Yu et al., 2021; L. Zhang et al., 1999b). Finally, SALTMED also includes equations for crop water uptake and relative yield, in which higher osmotic pressure can result in reduced water uptake by plants (Alkhasha & Al-Omran, 2019; Chauhdary et al., 2020; Silva et al., 2012). A detailed examination of the different plant models used by dynamical models for salinity, including comparisons of expected effects on yield is presented by Oster et al. (2012).

6. Other Models of Note

The dynamical models discussed so far focus on field-level analysis of secondary salinity, which is crucial for the effective management of salinity and sodicity in agricultural areas. We note, however, several recent models that are slightly outside of this scope, yet still might be of interest to policy makers and the wider soil science community. Hassani et al. utilize machine-learning techniques and available soil and climate data to develop a model capable of predicting regions in which salinity levels are most likely to be affected by climate change (Hassani et al., 2020, 2021). Perri et al. use simple stochastic models to study how primary soil salinity limits plant uptake of water, thereby acting as a form of aridity in many landscapes (Perri, Suweis, et al., 2018; Perri et al., 2020). On a regional level, Bailey et al. (2019) present a version of the SWAT model which can be used to study salt transport on the watershed scale. Finally, Vermeulen and Niekerk (2017) use machine learning techniques to identify areas most at risk to soil salinization based on geomorphic features, including topography.

7. Applications

Of all the dynamical models reviewed in Section 5, Hydrus has been the most widely applied to study the effects of salinity and sodicity on soils and rehabilitation techniques. Over 100 published papers have used Hydrus to investigate questions related to salinity and sodicity. While an overview of all of these papers is outside the scope of this article, in this section we highlight some of the most important research trends involving Hydrus and the other models covered in this review.

As noted in Section 5, Hydrus is particularly well suited to the study of field-scale conditions. One of the most common applications of Hydrus has been to compare simulated results to outcomes from field experiments. Multiple studies (Gonçalves et al., 2006; Ramos et al., 2011) have shown that Hydrus is able to satisfactorily track soil water content, salinity concentration, soil ESP, and other solute concentrations in simulations that replicate several-year field and lysimeter experiments using standard irrigation practices. Likewise, it has been demonstrated that Hydrus can be used to compare the effects of different irrigation practices, involving water of changing chemical compositions (Mallants, Šimůnek, & Torkzaban, 2017; Mallants, Šimůnek, van Genuchten, & Jacques, 2017; Phogat et al., 2018), responses to deficit irrigation conditions (Ramos et al., 2019), and different mulching techniques (Chen et al., 2022; Selim et al., 2013).

Hydrus simulations have also been widely used to study leaching efficiency. Shaygan et al. (2018) analyze Hydrus simulations against leaching experiments in which soils were treated with various physical amendments, while Berezniak et al. (2018) studied the effect of modifications to textural distributions in the soil profile on leaching of salts using both experimental lysimeters and Hydrus simulations. In this study, both Hydrus and the experimental results demonstrated that the introduction of a volume of coarse soil, located under a drip irrigation emitter, surrounded by finer texture soil increased leaching efficiency in the area around the dripper (Berezniak et al., 2018). Simulations by Yang et al. (2019), however, found that removal of salts from the root zone was more pronounced with sprinkler irrigation than with drip irrigation. Y. Zhang et al. (2021) study the efficacy of surface water leaching at various stages of growth and find that earlier leaching applications can reduce exposure to salt stress. Siyal et al. (2010) used Hydrus and experimental results to demonstrate the potential water savings from using partial ponding to leach salts from the root zone. Finally, Hydrus has also been used to study the effect of different climate conditions on leaching of salt-affected soils in Australia (Shaygan & Baumgartl, 2020), with results indicating that a greater number of individual rain events was most effective in removing salts from the root zone.

Yet another common application of Hydrus has been used to model the effects of different irrigation techniques, such as drip, sprinkler, and subsurface irrigation. Hanson et al. (2008, 2009) and Roberts et al. (2009) show that subsurface drip irrigation can enable greater salinity control, providing farmers a profitable and less wasteful alternative to flood irrigation.

In addition to questions related solely to salinity, Hydrus has also been used to study the effects of sodicity on soils, including rehabilitation efforts. Šimůnek and Suarez (1997) and Suarez (2001) compare UNSATCHEM simulations to a field study in which gypsum was applied to stimulate rehabilitation in a heavily sodic and saline soil. Their results show that UNSATCHEM satisfactorily predicted the actual EC and SAR values following rehabilitation treatment. A study published by Reading et al. (2012) compares Hydrus simulations to soil column experiments examining declines in K_s as water of varying chemical composition is applied to the soil. The general trends observed in the laboratory experiments were able to be simulated using HYDRUS. Differences between measured and simulated results were attributed to the limited flexibility of the function that represents chemistry-dependent hydraulic conductivity in HYDRUS. Recovery of K_s in Hydrus was faster than in experimental conditions, which can be expected given that the K_s function in Hydrus does not include hysteresis.

A sensitivity analysis conducted by Schoups et al. (2006) of the UNSATCHEM model investigated the effect of the removal of processes on the accuracy of the model's salinity predictions. Their findings suggest that major simplifications—including the removal of preferential flow, transport through soil macropores, hysteresis in soil wetting and drying, and non-equilibrium reactions between the solid phase and the soil solution—did not lead to significant changes in results. Schoups et al. (2006) conclude that their results support the use of simplified models when reducing computer processing time is a priority.

The SWAP model has likewise been widely used to study questions related to salinity, with a particular emphasis on understanding the effects of saline water on expected yield. P. Li and Ren (2021) use the coupled SWAP and WOFOST models to examine how irrigation with water of varying salinity levels affects wheat output and leaching levels under different rainfall regimes. A similar study conducted by Kumar et al. (2015) found that SWAP was able to effectively model salinity levels in the rootzone, and that the model was better able to predict changes in yield for salt-resistant wheat varieties as compared to salt-sensitive varieties. Ben-Asher et al. (2006) demonstrated that SWAP was able to effectively model the effects of irrigation with saline water on grapevine growth. Hassanli et al. (2016) compare SWAP's ability to simulate maize yields under saline conditions to results from the SALTMED and Aquacrop models. Their results suggest that SALTMED was the strongest of the evaluated models for predicting changes in maize yield. Jiang et al. (2011) use SWAP to simulate higher salt concentrations and lower soil water contents under deficit irrigation conditions. Finally, Eberhard et al. (2020) used SWAP to analyze the long-term impact of infiltration of saline groundwater. They find that rainfall can mitigate the accumulation of salts in the upper soil profile, even when salinity levels in the lower soil layers rise steadily.

A combination of the Hydrus and SWAP models, H2DSWAP, was introduced by Liu et al. (2022) for the study of maize yield under saline conditions. Their results suggest that the combined model is significantly more accurate for predicting soil water content and salt concentrations, with the model also able to satisfactorily match experimental results for yield and Leaf Area Index.

Application of the SOTE, Russo, and Van der Zee models has primarily focused on analyzing the effects of irrigation with saline and sodic water on soil hydraulic conductivity, with particular attention to the effects of irrigation with treated wastewater. SOTE (Kramer et al., 2022; Kramer & Mau, 2020; Yin et al., 2021) and Van der Zee (van der Zee et al., 2014) have demonstrated that changes in overall salinity concentration generally occur much quicker than changes in the relative amount of sodium bonded to the soil's exchange layer. In arid regions with seasonal rainfall, SOTE, Russo, and Van der Zee have shown that leaching of salts due to precipitation can increase the risk of soil degradation (Kramer et al., 2022; Kramer & Mau, 2020; Russo, 2013; van der Zee et al., 2014; Yin et al., 2021). SOTE and the Russo model have likewise been used to study the effects of longterm irrigation with treated wastewater, with simulations showing increased probability of degradation to hydraulic conductivity (Bardhan et al., 2016; Russo et al., 2015). The SOTE model, in particular, has been used to examine how hysteresis might affect our understanding of the risk of soil degradation (Kramer et al., 2022; Kramer & Mau, 2020). Inclusion of hysteresis when modeling changes in hydraulic conductivity has been shown to greatly increase the expected risk of degradation, with results being highly soil specific. An adapted version of the SOTE model has also been used to examine plant responses to salinity and sodicity (Yin et al., 2021) and how variations in plant tolerance to salinity levels effect overall water dynamics in agroecosystems (Yin et al., 2023). The Russo framework has been used to study how alternating between irrigation with treated wastewater and desalinated water can improve water uptake in orchards, as compared to irrigation with freshwater alone (Assouline et al., 2020; Russo, 2016; Russo et al., 2015, 2020).

8. Priorities for Future Research

While significant progress has been made in understanding salinity and sodicity dynamics and their effects on agricultural systems, a number of important gaps remain. In this section, we highlight some of the most important priorities for future research on salinity and sodicity in agricultural systems.

To date, there has been limited exploration of the expected effects of climate change on salinity and sodicity dynamics, despite ample opportunity for such studies. While the machine-learning approach developed by Hassani et al. (2020); Hassani et al. (2021) explores this question from the perspective of primary soil salinity, we are unaware of any study that analyzes how changing rainfall, temperature, and other climate variables are likely to affect salinity and sodicity levels in irrigated areas. Rising temperatures are likely to increase evaporative demand, which has the potential to aggravate the probability of rising salinity concentrations in soil systems. Rainfall patterns are crucial to the leaching of salts and the risk of soil degradation. The effect of changing rainfall patterns on salinity and sodicity patterns deserves special attention because the specific nature of the change—for example, an increase or decrease in extreme events, a shorter or longer rainfall season, more or less annual rainfall—has the potential to lead to markedly different results. Meteorological variables (e.g., evapotranspiration and precipitation) are inputs to many of the models discussed here and have been regularly used in studies not focused on salinity and sodicity. Explicit studies of how climate variables are likely to affect salinity and sodicity should therefore be easily achievable. Such studies are likely to become increasingly important as farmers and policy makers will have to develop irrigation strategies that can be used to mitigate the effects of climate change.

We are also unaware of any integration between the salinity and sodicity models reviewed here and general circulation models (GCMs) and Earth Systems Models used to study weather and climate on a global scale. Research has suggested that consideration of soil structure can have an important effect on Earth System Models (Fatichi et al., 2020). Future research should therefore consider not only how climate changes might affect salinity and sodicity dynamics, but also how resulting changes in soil structure might induce a feedback on other physical, chemical, and biological processes.

Application of machine-learning principles and statistics to the challenges posed by salinity and sodicity has remained limited up to now, despite the ample opportunity offered by such tools (Razavi et al., 2022). The approach introduced by Vermeulen and Niekerk (2017) should be modified to investigate regions that are particularly at risk of irrigation or groundwater-induced salinity, sodicity-driven soil degradation, or even easy targets for rehabilitative efforts. Machine learning and statistical analysis may also have great potential in increasing our ability to forecast the effect of irrigation patterns on plant output. Likewise, the predictive abilities offered by these tools could prove an asset in improving our ability to model hysteresis behaviors, if they can be used to identify clear patterns following variable changes in input and output.

There is also a need to further integrate the best models for plant response to salinity with the leading models for salinity and sodicity dynamics. While some of the dynamical models include the effects of changing osmotic potential on plant water uptake (Section 5.5), these models lag behind the best models developed for the effects of salinity on plant growth. Likewise, the leading models for the effect of saline water on plant growth are restricted to the study of static water-input conditions (Section 4). The integration of such models is critical to increasing our understanding of how and if marginal quality water resources can be used strategically, so that damage to plants and soils is minimized while savings in freshwater are maximized. For instance, it may be possible to identify specific points in the growing season during which high-salinity water has a minimal effect on plant yield. It is equally critical to be aware of periods when damage to plant growth resulting from the application of saline irrigation.

The ability to analyze the effects of salinity and sodicity on relative K_s also remains limited, despite ample potential for improvement. While the development and integration of a module for how hysteresis affects changes in K_s is an important step (Kramer et al., 2021, 2022), the hysteresis module should be available in more software programs, such as Hydrus or SWAP. Integrating a hysteresis module into dynamical modeling frameworks should actually be relatively simple, especially for the existing Python implementation of Hydrus, Phydrus (Collenteur et al., 2021). Such integration would allow a wider set of users to explore the effects of changing K_s in tandem with other soil and plant processes. It is worth noting that while inclusion of hysteresis in SOTE has at times been computationally expensive, this is largely because of applications that have focused on stochastic ensembles of hundreds or thousands of instances. However, each simulation instance is independent from the others (this class of problem is nicknamed embarrassingly parallel problem), and readily available cloud-computing services or multi-core processor servers would eliminate this obstacle. Furthermore, if used to study a single instance, the hysteresis module presented in Kramer et al. (2021) should not be regarded as computationally demanding.

Future developments in modeling capabilities can also be pushed forward with more focused experimental studies. Our ability to accurate characterize degradation risk and hysteresis patterns, for instance, is constrained by a relatively narrow body of experimental work. Additional lab and field experiments are critical to fully parameterize the Kramer et al. (2021) hysteresis module, which would in turn allow for more accurate modeling assessments. Long-term field studies monitoring how changes in salinity and sodicity affect increases and decreases in hydraulic conductivity, and other key soil variables, are particularly lacking and essential for better evaluation of existing models and development of new modeling frameworks.

Finally, better integration of dynamical models for the effects of salinity and sodicity with economic models is imperative. While the economic impact of salinity has been widely studied, most research has focused on understanding the issue from a regional or national perspective (Kan & Rapaport-Rom, 2012; Reznik et al., 2017; Schwabe et al., 2006; Slater et al., 2020). Studies that focus on the farm-level, meanwhile, have generally considered static input conditions (Baum et al., 2016; Ben-Gal et al., 2013; Kan, 2003, 2007; Kaner et al., 2017). We are not aware of any study that attempts to quantify the economic impact of soil degradation resulting from changing saline and sodic input conditions at the farm level. By integrating economic and dynamical models, policy makers will have better tools for analyzing the short- and long-term costs of different water management strategies, the profitability of certain crops, the actual cost of long-term damage to soil structure, and subsequent rehabilitation.

Data Availability Statement

An updated version of the map presented in Figure 1 can be found on FAO's website (FAO, 2023).

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