5

Soil Salinization and Management of Salty Soils

5.1. Introduction

The term salinization defines a process of accumulation or enrichment of salts (from the Latin *sal*), which is expressed in all terrestrial, aquatic and atmospheric environments, especially in the soil, a very particular three-phase (solid–aqueous–gaseous) natural object. Salinization occurs either naturally in surface waters (rivers, lakes), groundwater, dry environments, soils and wetlands, or artificially in soils and waters during anthropogenic activities (irrigation and soil fertilization, domestic and industrial waste, etc.).

5.2. Natural salty environments

5.2.1. *Salts, dissolved particulate entities*

Salts are defined in several ways depending on the chosen context. For a chemist, salt is essentially the product of the action of a strong acid and a strong base (neutralization) or a strong acid and a non-noble metal. For a geoscientist, salts define all minerals that can be formed by the concentration and combination of major ions (chloride, sulfate and carbonate for anions; calcium, magnesium, sodium and potassium for cations). Minor or trace ions may be associated (borate, nitrate, phosphate, heavy metals). The pedologist specialized in salty soil will only consider salts that are more soluble than hydrated calcium sulfate (gypsum in gypsum soils) and calcium and/or

---

Chapter written by Jean-Pierre MONTOROI.

Soils as a Key Component of the Critical Zone 5: Degradation and Rehabilitation,
First Edition. Edited by Christian Valentin

magnesium carbonates (calcite, dolomite in calcareous soils). These include sodium chloride (halite), better known to humans as “table salt”. It is ingested daily to satisfy their physiological needs in the same way as other living beings, whether it be animals or plants [FLO 05, PAY 16].

Salts are present in nature in two characteristic states:

– a crystallized state that is easily observable in solid systems (rocks, soils);

– a dissolved state that is not perceptible in hydric systems (continental, marine, meteoric, geothermal waters), magmatic systems (fluid, viscous lava) and colloidal systems (clay minerals, organic matter).

Salts change from the crystallized state to the dissolved state by dissolution and conversely from the dissolved state to the crystallized state by precipitation, the two processes being intimately linked during the planetary cycle of the water.

5.2.2. *Typical landscapes*

Salinization of natural environments, or “primary” salinization, exists at all latitudes and in all climates [CHE 98, SZA 89]. This is particularly the case when salt sources are close at the surface and in depth, and where evaporation processes dominate permanently or temporarily.

Salts have:

– a continental origin (evaporitic or diapiric “fossil” deposits; magmatic and/or volcanic rocks rich in weatherable minerals, especially sodium; geothermal springs; highly mineralized waters from rivers and lakes; intrusions of groundwater, artesian or not, in salt deposits);

– an oceanic or marine origin (underground intrusions, temporary submergence by exceptional tidal waves).

The edges of salt lakes, the endoreic depressions that are alternately wet and dry (*chotts, sebkhas, takyrs, playas* or *salars*), the floodable fluvial and marine ecosystems (mangroves, estuarine mudflats, salty marshes and meadows) and the sea coasts (lagoons, *sebkhas*) are all natural salinized sites (Figure 5.1). Specific microorganisms named “halophiles” develop there, sometimes under extreme conditions [ORE 02].

5.2.3. *Continuous movement of salts*

The dynamics of salts, in the crystallized and/or dissolved state, are permanent or temporary, diffuse or massive, local or generalized, slow or rapid, and superficial or deep. It is closely linked to the mobility of aqueous, viscous and gaseous fluids circulating on and in the superficial formations of continental and oceanic crusts. Salinization (gain of salts) and desalinization (loss of salts) processes ensure the redistribution of salts in natural landscapes. They are constantly active and their kinetics are variable. The dissolution of minerals predominates in wet climates (geochemical erosion), while dry climates promote their precipitation (geochemical neoformation).

Figure 5.1. *Salty continental environment on the edge of the Melah wadi (melah meaning "salty" in Arabic): saline efflorescence and halophyte vegetation; Metlaoui region, southern Tunisia (photo: J.-P. Montoroi). For a color version of this figure, see www.iste.co.uk/valentin/soils5.zip.*

In dissolved or even particulate form (poorly soluble salts), salts are transported vertically and laterally by meteoric waters, surface waters (rain, rivers, lakes, inland seas, oceans) and underground waters (free or confined aquifers; resurgent, artesian or geothermal springs). They are also transported at a more or less viscous liquid–solid state by the superficial and underground lava flows. Crystallized salts are regularly transported during periods of prolonged drought and by strong continental winds (sirocco, harmattan, mistral, etc.). Depending on the moisture conditions of the superficial formations, local redistributions can also be observed. From oceanic, marine and lacustrine water bodies, aeolian spray transfers dissolved and/or finely crystallized salts onto surrounding land surfaces. This is particularly the case for sea spray, which can be deposited all along the coast and, sometimes, several tens of kilometers inland. More episodically, so-called "gray" volcanic eruptions are sources of crystallized salts in pyroclastic deposits that are projected and dispersed in the atmosphere over varying distances.

Otherwise, it must always be kept in mind that the ions constituting the salts are associated everywhere with solid mineral phases in exchangeable, absorbed or adsorbed form. By reacting physical-chemically with liquid and gaseous transport agents, they transform, recombine and participate in the movement of solid particles from autochthonous origin (terrestrial dynamics) or allochthonous origin (extraterrestrial dynamics through the impact of meteorites that have become terrestrial), ranging from microscopic size (ionic interaction movements) to macroscopic size (tectonic plate movements), and at all time and space scales. As for water, we can speak of a cycle of soluble salts on the planet Earth (Figure 5.2) [CHH 96, WIL 99].

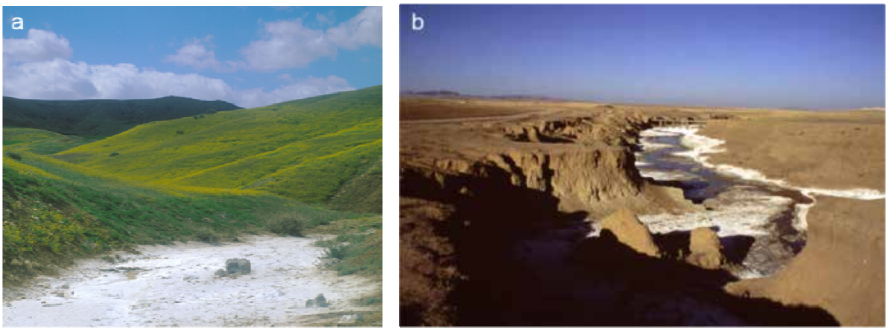

Figure 5.2. *Apparent salinization of landscapes (a) of hills and (b) foothills by groundwater and/or river flow; Atlas Ridge region, central Tunisia (photo: J.-P. Montoroi). For a color version of this figure, see www.iste.co.uk/valentin/soils5.zip.*

5.2.4. *Ecosystemic services*

Natural salty landscapes provide significant ecosystem services to humans: salt production (salt-farming) and plant species (salty plant cropping). Natural water evaporation concentrates the dissolved mineral elements and leads to the precipitation of a set of salts in a thermodynamic order. The crystallized salts on the soil surface are regularly collected by people for their own needs and those of domestic animals [BER 72]. The process of salt formation is artificially forced by man in the solar exploitation of salt marshes, in coastal or estuarine areas, and in the igneous exploitation of suitable ovens in continental environments. Solar or igneous salt farming carried out either traditionally on a village scale, or industrially on a regional or even national scale (Figure 5.3).

A specific vegetation, called halophytic, has adapted to salty environments [FLO 08]. Depending on the degree of soil salinity, it constitutes a more or less scattered cover that can be grazed by domestic animals (salty pastoralism) and wild animals. Halophytes occupy the deltaic and endoreic alluvial plains that are temporarily wet. These wetlands are biodiversity reserves that are protected by international conventions. Otherwise, the traditional and industrial production of halophytes is developing for gastronomic, medicinal and cosmetic applications.

In addition, the mining of saliferous geological deposits produces the salts needed not only for food (nutrition, conservation), but also for industrial needs (chemical processes, road salting, etc.). Useful metals such as lithium are very present in evaporites.

Figure 5.3. *Harvest of salts formed (a) on the surface of uncultivated salty soils, bare tannes from Casamance, Senegal; (b) in a salt marsh, Vermelha lagoon, Brazil (photos: J.-P. Montoroi). For a color version of this figure, see www.iste.co.uk/valentin/soils5.zip.*

5.3. Characterization and functioning of salty soils

5.3.1. *Diagnosis of the degree of salinization*

Apart from the visible manifestations of salinity on the soil surface (efflorescences, infertility spots, etc.), it is difficult to diagnose the extent of the salinization phenomenon without having to go through a preliminary analytical phase [RHO 92]. Measuring soil salinity is done by using several approaches, according to the objective that has been set (Table 5.1). The values of $EC_{1/x}$, EC_{es} or EC_{ss} are interpretable in relative values, the absolute values being dependent on the degree of dilution of the extracted solutions. The EC_a values incorporate a soil volume that can be electrically conductive by factors other than salinity (clay and/or water content).

5.3.2. *Intrinsic physical–chemical processes*

5.3.2.1. *Salinization stricto sensu*

The soil salinization process occurs when the mineralization of the soil solution exceeds a certain threshold under the influence of a physical mechanism (evaporation, insufficient internal drainage, mineral weathering and accumulation) [BRE 82, FIT 03, MAR 06].

Laboratory methods	**Parameters measured**	**Phase involved**	**Measuring instruments**
Soil sampling	EC of diluted extract [$EC_{1/x}$] EC of saturated extract [EC_{es}]	Mineralized aqueous	– Electrical conductivity meter – Chemical analyses
Field methods	**Parameters measured**	**Phase involved**	**Measuring instruments**
Spatializing (mobile sensors)	Bulk EC (or apparent) [EC_a]	– Mineralized aqueous – Solid (clay)	– Electromagnetic conductivity meter – Electrical resistivity tomography
Stationary (sensors *in situ*)	Bulk EC (or apparent) [EC_a]	– Mineralized aqueous – Solid (clay)	– Capacitive probe (TDR, 5FT) – Four-electrode probe
	EC of soil solution [EC_{ss}]	Mineralized aqueous	– Salinity sensor – Porous ceramic

Table 5.1. *Methods for diagnosing soil salinity*

5.3.2.2. *Salinization and sulfate reduction*

In tropical or temperate coastal environments that are rich in organic deposits (mangrove, coastal marsh and "polder"), the salinization process is associated with a microbial sulfate-reduction process of iron and sulfur, which depends on local hydrological conditions: reducing periods (precipitation of Fe sulfides such as pyrite) alternate with oxidizing periods (acidification, release of sulfates and precipitation of jarosite) [DEN 95, FAL 14, FAN 97, FIT 03, MON 96].

5.3.2.3. *Sodization*

The sodization process occurs when the organic–mineral exchange complex is gradually saturated by the Na^+ ion. Aggregates become unstable above a certain threshold and the degradation of soil physical properties is possible. The cations present in the soil solution are exchanged in the organic–mineral complex. The Na/cationic exchange complex (CEC) ratio or the exchangeable sodium percentage (ESP) parameter is defined to estimate the saturation degree of the CEC. The modification of the sodium percentage by a solution characterizes its sodicity. Many authors have studied the relationships between cations in solution and cations adsorbed in the complex by defining selectivity coefficients according to the nature of the present clay minerals. There is a relationship between the sodium adsorption ratio (SAR) parameter and the chemical composition of the soil solution expressed in $mol_c\ L^{-1}$:

$$\mathrm{SAR} = \mathrm{Na}^+/((\mathrm{Ca}^{2+} + \mathrm{Mg}^{2+})/2)^{0.5}$$

The ESP and SAR parameters are linked by the empirical relationship [RIC 54]:

$$\mathrm{ESP} = \mathrm{Na}^+/\mathrm{CEC}\ (\%) = 100/(1 + (1/(0.0147\ \mathrm{SAR} - 0.0126)))$$

These relationships are in fact unreliable for accurately determining the chemical composition of the exchange complex. New concepts have been proposed for SAR calculation [RIE 91].

5.3.2.4. *Alkalization*

The alkalization process occurs when a soil with a sodium-saturated complex is physically transformed following exchange reactions between the Na^+ ion and protons (H^+) during a wetting period.

If it is a meteoric supply that is always slightly enriched with dissolved CO_2, the exchange reaction is:

$$Na^+ \text{ complex} + H_2CO_3 \rightleftarrows H^+ \text{ complex} + Na_2CO_3$$

As Na_2CO_3 is easily soluble, Na^+ and OH^- ions are released in solution:

$$Na_2CO_3 + 2H_2O \longrightarrow 2Na^+ + 2OH^- + H_2CO_3$$

If it is fresh water (irrigation), the reaction can be written more simply:

$$Na^+ \text{ complex} + H_2O \rightleftarrows H^+ \text{ complex} + Na^+ + OH^-$$

As sodization and alkalization are closely related, we speak more generally of the alkalinization process. The Na^+/H^+ exchange reactions cause a degradation of the soil's physical properties due to the protonization of clay minerals and the increase in pH. Protonated clays become more fragile and are easily dispersed. Clay dispersion creates a compact horizon with a prismatic, massive or columnar structure. As porosity decreases, the permeability to water and air of alkalinized soils decreases. Reducing conditions can appear, favoring nitrogen losses by denitrification. The pH values become higher than 8.5 and can reach 10, as the organic matter solubilizes and migrates. The partial Na^+ desaturation of the organic–mineral complex promotes clay eluviation that is associated with a pH decrease in the upper horizons and clay leaching towards the lower horizons. Complete Na^+ desaturation leads to a clear differentiation of the solum with a bleached and acidified horizon (pH between 4 and 6.5) on the surface, and an alkalinized horizon (pH between 9 and 10) in depth.

Seasonal variations of the water regime and the physical–chemical conditions of a clayey, saline and sodic soil are at the origin of major morphological transformations. Physical processes such as fracturing, bursting, driving, collapsing and dispersing of solid constituents alter their assembly, distribution and orientation. Soil reorganization can lead to the formation of a cracking network and to its development according to the water history of the material, notably the maximum constraints it undergoes.

Laboratory experiments show that solution transfers can be very slow due to the reorganization of clay particles during desiccation. The crystalline structure of illite disaggregates under the effect of the air pressure that is contained in the porosity of this clay mineral, especially if the wetting velocity is high. During desiccation, the illitic material tends towards compaction. On the other hand, montmorillonite maintains its cohesion because its low hydraulic conductivity prevents air overpressure. A swelling pressure slowly develops and a cracking system develops during dessication. A concentrated saline solution increases the hydraulic conductivity of montmorillonite, while its swelling decreases [TES 92]. The cracking and compaction processes depend essentially on the mineralogical characteristics of the clay particles, while the clay swelling mechanism can be favored by their geochemical environment: significant swelling is obtained with sodium-saturated clay. When the solutions are highly mineralized, there is no disaggregation, but rather flocculation of the clay particles as long as the alkalinization processes do not occur.

5.3.3. *Chemical concentration and evolution pathways of soil water*

5.3.3.1. *Residual alkalinity*

The total alkalinity ($Alk._{total}$) of a solution is measured by titration and corresponds to the amount of H^+ ions necessary to neutralize proton-acceptor anions. Neglecting organic anions ($R\text{-}COO^-$), it is specified according to the following general relationship [ALD 76]:

$$Alk._{total}\,(mol_c\ L^{-1}) = (2CO_3^{2-} + HCO_3^-) + (3PO_4^{3-} + 2HPO_4^{2-} + H_2PO_4^-) +$$

$$(2S^{2-} + HS^-) + (H_3SiO_4^- + H_2SiO_4^{2-}) + \ldots + OH^- - H^+$$

or $Alk._{total} = Alk._{carbonates} + Alk._{phosphates} + Alk._{sulfides} + \ldots + OH^- - H^+$

Taking the electrical neutrality relationship into account, it can also be defined as the balance of other ionic species present in solution:

$$Alk._{total}\,(mol_c\ L^{-1}) = Na^+ + K^+ + 2Ca^{2+} + 2Mg^{2+} + 3Al^{3+} + 2Fe^{2+}$$

$$Cl^- - F^- - 2SO_4^{2-} - NO_3^-$$

The alkalinity of natural waters is most often assimilated to the only carbonate alkalinity ($Alk._{total} \approx Alk._{carbonates} \approx 2CO_3^{2-} + HCO_3^-$). The dissolution reactions during mineral weathering increase the alkalinity of solutions, because they are sources of cations. In an acidic environment, alkalinity is negative. At a given temperature, if only the buffer capacity of

$\text{Alk.}_{\text{carbonates}}$ is considered, then the $\text{Alk.}_{\text{total}}$ of a solution depends only on the partial pressure of CO_2 (p_{CO2}) and pH. The p_{CO2} increase in soil causes the alkalinity of the soil solution to increase.

The notion of residual alkalinity makes it possible to better understand sodization phenomena, which are not only the result of an absolute increase in sodium in the solution, but above all the result of a sudden decrease in the content of certain ions as a consequence of the precipitation of minerals containing them. For example, calcite is a poorly soluble mineral that precipitates very rapidly during the concentration of solutions. Residual alkalinity of calcite (RAC) is defined as the difference between the amount of charged carbonate ions and the amount of charged calcium ion, according to the relationship:

$$\text{RAC}\ (\text{mol}_c\ \text{L}^{-1}) = 2CO_3^{2-} + HCO_3^{-} - 2Ca^{2+} = \text{Alk.}_{\text{carbonates}} - 2Ca^{2+}$$

Knowing the RAC value, it is possible to predict the evolutionary trend of the solutions during their concentration, as soon as saturation with calcite is reached:

– if RAC > 0, the carbonate content continues to increase while the calcium content decreases by participating in calcite precipitation. Concomitantly, sodium concentrates and progressively saturates the organic–mineral complex by ionic exchange and adsorption (alkaline or carbonated pathway);

– if RAC < 0, the carbonate alkalinity decreases and the calcium content increases at a neutral pH, preventing the harmful effects of sodium (neutral saline pathway);

– if RAC = 0, the carbonate and calcium contents remain constant before and after calcite precipitation until depletion.

The concept of residual alkalinity can be extended to other minerals capable of successfully precipitating during the concentration of solutions by subtracting from the carbonate alkalinity the amount of charged cations and adding the amount of charged anions participating in precipitation [ALD 76]. Generalized residual alkalinity (GRA) is defined by the following relationship:

$$\text{GRA}\ (\text{mol}_c\ \text{L}^{-1}) = \text{Alk.}_{\text{carbonates}} - \text{n cation}^{n+} + \text{m anion}^{m-}$$

For example, with gypsum precipitating after calcite, residual alkalinity of calcite-gypsum (RACG) will be defined.

5.3.3.2. *Ion speciation, ionic adsorption and geochemical models*

The chemical analysis of an electrolytic solution, expressed in terms of the total concentrations of dissolved elements, does not distinguish the forms under which aqueous species are found. These are present as simple or free ions, and complex ions (also called ion pairs) which are a combination, charged or neutral, of several simple ions. The different forms are in equilibrium with each other in the aqueous solution and may depend on the pH. The distribution of aqueous species is obtained by a calculation involving equilibrium reactions between aqueous and crystallized species and, between the aqueous species themselves. The results are expressed either in terms of concentration (in mol L^{-1}) or in terms of activity, a dimensionless parameter, which is linked to concentration by an activity coefficient (in L mol^{-1}).

The activity of an ion or an aqueous species represents in fact its effective concentration or its thermodynamic concentration. It is in terms of activity that the equilibrium constants of chemical reactions are expressed [SPO 89]. The value of the activity coefficients for each species is approximated using empirical laws (Debye–Hückel, Davies, etc.), which are established as a function of the ionic strength of the solution and of parameters that are either temperature dependent or relative to the size of the hydrated ions. Computer programs allow the calculation of ion speciation at equilibrium (25°C, 1 atm) and within very specific limits. The ionic adsorption mechanisms on mineral surfaces (clay colloids, silica, oxides) and/or organic surfaces are modeled taking a multilayer system of electrostatic interactions and the size of hydrated ions [CAM 91] into account.

5.3.4. *Mineralogy of saline efflorescences*

Depending on the initial chemical facies of the salty solutions, in other words, the ratio of ions between them, their concentration follows different salt precipitation pathways (acid, neutral saline, alkaline). The main salts that can be found in saline efflorescences or crusts are:

– for the acid pathway: rozenite ($Fe^{II}(SO_4)$, $4H_2O$), alunogen ($Al_2(SO_4)_3$, $17H_2O$), tamarugite ($NaAl(SO_4)_2$, $6H_2O$), jarosite ($KFe^{III}_3(SO_4)_2(OH)_6$), natrojarosite ($NaFe^{III}_3(SO_4)_2(OH)_6$), halotrichite ($Fe^{II}AI_2(S0_4)_4$, $22H_20$) (Figure 5.4);

– for the neutral saline pathway: calcite ($CaCO_3$), gypsum ($CaSO_4$, $2H_2O$), magnesium sulfates ($Mg(SO_4)$, nH_2O), halite (NaCl), sylvite (KCl);

– for the alkaline pathway: calcite or magnesium calcite, fluorite (CaF_2), thenardite (Na_2SO_4), mirabilite (Na_2SO_4, $10H_2O$), magnesium silicates, natron (Na_2CO_3, $10H_2O$), trona ($Na_3H(CO_3)_2$, $2H_2O$).

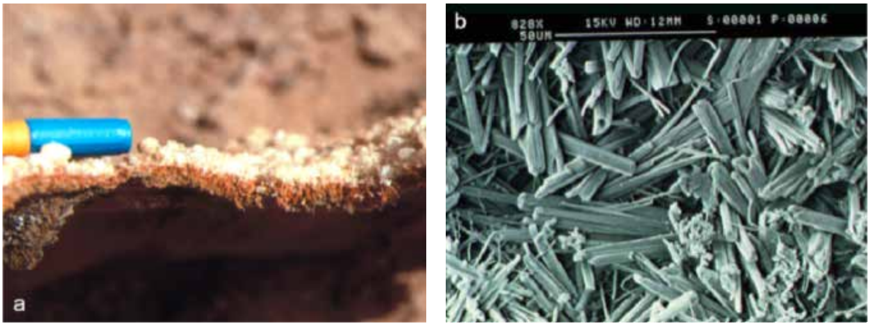

Figure 5.4. *Salts observed at the surface of an acid sulfate soil (a) on a macroscopic scale in the form of indurated crusts, Bao Bolon, Senegal; (b) on a microscopic scale, halotrichite crystals, Djiguinoum, Casamance, Senegal (photos: J.-P. Montoroi). For a color version of this figure, see www.iste.co.uk/valentin/soils5.zip.*

5.4. Typology of salty soils

5.4.1. *Soil characteristics*

Depending on the intensity of the salinization and alkalinization processes involved, three main categories of salty soils can be defined: saline soils *stricto sensu*, saline soils with sulfate-reduction/oxidation and alkaline soils [BRE 82, CHE 98, LOY 95, SUM 93]. The main physical–chemical characteristics of saline and alkaline soils are presented in Table 5.2.

Characteristics	**Non-saline soil**	**Saline soil**			**Alkaline soil**	
		Calcic-magnesic	**Sodic**	**Sulfate-reducted**	**Undifferentiated**	**Leached and degraded**
EC* (dS m^{-1})	<4	>4	>4	>4	Indifferent	<4
Na/CEC (%)	<15	<15	>15	<15	>15	>15
Soil pH	neutral	<8.5	<8.5	>8.5 or <4	>8.5	Indifferent to acid

Characteristics	Non-saline soil	Saline soil			Alkaline soil	
		Calcic-magnesic	Sodic	Sulfate-reducted	Undifferentiated	Leached and degraded
Soil structure	n.d.	n.d.	n.d.	n.d.	d.	d.
Efflorescence	–	Na, Ca, Mg chlorides (white salt)	Na chlorides, Na, Mg sulfates (white salt)	Al and Fe sulfates	Alkaline humates (black salt)	–

Table 5.2. *Physical and chemical characteristics of saline and alkaline soils.* **Electrical conductivity of the soil solution from saturated extract; n.d.: non-degraded structure, d.: degraded structure*

5.4.2. *Vertical distribution of salinity*

The vertical distribution of soil salinity ($EC_{1/x}$, EC_{es}, EC_a or EC_{ss}, see Table 5.1) defines the saline profile corresponding to a particular saline dynamic. There are several types belonging either to distinct environments or to the same environment when hydrological conditions change seasonally (Figure 5.5). The presence of a shallow saline groundwater and a very resistant but poorly covering halophyte vegetation induces an upward salinization process (maximum salinity at the surface), whereas a good vegetation cover (halophyte lawn) promoting the infiltration and drainage of salts creates a downward salinization process (maximum salinity in-depth). Water supplies from the surface (rain or irrigation) on an ascending saline profile produce a dissolution of precipitated salts and a migration of dissolved salts in depth (surface desalinization and maximum salinity within the soil profile).

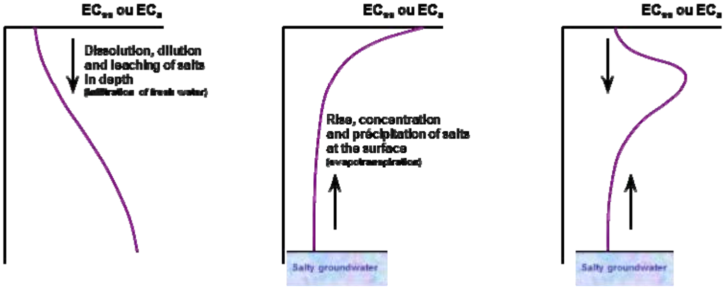

Figure 5.5. *Main types of vertical distribution of salinity*

5.4.3. *Spatial distribution of salinity*

The spatial distribution of soil salinity is transcribed from mapping documents, in which the accuracy depends on the selected measurement method, sampling and interpolation model (Figure 5.6). The maps produced are important tools for identifying areas of high saline issue and guiding remediation actions. However, they have the disadvantage of providing only qualitative information and integrating other factors that influence electrical conductivity (EC) (clay content, water content, etc.). Finer but more time-consuming measurements are needed to quantify processes.

5.4.4. *Classification of salty soils*

The generic term "salty soils" commonly uses other names: saline and sodic soils, salsodic soils, halomorphic soils. More specifically, saline soils are also called salt-affected soils and for alkaline soils, alkali soils or sodic soils. In a more normative manner, salty soils are listed in national and international soil classifications under many terms. The main names are summarized in Table 5.3, taking the French soil reference system [BAI 09], the world soil reference system [IUS 14] and the American soil classification [SOI 14] into consideration. Note that the threshold values for EC and ESP-SAR are not the same in all classification systems, particularly in the Australian classification.

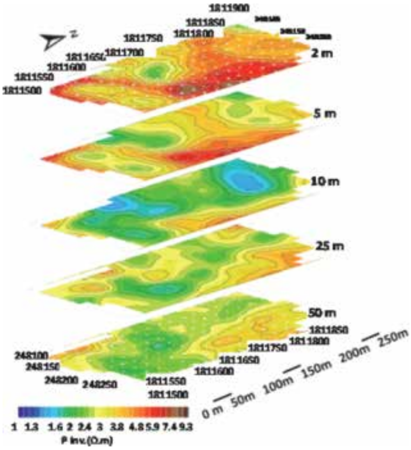

Figure 5.6. *Vertical and spatial distributions of the* EC_a *by the time domain electromagnetic method (saline soils and superficial formations of the Khon Kaen region, northeast Thailand), from [MON 04]. For a color version of this figure, see www.iste.co.uk/valentin/soils5.zip.*

Soil processes		**[IUS 14]**		**[BAI 09]**		**[SSS 14]**
		Classification	**Diagnostic horizon**	**Classification**	**Diagnostic horizon**	
Salinization *stricto sensu*	**Calcium-magnesium complex**	Solontchak (Carbonatic)	Salic	Carbonated salisol	Salic (Sa)	Aridisol salid
	Sodic complex	Solontchak (Chlorodic or Sulphatic)	Salic	Chlorinated or sulfated salisol	Salic	
Salinization and sulfate-reduction	**Rich in sulphides** of reduced iron	Fluvisol or Gleysol (Protothionic)	Sulfidic material	Thiosol	Thionic or sulfidic material (TH)	
	Iron-aluminum complex	Fluvisol or Gleysol (Hyperthionic or Orthothionic)	Thionic	Salic, rubic or alunic sulfatosol	Sulfated (U)	
Alkalinization	**Undifferentiated profile**	Solonetz	Natric	Undifferentiated sodisol	Sodic (NaA, NaS)	“Natric Great Groups” of several “orders” (Inceptisol, Entisol, Aridisol)
	Leached profile	Haplic Solonetz	Natric	Solonetzic sodisol	Non-albic eluvial (Ena) sodic clays (NaBT)	
	Degraded profile	Solonetz (Albic)	Natric	Solodized sodisol	Albic eluvial (Ea) sodic clays (NaBT)	

Table 5.3. *Main classifications of saline and alkaline soils*

5.4.5. *Worldwide distribution of salty soils*

Salty soils are naturally present in more than 100 countries around the world. The areas covered vary according to different authors, 9.55 million km^2, or 6.4% of the continents or 19 times the French territory according to [SZA 89], 8.31 million km^2 according to [MAR 05] (Figure 5.7).

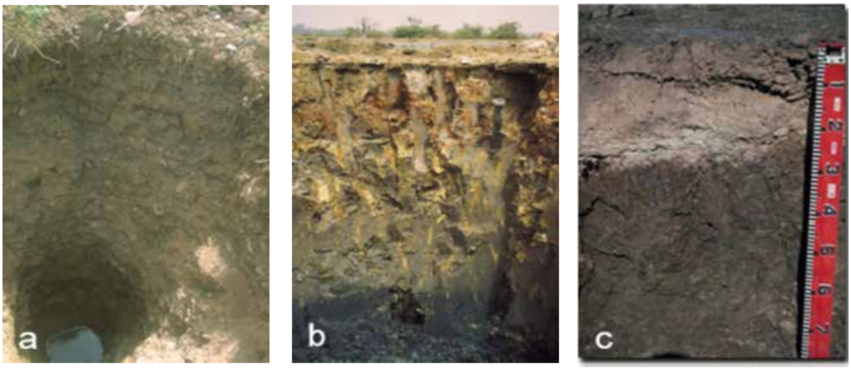

Figure 5.7. *Main types of salty soils [IUS 14]: (a) solontchak (stricto sensu saline soil; (b) hyperthionic gleysol (sulfate-reducted saline soil); (c) solonetz (alkaline soil) (photos: (a and b) J.-P. Montoroi, (c) M. Imhoff). For a color version of this figure, see www.iste.co.uk/valentin/soils5.zip.*

5.5. Secondary soil salinization

5.5.1. *Anthropogenic input of salts in soils*

The so-called "secondary" salinization of soils occurs through human activities that concentrate or transfer more or less mineralized water bodies (groundwater, surface water, seawater) and solid and gaseous particles. Anthropogenic inputs of salts into soils are specific to both saline and non-saline irrigated areas [SER 78], by pumping fresh waters and/or saline waters, underground waters (drilling) and/or surface water (dams, rivers). They are generalized to all types of soils, irrigated and non-irrigated, saline and non-saline, by indirect pollutions (domestic, urban, industrial) and by agricultural inputs (mineral and/or organic fertilization). Secondary salinization processes are cyclical, in time and/or space, and in urban and/or agricultural environments (Figure 5.8). Industrial ore processing, the decomposition of industrial products containing salts, the biogeochemical weathering of urban buildings and infrastructures, the salting of roads, etc., are other anthropogenic sources of salts locally enriching the soils. Deforestation by burning, erosion (aeolian, chemical, hydric) and global warming are all natural phenomena as well as forcing factors linked to human activities [GHA 95].

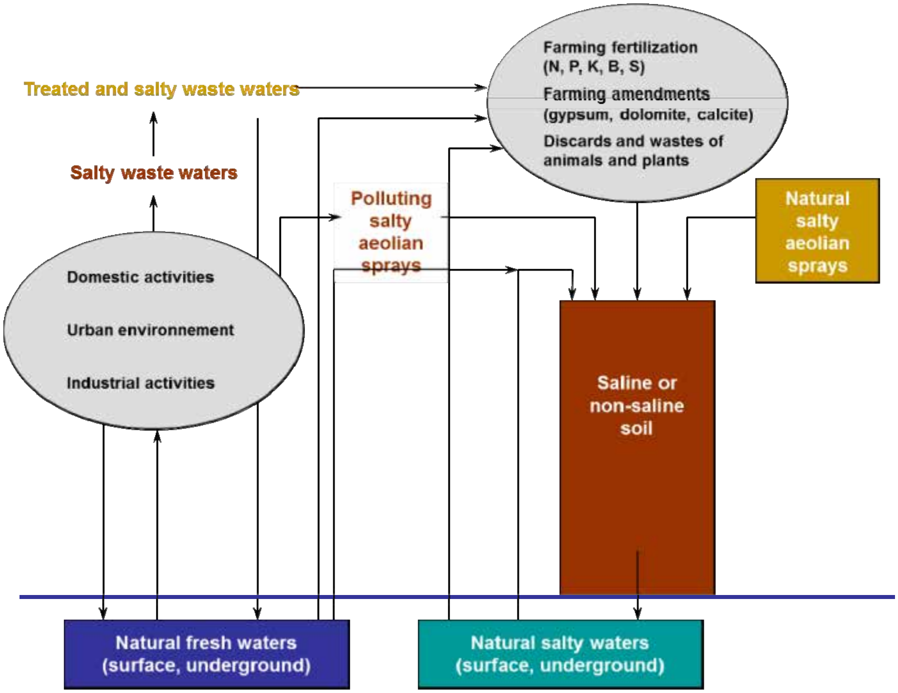

Figure 5.8. *Urban and agricultural cycles of secondary salinization cycles (from modified [VEN 04])*

5.5.2. *Salinization of irrigated systems*

The intensive development of irrigated agriculture in arid and semiarid regions induces a concomitant extension of salty lands linked to the poor chemical quality of irrigation water and the poor irrigation management [BAR 95, DOS 80, GON 92, HAC 98, HAL 85, HAM 01, MAR 96]. Irrigated soils degrade chemically, physically and biologically in the short term and are often abandoned by farmers for lack of favorable conditions to rehabilitate them. Salty soils occupy at least 20% of irrigated lands. To a lesser degree, similar effects can be observed locally in more temperate climates.

Naturally, rainwater has a dissolving power on soil minerals, especially the highly soluble minerals present in salty soils. Their abundance and the good soil infiltration capacity allow the leaching of soluble salts in depth towards the underground waters and their transfer to the lower parts of pedological formations. This is also the case with fresh water used in irrigation. On the other hand, if the irrigation water is already saline, the risks of salinization are high [GRU 07].

Richards [RIC 54] proposes two criteria for assessing the quality of irrigation water: EC, defining the rate of water mineralization, and SAR, estimating its alkalinizing power. The result is a classification of irrigation waters and the risks involved for its use in irrigated agriculture. More recent guidelines have been presented to rapidly assess the water suitability for irrigation [AYE 85].

5.5.3. *Control of salts in irrigation*

The basic principle for a plant to grow in salty soil is to maintain satisfactory salinity in the root zone by removing salts with a deep leaching. The water balance of the considered soil volume must be negative. Water inputs must be lower than outputs and allow internal drainage of the saline soil solution. In non-saline soil, the irrigation doses are calculated to compensate for the actual plant evapotranspiration and to maintain good soil moisture [VAL 87]. In saline soil, which involves being desalinized over a certain depth, an additional quantity of water must be added in order to leach the salts. The effective leaching dose or fraction is 15% for a coarse-textured soil and 10% for a fine-textured and low permeable soil (limited internal drainage). During the plant growth period, the leaching fractions at each irrigation can be increased [MAR 09].

If a groundwater table, saline or not, is present within the soil, it will be necessary to manage the leaching flow in order to keep it in depth and avoid the rise of salts in the root zone [BOI 02, SHA 84]. Irrigation of non-saline soil with poor quality water will promote salinization and, conversely, desalinization of saline soil will be induced by irrigation with good quality water. If soil salinity is high, irrigation with poor quality water is feasible within reasonable limits [BEL 99, DUA 13].

5.5.4. *Use of non-conventional waters*

From an environmental point of view, saline drainage water, produced by an irrigated area, is recyclable, insofar as its salinity is acceptable compared to that of the soils to be irrigated. Treated and saline wastewater, which is produced by the urban cycle of secondary salinization (see Figure 5.8), can also be used to irrigate soils with higher salinity. We speak of “saline” agriculture, whose techniques require a prior diagnosis of salinization processes. The use of non-conventional saline and/or sodic waters will limit the pressure on conventional, fresh and low-renewable water resources and follow a cyclical strategy. Irrigation of a salt-sensitive crop with good quality water will alternate with irrigation of a less salt-sensitive crop with saline water. The strategy of mixing the two types of water is also a viable solution. It will depend on the volumes considered for the irrigation project (Figure 5.9).

Figure 5.9. *Water management in irrigated areas: (a) surface submersion irrigation, El Guettar oasis, southern Tunisia; (b) drip irrigation, Kairouan region, central Tunisia (photos: J.-P. Montoroi). For a color version of this figure, see www.iste.co.uk/valentin/soils5.zip.*

5.6. Agricultural development of salty soils

5.6.1. *Historical context*

The salinization issues of agricultural lands go back to the origins of rain-fed and irrigated agriculture. The floods of capricious rivers were the first forms of natural irrigation that farmers used during the flood recession. In addition, advances in farmers' technical knowledge have made it possible to better control the natural elements through increasingly sophisticated hydraulic developments. The water supplies to the plot were managed according to the crop calendar and the state organization of societies. The impossibility of controlling soil salinization threatened many civilizations in ancient and modern times, some having lost their prosperity after several centuries of existence. This is the case of the hydraulic societies in Mesopotamia, which have at times disappeared due to other factors such as poor social organization, decadent central power and natural disasters [JOB 92].

5.6.2. *Effects of salty soil water on plants*

In salty environments, plant species have great difficulty developing because water availability is lower. In absolute terms, the osmotic pressure of an electrolytic solution (mineralized or saline water) corresponds to the depression that the plant must exert in order to collect it. It is proportional to the salinity of the soil solution according to the empirical relation: ψ (atm) = – 0.36 EC (dS m^{-1})). For example, all plants in contact with sea water (EC = 42 dS m^{-1}) are irreparably wilted ($\psi \approx$ 16 atm). In reality, the potential of water in saline soil is higher, in absolute terms, because the osmotic potential of saline water is added to the matrix potential of the soil. In saline soil, plant wilting occurs at a higher water content than in non-saline soil (Figure 5.10).

In order to resist the osmotic effects of soil solution, plants have specific or combined adaptations:

– of a physiological nature: production of specific compounds (proline) limiting saline stress [LOK 12];

– of a morphological nature: precipitation of salt crystals in foliar stomata, concentration of salts in specialized cells of the foliar epidermis (salt glands) and concentration of salts in cellular vacuoles causing turgidity of plants (succulent plants gorged with saline water) [JAV 89].

Nutritional imbalances, linked to excess sodium (Na^+) in comparison with calcium (Ca^{2+}) and magnesium (Mg^{2+}), appear during plant growth. The toxicity of the Cl^- ion also affects many plants when the concentration exceeds 5–10 $mmol_c\ L^{-1}$ (leaf necrosis by chlorosis).

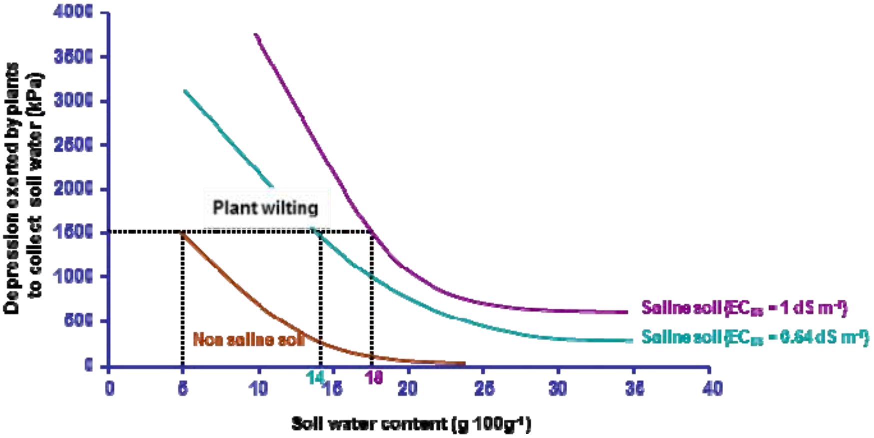

Figure 5.10. *Effect of soil salinity on water availability for plants (from [REN 06])*

5.6.3. *Agronomic solutions*

Depending on the intensity of salinization and alkalinization processes, various agronomic techniques can be applied to remediate saline soils, at varying time and space scales. The techniques require human and financial resources, depending on the social organizations involved. They have long been applied empirically. Modern technologies (instrumentation, modeling) allow a better diagnosis upstream of irrigation projects and a rationalization of resources during their implementation.

The management of saline soils primarily requires the elimination of excess salts in the soil, particularly sodic salts. In the best case, this will involve mobilizing soluble salts in the soil (leaching process) and draining saline water from the soil at depth or laterally into an internal soil drainage network. In addition, the drainage of the saline groundwater allows the total or partial suppression of the initial source of salts. If natural drainage is insufficient, an artificial drainage system must be installed (Figure 5.11).

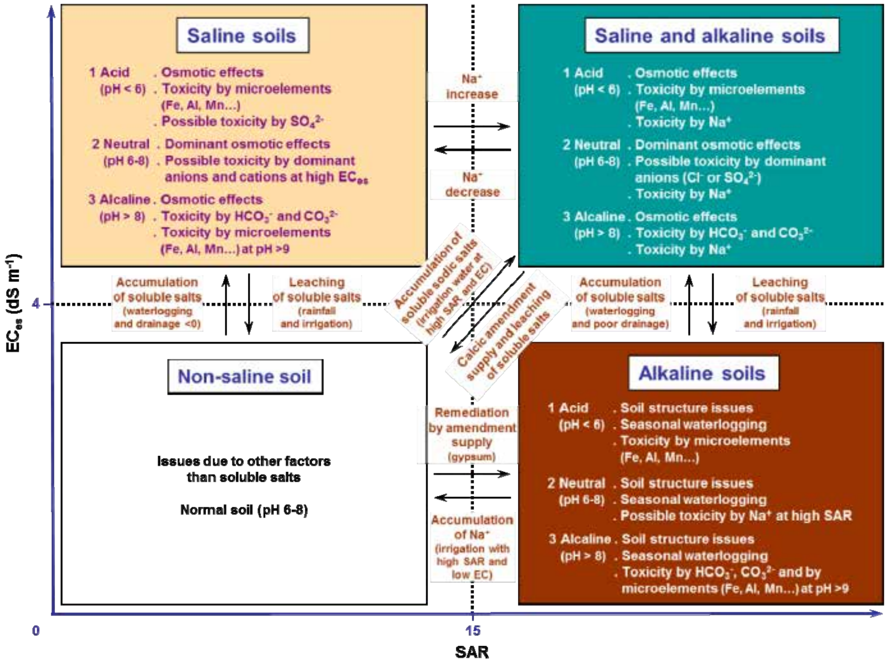

Figure 5.11. *Management practices of saline and sodic soils*

All cropping practices aimed at improving soil structure (better porosity) and promoting water infiltration (better permeability) have a positive impact on salt leaching and internal drainage. They are all the more efficient when rainwater or irrigation water is abundant and of good chemical quality. However, excessive water inflows and poor drainage cause the saline groundwater to rise, and even faster if it is shallow. Deficient water inflows limit salt leaching and increase saline soil degradation, and even more so if the climate is arid and the water supplied is salty. The main leaching techniques include surface raking of salts, mole ploughing, elevation of leveled plots, ridge ploughing and organic matter supply (Figure 5.12). Gypsum or limestone amendments enrich sodic clays that are sensitive to dispersion with exchangeable Ca^{2+} and promote soil structure by flocculation and aggregation. Phytoremediation of saline soils is efficient, inexpensive and environmentally acceptable [QAD 01]. In alkaline soils, the roots of remediating plants slowly dissolve soil calcite, providing calcium (Ca^{2+}) to replace sodium (Na^+) from cationic exchange sites. Although it is slower compared to mineral amendments, phytoremediation promotes soil aggregation, soil hydraulic properties and carbon sequestration. Halophytic plants are also used for remediation of saline soils [MAN 11].

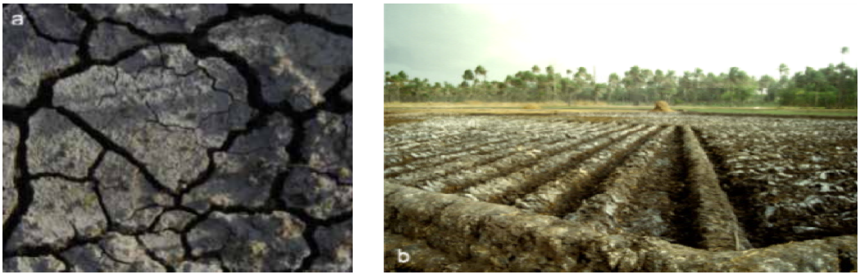

Figure 5.12. *Saline clayey soil: (a) undeveloped, compacted and cracked; (b) constructed as ridges in order to improve rainwater leaching, Basse-Casamance, Senegal (photos: J.-P. Montoroi). For a color version of this figure, see www.iste.co.uk/valentin/soils5.zip.*

Cultivated plants are classified according to their salt tolerance level. With respect to the optimal yield of a given crop, the increasing yield loss with soil salinity is determined and the crops are compared with each other at the 50% loss threshold [AYE 85, ROZ 08]. The effects of salinity on plants are negligible for EC values below 2 dS m^{-1} and lethal for EC values above 15 dS m^{-1}. The threshold value, above which adverse effects on plant growth occur, not only depends on the type of plant, but also on the type of soil and its water status. Depending on local saline constraints, the most halotolerant plants will be chosen to enhance the agricultural value of salty soils. In addition, the industrial cultivation of halophytes (salty plant cropping), which is booming in some countries, offers additional income.

5.6.4. *Macroeconomic solutions*

Salty soil management requires a sufficient water supply in order to control soil salinity. Freshwater resources in arid and semiarid regions exist, but they are either non-renewable or poorly renewable (deep aquifers), or variable, abundant and poorly controllable (catastrophic floods). Depending on the pedological and geological formations crossed, the waters acquire various chemical facies, often unsuitable for agriculture [GRU 07].

Runoff water storage facilities allow their use for irrigation of irrigated areas, upstream or downstream, on very varied surfaces. Depending on the catchment area, infrastructures can range from large hydraulic dams to small hill lakes. Seawater desalination techniques are another way to supplement freshwater resources at prohibitive operating costs.

5.6.5. *Social and political solutions*

Many parts of the world naturally face limited supplies of fresh water. In irrigated systems, considerable amounts of water are lost through surface evaporation from the soil during transport and irrigation, leakage during storage and transport to the plot, uncontrolled runoff and drainage. These losses are estimated at about 30%. This results in additional costs for the operation of irrigated perimeters. Depending on the size of these perimeters, the social organization of water rotations is also an important element to take into account, as it is a homogeneous and regular organization ensuring the sustainability of the system [BEN 15]. The effective intervention of the public or private sector in the field of hydraulic infrastructures is also the guarantee of a profitable agricultural production.

5.7. Conclusions

Natural salty environments present a wide variety of landscapes ranging from diffuse salinization to extreme salinization. Salty soils develop there in relation with a remarkable biodiversity that offers available resources to local populations. The process of secondary or anthropogenic salinization changes the composition of natural waters (lakes, rivers, groundwaters); degrades the quality of water required to satisfy domestic, agricultural and industrial needs; contributes to the loss of biodiversity and soil fertility; modifies local climatic conditions; creates health problems; and drastically reduces agricultural and fish farming activities.

Agricultural production is directly affected by the physical–chemical degradation of water and soil, especially in dry, arid and semiarid regions. Remediation of salty soils can be achieved through substantial financial investments, which mainly penalizes countries with limited incomes. Good salty soil irrigation and drainage techniques are a guarantee of success, but the poor chemical quality of irrigation water is a constraint on the sustainable development of irrigated areas. The local grouping of farmers in collective structures promotes the dissemination of technical knowledge and access to credit institutions.

Scientific research is still needed in order to not only deepen knowledge on the characterization and physical–chemical functioning of salty soils, but also on the adaptation and tolerance of plants and animals to saline stress. The functional contribution of microorganism biodiversity to organic matter degradation processes and biogeochemical reactions in salty soils is still poorly documented.

RESEARCH QUESTIONS.–

1) Are saline crusts and efflorescences organic? To what degree, nature and process?

2) What is the impact of urban, industrial and agricultural activities on salinization processes, particularly in terms of metal and organic pollution?

3) What is the contribution of salty aerosols (natural and/or polluting) to the hydro-saline and biological functioning of soils?

4) What is the contribution of chemical erosion (dissolution of minerals, ionic desorption of colloids, mineralization of soil solution, etc.) in material transfers by erosion and salinization processes?

RECOMMENDATIONS.–

1) In an environmental context that favors salinization processes, combine techniques that maintain the aggregated soil structure, limit soil evapotranspiration and promote water infiltration for better salt leaching into the soil.

2) To the extent that water is accessible and available, strengthen and develop means to improve the chemical quality of irrigation water (seasonal mixing) and social water management (rural communities).

3) In saline agriculture, control the mineral salt content of food products in relation to the physiological needs of living beings.

4) Develop ecosystem services in natural salty environments as a complement to resources for local populations, in particular through the production of halophytes (salty plant cropping) and salts (salt-farming).

5.8. References

[ALD 76] AL-DROUBI A., Géochimie des sels et des solutions concentrées par évaporation. Modèle thermodynamique de simulation. Application aux sols salés du Tchad, Thesis, Louis Pasteur University, Strasbourg, 1976.

[AYE 85] AYERS R.S., WESTCOT, D.W., Water quality of agriculture, irrigation and drainage, no. 29, Report, FAO, Rome, 1985.

[BAI 09] BAIZE D., GIRARD M.C., *Référentiel pédologique 2008*, Éditions Quæ, Versailles, 2009.

[BAR 95] BARBIERO L., *Les sols alcalinisés sur socle dans la vallée du fleuve Niger. Origines de l'alcalinisation et évolution des sols sous irrigation*, ORSTOM, Paris, 1995.

[BEL 99] BELTRAN J.M., "Irrigation with saline water: benefits and environmental impact", *Agricultural Water Management*, vol. 40, pp. 183–194, 1999.

[BEN 15] BEN MUSTAPHA A., FAYSSE N., MARLET S. *et al.*, "Une action collective analysée par ses acteurs: une association d'irrigants en Tunisie", *Natures Sciences Sociétés*, vol. 23, pp. 356–366, 2015.

[BER 72] BERNUS E., BERNUS S., *Du sel et des dattes. Introduction à l'étude de la communauté d'In Gall et de Tegidda-n-tesemt*, CNRSH, Niamey, 1972.

[BOI 02] BOIVIN P., FAVRE F., HAMMECKER C. *et al.*, "Processes driving soil solution chemistry in a flooded rice-cropped vertisol: analysis of a long-time monitoring data", *Geoderma*, vol. 110, pp. 87–107, 2002.

[BRE 82] BRESLER E., MCNEAL B.L., CARTER D.L., *Saline and Sodic Soils. Principles, Dynamics, Modeling*, Springer-Verlag, Berlin, 1982.

[CAM 91] CAMBIER P., "Modélisation des phénomènes d'adsorption des solutés sur les surfaces minérales. Synthèse bibliographique", *Science du sol*, vol. 29, no. 3, pp. 245–264, 1991.

[CHE 98] CHEVERRY C., BOURRIÉ G., "La salinisation des sols", in STENGEL P., GELIN S. (eds), *Sol: Interface Fragile*, INRA Éditions, Paris, pp. 109–127, 1998.

[CHH 96] CHHABRA R., *Soil Salinity and Water Quality*, A.A. Balkema, Rotterdam, 1996.

[DEN 95] DENT D.L., PONS L.J., "A world perspective on acid sulfate soils", *Geoderma*, vol. 67, pp. 263–276, 1995.

[DOS 80] DOSSO M., Géochimie des sols salés et des eaux d'irrigation. Aménagement de la basse vallée de l'Euphrate en Syrie, Thesis, INP, Toulouse, 1980.

[DUA 13] DUAN R., FEDLER C.B., “Salt management for sustainable degraded water land application under changing climatic conditions”, *Environmental Science & Technology*, vol. 47, pp. 10113–10114, 2013.

[FAL 14] FALL L.A., MONTOROI J.P., STAHR K., “Coastal acid sulfate soils in the Saloum River basin, Senegal”, *Soil Research*, vol. 52, no. 7, pp. 671–684, 2014.

[FAN 97] FANNING D.S., BURCH S.N., “Acid sulfate soils and some associated environmental problems”, *Advances in GeoEcology*, vol. 30, pp. 145–158, 1997.

[FIT 03] FITZPATRICK R.W., MERRY R.H., COX J.W. *et al.*, Assessment of physico-chemical changes in dryland saline soils when drained or disturbed for developing management options, Technical Report, vol. 2, no. 3, CSIRO, 2003.

[FLO 05] FLOWERS T.J., FLOWERS S.A., “Why does salinity pose such a difficult problem for plant breeders?”, *Agriculture Water Management*, vol. 78, pp. 15–24, 2005.

[FLO 08] FLOWERS T.J., COLMER T.D., “Salinity tolerance in halophytes”, *New Phytologist*, vol. 179, pp. 945–963, 2008.

[GHA 95] GHASSEMI I., JAKEMAN A.J., NIX H.A., *Salinisation of land and water resources. Human causes, extent, management and case studies*, Cabi, Wallingford, 1995.

[GON 92] GONZALES-BARRIOS J.L., Eaux d’irrigation et salinité des sols en zone aride mexicaine. Exemple dans la “Comarca Lagunera”, Thesis, University of Montpellier II, 1992.

[GRU 07] GRUNDY M., SILBURN D., CHAMBERLAIN T., “A risk framework for preventing salinity”, *Environmental Hazards*, vol. 7, pp. 97–105, 2007.

[HAC 98] HACHICHA M., Mise en valeur des sols salés. Organisation, fonctionnement et évolution de sols salés du nord de la Tunisie, Thesis, École nationale supérieure agronomique de Rennes, 1998.

[HAL 85] HALITIM A., Contribution à l’étude des sols des zones arides (hautes plaines steppiques de l’Algérie). Morphologie, distribution et rôle des sels dans la genèse et le comportement des sols, Thesis, University of Rennes, 1985.

[HAM 01] HAMDI-AISSA B., Le fonctionnement actuel et passé de sols du Nord Sahara (cuvette d’Ouargla). Approche micromorphologique, géochimique, minéralogique et organisation spatiale, Thesis, Institut national agronomique de Paris-Grignon, 2001.

[IUS 14] IUSS WORKING GROUP WRB, World reference base for soil resources 2014. International soil classification system for naming soils and creating legends for soil maps, World Soil Resources Reports, no. 106, FAO, Rome, 2014.

[JAV 89] JAVOR B., *Hypersaline Environments: Microbiology and Biogeochemistry*, Springer-Verlag, Berlin, 1989.

[JOB 92] JOB J.O., “Les premiers aménagements hydroagricoles en Mésopotamie et les problèmes de sels”, *Didactiques*, ORSTOM, Paris, 1992.

[LOK 12] LOKHANDE V.H., SUPRASANNA P., “Prospects of halophytes in understanding and managing abiotic stress tolerance”, in AHMAD P., PRASAD M.N.V. (eds), *Environmental Adaptations and Stress Tolerance of Plants in the Era of Climate Change*, Springer, New York, pp. 29–56, 2012.

[LOY 95] LOYER J.Y., “Solums salsodiques. Salisols et sodisols”, *Référentiel pédologique*, AFES-INRA Éditions, Paris, 1995.

[MAN 11] MANOUSAKI E., KALOGERAKIS N., “Halophytes, an emerging trend in phytoremediation”, *International Journal of Phytoremediation*, vol. 13, pp. 959–969, 2011.

[MAR 06] MARLET S., JOB J.O., “Processus et gestion de la salinité des sols”, in TIERCELIN J.R., VIDAL A. (eds), *Traité d’irrigation*, Lavoisier, Paris, pp. 797–822, 2006.

[MAR 09] MARLET S., BOUKSILA F., BAHRI A., “Water and salt balance at irrigation scheme scale: a comprehensive approach for salinity assessment in a Saharan oasis”, *Agricultural Water Management*, vol. 96, pp. 1311–1322, 2009.

[MAR 96] MARLET S., Alcalinisation des sols dans la vallée du fleuve Niger. Modélisation des mécanismes physico-chimiques et évolution des sols sous irrigation, Thesis, École nationale supérieure agronomique de Montpellier, 1996.

[MAR 05] MARTINEZ-BELTRAN J., MANZUR C.L., “Overview of salinity problems in the world and FAO strategies to address the problem”, *Proceedings of the international salinity forum*, Riverside, April 25–27, 2005.

[MON 04] MONTOROI J.P., BOUZID N., GRÜNBERGER O. *et al.*, “Geophysical characterization of saline patches in Northeastern Thailand”, in RIEB S., WONGPORNCHAI P., CHANTRAPRASERT S. (eds), *Proceedings of the International Conference on Applied Geophysics*, Chiang Mai University, Thailand, November 26–27, 2004.

[MON 96] MONTOROI J.P., *Gestion durable des sols de l’écosystème de mangrove en Casamance (Sénégal). Dynamique de l’eau et des sels en période de sécheresse*, ORSTOM, Paris, 1996.

[ORE 02] OREN A., *Halophilic Microorganisms and Their Environments*, Kluwer Academic Publishers, Dordrecht, 2002.

[PAY 16] PAYEN S., BASSET-MENS C., NÚÑEZ M. *et al.*, "Salinisation impacts in life cycle assessment: a review of challenges and options towards their consistent integration", *International Journal of Life Cycle Assessment*, vol. 21, pp. 577–594, 2016.

[QAD 01] QADIR M., SCHUBERT S., GHAFOOR A. *et al.*, "Amelioration strategies for sodic soils: a review", *Land Degradation Development*, vol. 12, pp. 357–386, 2001.

[REN 06] RENGASAMY P., "World salinization with emphasis on Australia", *Journal of Experimental Botany*, vol. 57, no. 5, pp. 1017–1023, 2006.

[RHO 92] RHOADES J.D., "Instrumental field methods of salinity appraisal", in TOPP G.C., REYNOLDS W.D., GREEN R.E. (eds), *Advances in Measurement of Soil Physical Properties: Bringing Theory into Practice*, Soil Science Society Edition, Madison, WI, 1992.

[RIC 54] RICHARDS L.A., *Diagnosis and Improvement of Saline and Alkali Soils*, Agricultural Handbook 60, Washington DC, 1954.

[RIE 91] RIEU M., TOUMA J., GUEYI H.R., "Sodium-calcium exchange on Brazilian soils: modeling the variations of selectiviy coefficients", *Soil Science Society of America Journal*, vol. 55, pp. 1294–1300, 1991.

[ROZ 08] ROZEMA J., FLOWERS T.J., "Crops for a salinized world", *Science*, vol. 322, pp. 1478–1480, 2008.

[SER 78] SERVANT J.M., "La salinité dans le sol et les eaux: caractérisation et problèmes d'irrigation-drainage", *Bulletin du BRGM*, Section III, vol. 2, pp. 123–142, 1978.

[SHA 84] SHAINBERG I., SHALHEVET J., *Soil Salinity under Irrigation. Processes and Management*, Springer-Verlag, Berlin, 1984.

[SPO 89] SPOSITO G., *The Chemistry of Soils*, Oxford University Press, Oxford, 1989.

[SOI 14] SOIL SURVEY STAFF, *Keys to Soil Taxonomy,* 12th ed., USDA-NRCS, National Soil Survey Center, Lincoln, NE, 2014.

[SUM 93] SUMNER M.E., "Sodic soils: new perspectives", *Australian Journal of Soil Research*, vol. 31, pp. 683–750, 1993.

[SZA 89] SZABOLCS I., *Salt-Affected Soils*, CRC Press, Boca Raton, FA, 1989.

[TES 92] TESSIER D., LAJUDIE A., PETIT J.C., "Relation between the macroscopic behavior of clays and their microstructural properties", *Applied Geochemistry*, vol. 1, pp. 151–161, 1992.

[VAL 87] VALLES V., Étude et modélisation des transferts d'eau et de sel dans un sol argileux. Application au calcul des doses d'irrigation, Thesis, Louis Pasteur University, Strasbourg, 1987.

[VEN 03] VENGOSH A., "Salinization and saline environments", in HOLLAND H.D., TUREKIAN K.K. (eds), *Treatise on Geochemistry*, Elsevier Science, Amsterdam, pp. 333–365, 2003.

[WIL 99] WILLIAMS W.D., "Salinisation: a major threat to water resources in the arid and semi-arid regions of the world", *Lakes Reservation Research Management*, vol. 4, pp. 85–91, 1999.

Montoroi Jean-Pierre.

Soil salinization and management of salty soils.

In : Valentin Christian (ed.). Soils as a key component of the critical zone 5 : degradation and rehabilitation. Londres : ISTE, Wiley, 2018, p. 97-126.

(Geosciences Series. Soils Set ; 5).

ISBN 978-1-78630-219-9