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SODIC SOILS

Distribution, Properties, Management, and Environmental Consequences

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Distribution of Sodic Soils: The World Scene

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2.1 INTRODUCTION

The world distribution of sodic soils, which are usually considered a subset of salt-affected soils (Shainberg and Letey, 1984; FAO, 1988; Szabolcs, 1989; Gupta and Abrol, 1990a), has been discussed by Szabolcs (1989) in combination with salinesoils. However, much confusion exists in the literature concerning the use of such terms as saline sodic, alkaline or not, saline nonsodic, and sodic nonsaline soils (Kelley, 1951). In most cases, sodic soils have been defined on the basis of morphological (columnar structure) and chemical properties [exchangeable sodium (Na) percentage (ESP) or sodium adsorption ratio (SAR)] of the B horizon.

Sodic soils are characterized by dense impermeable sodic B horizons. These soils are frequently truncated as a result of the removal of the overlaying surface horizons by water erosion due to the impermeable sodic horizon. The sodic B horizon is very erodible on account of the highly dispersed and easily mobilized nature of the clay fraction (Levy and van der Watt, 1988; van der Watt and Valentin, 1992; Chapter 3). Hence, both sheet and gully erosion are common on these soils (Chapter 5).

Many sodic soils are unsuitable for agriculture, but heavier textured profiles, in which the sodic horizon is as deep as 0.8 m, can be utilized for production, usually under irrigation, provided that great care is taken in their management. For the most part, sodic soils support native grasses for grazing and small grain production. In the dry state, sodic soil materials are difficult to wet with applied water, which is not readily absorbed due to crust formation. This will result in runoff (Levy and van der Watt, 1988), first removing dispersed clay and subsequently, the other particle-size fractions of the material. These properties are responsible for the highly erodible nature of the sodic materials (Chapter 5). Their resistance to wetting further renders sodic material unsuitable for the construction of dams and roads and for most other civil engineering purposes, since such material cannot be compacted by mechanical means. Dams constructed from sodic materials are very prone to piping, and in the case of roads, uneven subsidence leads to a breakup of the surface mat (Chapter 9).

An attempt will be made to estimate the extent of soils showing sodic characteristics and behavior using three levels of ESP – < 6, 6–15, and > 15 – as the criteria to group soils. These threshold values have been selected on the basis of much published work, indicating that moderately strong sodic characteristics are exhibited when soils reach ESP greater than 6 anywhere in the upper 1 m of soil (Northcote and Skene, 1972) (Chapter 1). These subdivisions correspond roughly to the Nonsodic ($SAR_{1:5} \leq 3$, $ESP \leq 6$), Sodic ($SAR_{1:5} \sim 3$–10, $ESP \sim 6$–15) and Very Sodic ($SAR_{1:5} \geq 10$, $ESP \geq 15$) categories proposed in Chapter 1. The reason why these categories are approximate is because the intensity of sodic behavior is modified by the presence of salts (see Fig. 1.7). The latest map and attribute data available from the FAO (1988, 1991) will be used to estimate the extent of soils exhibiting sodic behavior.

2.2 A WORLD SODIC SOILS MAP

2.2.1 Problems Associated with Development

The production of such a map using new definitions as suggested in Chapter 1, is an undertaking fraught with many difficulties. First of all, problems arise because the criteria used to define map units are different depending on factors such as the classification system and scale used, the purpose of the map, the availability of chemical and physical data, and inadequate or incomplete profile descriptions. For example, 600 soil maps of different scales and legends, involving the collation of systematic and reconnaissance surveys, were used to compile the FAO/UNESCO *Soil Map of the World* (FAO, 1974; 1988). One of the most crucial aspects of the project was the correlation of soil map units to produce a legend involving the use of physiography, vegetation, climate, geology, and land use information as surrogates for limited soil data. Criteria used to define map units were pedogenesis, characteristics and distribution of major soil groups as identified in the major soil classification systems used, significance of soil resources for production, and feasibility of representation on a small scale (1:5 000 000) map. The map units consisted of soil associations, each of which was composed of dominant (occupying the largest area) soil, subdominant soils (occupying more than 20% of the map unit), and inclusions (occupying less than 20% of the map unit).

Another source of confusion is the terminology used to describe pedogenic processes leading to the development of sodic soils, e.g., salinization, solonization, alkalization, solodization, sodification, and the terminology used to refer to the soils themselves. Because these terms have been used somewhat loosely, the separation of soils exhibiting sodic behavior becomes difficult. For example, Isbell (1958) discusses changes in the usage of the term Solonetz and the introduction of the term Solodized Solonetz as the emphasis of the classification shifted from chemical properties to morphology. The evolution of the terms used to describe sodic soils has been discussed by Kelley (1951) and in Chapter 1, to which interested readers are referred.

2.2.2 Differences in Soil Classification Systems

Szabolcs (1991) has reviewed the properties of salt-affected soils as they impact on some of the major soil classifications. Although most classifications consider soil profile morphology (presence of a diagnostic horizon, soil structure) and chemical properties [exchangeable sodium percentage (ESP), sodium adsorption ratio (SAR), and pH] in the definition of sodicity, there are marked differences between classification systems, all of which have been influenced to some extent by the 1938 Great Soil Group system (Baldwin *et al.*, 1938). However, several soil classification systems have changed significantly since 1990.

In the current FAO/UNESCO *Soil Map of the World* legend (FAO, 1988), Solonetz soil units are those that have a natric B horizon and lack an albic E horizon, and which exhibit hydromorphic characteristics in at least part of the horizon. A natric horizon which is a special type of argillic (now redefined and called argic) horizon has the following additional properties:

1. a columnar or prismatic structure in some part of the B horizon, or a blocky structure with tongues of an eluvial horizon in which there are uncoated silt or sand grains extending more than 25 mm into the horizon;

2. an ESP above 15 within the upper 0.4 m of the horizon, or more exchangeable magnesium (Mg) plus Na than calcium (Ca) plus exchange acidity (at pH 8.2) within the upper 0.4 m of the horizon provided that ESP is greater than 15 in some subhorizon within 2 m of the surface.

While soils with a natric horizon could be classified as Orthic/Mollic/Gleyic Solonetz and/or Solodic Planosols according to the 1974 FAO legend (FAO, 1974), sodic soils have been accommodated exclusively as Solonetz (Gleyic/Stagnic/Mollic/Gypsic/Calcic/Haplic) in the revised legend (FAO, 1988). The diagnostic natric horizon is no longer permitted in the Planosol unit (i.e., Solodic Planosols no longer exist) but the occurrence of diagnostic sodic soil properties is recognized. *Sodic properties*, defined as ESP greater than 15 or ESP + EMgP (exchangeable Mg percentage) about 50, are used to identify Sodic Solonchaks (FAO, 1988). The *sodic phase* describes soils in which ESP exceeds 6 in some horizons within 1 m of the surface. These subdivisions are fortuitous because they are essentially the same as those proposed in Chapter 1.

Solonchak soils, which are the other major component of salt-affected soils, are seldom if ever cultivated because of their very high salt contents and will not be discussed at length here. They have salic but not fluvic properties and contain no diagnostic horizons other than an A, a histic H, a cambic B, a calcic or a gypsic horizon. To exhibit *salic properties*, the electrical conductivity of the saturation extract (EC_e) within 0.3 m of the surface must exceed 15, dS m^{-1} at some time during the year, or if the pH is above 8.5, 4 dS m^{-1}. Sodic Solonchak soils must have sodic properties at least between 0.2 and 0.5 m of the surface, and lack gleyic properties and permafrost within 1 and 2 m of the surface, respectively. In the *salic phase*, the EC_e must exceed 4 dS m^{-1} in some horizon within 1 m of the surface.

Recently the World Reference Base for Soil Resources was introduced as a new basis for correlation between national systems of soil classification, eventually to supersede the revised FAO/UNESCO legend (FAO, 1988).

Under this system, the following eight units are proposed for Solonetz, in key order: Gleyic, Stagnic, Salic, Albic, Mollic, Gypsic, Calcic, and Orthic (Spaargaren, 1994).

In the latest Soil Taxonomy (US Soil Survey Staff, 1992), the definition of a natric horizon is essentially identical to that of the FAO/UNESCO legend with sodic (natric) characteristics impacting at the Great Group rather than at the highest (Order) level. Szabolcs (1991) points out that the 2 m depth requirement in the definition of natric horizons is too deep because the diagnostic horizon must be higher in the profile to determine the soil type. Moreover, Soil Taxonomy does not exploit the relationship between sodicity and the soil water regime (Seelig *et al.*, 1990).

In Australia, Isbell (1995b) has reviewed the development and use of sodicity in classification systems. In the new Australian Soil Classification System, Isbell (1994) recognizes an order (highest categorical level) called Sodosols which has "a clear or abrupt textural B horizon which is sodic (ESP of 6 or more) in the major part of the upper 0.2 m of the B2 horizon (or the whole B2 horizon if it is less than 0.2 m thick) and the pH (1:5 H_2O) is 5.5 or greater." Further use of sodicity is made at the Great Group level of Sodosols: subnatric (ESP 6–14), natric (ESP 15–25), and hypernatric (ESP > 25). In seven other orders, B horizon sodicity is used at the Great Group or Subgroup level. The new Sodosols include most of the soils previously called Solodic, Solodized Solonetz, Sodic Red-Brown Earths, and Desert Loams as well as some of the Soloths in the Great Soil Group classification (Stace *et al.*, 1968). Many of the duplex soils in the Factual Key (Northcote, 1979) also fall into this Order.

The French *Référentiel Pédologique* (Baize, 1990), which is an open-ended pedological reference base rather than a hierarchical classification system, defines *Salsodic* soils by the presence of salic or sodic horizons. A sodic horizon is defined as

> a horizon at least 0.1 m thick that is present within 0.8 m of the surface and is characterized by either a massive structure or coarse polyhedric, prismatic or columnar structure (which is the case in certain solums that have evolved in more humid pedoclimates) but always with very low intra-pedal porosity in both rainy and dry seasons. This structural degradation is provoked by a more or less elevated level of exchangeable and hydrolyzable Na of the order of 15% of the CEC. This limit can be lower when the 'missing' Na is compensated by a high level of Mg on the exchange complex, especially if the level of Mg is disproportional to the level of Ca. Depending on the nature of clay minerals present, an ESP less than 15% can also cause structural degradation. The level of soluble salts present in this horizon is nil or very low.

Two terms are used to distinguish saline soils (Salisols chloruro-sulfatés and Salisols carbonatés), three for sodic soils (Sodisols indifferenciés, Sodisols solonetziques, Sodisols solodisés), and two reflect the presence of both salic and sodic horizons (Sodisalisols and Salisodisols), depending on the sequential order of the two diagnostic horizons.

In the Canadian System of Soil Classification (Agriculture Canada Expert Committee on Soil Survey, 1987), the definition of a solonetzic B horizon is based on morphological and chemical criteria:

> These horizons have prismatic or columnar primary structure that breaks down to blocky secondary structure; both structural units have hard to extremely hard consistence when dry. The ratio of exchangeable Ca to Na is 10 or less.

The Canadian System of Soil Classification is unique in using the Ca:Na ratio rather than ESP as a classification criterion.

The Orders used to classify sodic soils in different classification systems are presented in Table 2.1.

2.3 GENESIS AND CATENA

Naturally sodic soils as represented by the Solonetz are thought to develop as a result of a sequence of pedogenic processes according to the model developed by the early Russian pedologist K. K. Gedroiz [summarized by Miller and Pawluk (1994)]:

1. Salinization due to saline parent material or capillary rise of saline groundwater tables is the source of soluble Na necessary for the formation of solonetzic soils. Key to the existence of saline conditions is a net evaporative hydrological regime as found in arid or semiarid environments. Subsequent desalinization marks the onset of solonetzic soil formation.

2. Solonization starts with the leaching of salt by dilute percolating rainwater, which leads to the dispersion of clays if ESP exceeds 10–15 and total soluble salt content is 0.1–0.15% or less. The illuviation of dispersed clays leads to an abrupt textural change between A and B horizons.

3. Solodization is driven by Na-induced hydrolysis and eluviation at the top of the (increasingly) slowly permeable B horizon.

TABLE 2.1 Orders in which sodic soils occur in various classification systems

FAO Revised Legend[a]		Australian[b]	French[c]		
Solonchak	Solonetz	Sodosol	Salisol	Sodisol	Sodisalisol/Salisodisol
Haplic	Haplic	Red	Chlorosulfatés	indifferenciés	
Molic	Molic	Brown	Carbonatés	Solonetzques	
Calcic	Calcic	Yellow		Solodisés	
Gypsic	Gypsic	Grey			
Glayic	Stagnic	Black			
Gelic	Gleyic				

Soil Taxonomy[d]				Russian System[e]	
Alfisol	Aridsol	Mollisol	Vertisol		Solonetz
Natraqualfs	Natrargids	Natralbolls	Natraquerts		Chernozemic
Natriboralfs	Natrigypsids	Natraquolls	Sodic Endoaquerts		Chernozemic Solonchak
Natrudalfs		Natrustolls	Sodic Calciusterts		Solonchakic Chernozemic
Natrustalfs		Natrixerolls	Sodic Gypsiusterts		Deep-solonchakic Chernozemic
Natrixeralfs		Natrudolls	Sodic Haplusterts		Deep-Salinized Chernozemic
			Sodic Salusterts		Chestnut Solonchak
			Sodic Haplloxererts		Solonchakic Chestnut
			Sodic Durixererts	Automorphic Solonetz	Semidesert
					Meadow Chernozemic
					Meadow Chernozemic Solonchak
					Solonchak Meadow Chernozemic
					Deep Solonchakic Meadow
					Meadow Chestnut
				Semi-hydromorphic Solonetz	Meadow Semidesert
					Semhydromorphic Cryogenic
				Hydromorphic Solonetz	

[a]FAO (1988)
[b]Isbell (1994)
[c]AFES (1990)
[d]US Soil Survey Staff (1992)
[e]Egorov (1987)

The catenary relationship of solonetzic soils that fits this genetic model, from hillcrest to footslope, Solod → Solodized Solonetz → Solonetz has been observed in Canada (Miller and Pawluk, 1994), Australia (Oertel and Blackburn, 1970), and North America (Munn and Boehm, 1983). The reverse sequence, with Solod at the lowest and Solonetz at the highest position has also been observed in Canada (Cairns, 1961; Anderson, 1987). According to Szabolcs (1989), the most characteristic Solods usually develop in microdepressions.

Sodium carbonate (Na_2CO_3), which is generally the dominant salt involved in the genesis of alkaline sodic soils, can form in two ways: (a) by evaporation of water having an excess of Na bicarbonate ($NaHCO_3$), or (b) biochemically by microbial reduction of sodium sulfate (Na_2SO_4) (FAO, 1991). A major source of $NaHCO_3$ is the weathering of albite to kaolinite,

$$4NaAlSi_3O_8 + 4H_2CO_3 + 18H_2O \Rightarrow 4Na^+ + 4HCO_3^- + 8H_4SiO_4 + Al_4Si_4O_{10}(OH)_8 \quad [2.1]$$

and montmorillonite,

$$2NaAlSi_3O_8 + 2H_2CO_3 + 4H_2O \Rightarrow 2Na^+ + 2HCO_3^- + 2H_4SiO_4 + Al_2Si_4O_{10}(OH)_2 \quad [2.2]$$

Both these reactions generate equivalent amounts of Na^+ and HCO_3^- and substantial amounts of silicic acid (H_4SiO_4).

On the other hand, Na-induced hydrolysis would only release H_4SiO_4 if clay minerals broke down. Because water-soluble silicon (Si) levels and quantitative mineralogy are rarely determined during soil analyses, it is impossible to determine which one of these mechanisms might be the more dominant.

Although the presence of "silica (or quartz) powdering" along cracks and ped faces in the upper soil profile has been interpreted as evidence of solodization (Rozanov, 1961; Szabolcs, 1989), Hallsworth and Waring (1964) have postulated that the silt-sized siliceous material accumulating at the top of the B horizon in Solodized Solonetz consists of finely divided opaline silica phytoliths that wash through the coarser A horizon and accumulate at the top of the finer textured B horizon. Many authors (see Munn and Boehm, 1983) have reported on the degradation of smectite in the upper horizons of sodic soils, but recent work by Kohut and Dudas (1994) suggests that some of the X-ray diffraction (XRD) evidence of smectite degradation may be an artifact, due to interaction of clay with organic matter. Actually, some evidence for the enrichment of sodic soils with smectite due to mineral transformations under alkaline conditions has been presented (Cheverry, 1974; Tardy *et al.*, 1974; Droubi *et al.*, 1976; Szabolcs, 1989) .

2.4 DISTRIBUTION OF SODIC SOILS

2.4.1 Approach Used

In order to plot the distribution of sodic soils on a world and continent basis, the CD-ROM version of the FAO/UNESCO *Soil Map of the World* was used to construct the maps and estimate the areas presented in Table 2.2 using the terminology corresponding to the definitions in the 1974 and revised FAO/UNESCO *Soil Map of the World* legends. The total worldwide extent of salt-affected soils (Solonchak, Solonetz, and salic and sodic phases combined) and of those with sodic characteristics (Solonetz plus sodic phases) is illustrated in Figs. 2.1 and 2.2, respectively, while total areas affected are presented in Tables 2.2 and 2.3. These revised estimates, based on the full composition of each map unit, lead to a significant increase in the areal estimates for Solonchak soils and to a near doubling in the estimated extent of Solonetz (Table 2.2) as compared to previous estimates of 187 million ha for Solonchak and 135 million ha for Solonetz (FAO, 1991). The reason for these differences is that because large areas of Solonetz are rare, they were mapped as associated and included soils and, consequently, overlooked in earlier estimates.

The definition of sodic soils used in this treatise (Chapter 1) is based on land management considerations rather than the pedological approach used to produce most soil maps. Fortunately, the sodic soils classes (Nonsodic, Sodic and Very Sodic) in Chapter 1 can be approximated by combining the sodic phases of the FAO/UNESCO *Soil Map of the World* with the Solonetz map units and separating soils into groups with ESP < 6, 6–15 and > 15 in some horizon within 1 m of the surface for the world (Fig. 2.2) and the continents on which sodic soils occur frequently (see Figs. 2.3–2.6). It has not been possible to identify areas of spontaneous or mechanically dispersible soils (Chapter 1) because such data are seldom measured during routine soil characterizations. However, some new initiatives toward the development of international digital soil data bases, such as SOTER (FAO, 1993), and national data bases (Lytle, 1993) will make it possible, in the future, to produce interpretative soil maps that are custom-made to answer specific problems independent of the initial mapping criteria. However, differences in data collection and methods of analysis (Chapter 1) will continue to cause difficulties in integrating quantitative data to generate new maps.

TABLE 2.2 Worldwide areal extent of Solonchak and Solonetz

Great Group	Total area of Solonchak ('000 ha)				Total Area of Solonetz ('000 ha)			
	Texture				Texture			
	Coarse	Medium	Fine	Total	Coarse	Medium	Fine	Total
Orthic	1 765	150 681	28 460	180 906	14 149	130 649	16 647	161 445
Mollic	0	8 032	1 863	9 895	0	19 280	17 973	37 253
Takyric	0	95	13 172	15 267				
Gleyic	252	32 319	12 688	45 259	0	11 163	355	11 518
TOTAL	2 017	191 127	56 183	249 927	14 149	161 092	34 975	210 216

TABLE 2.3 Total area of saline and sodic phases by FAO Soil Group (1994 legend) in '000 ha

FAO Soil Group	Saline Phase (EC >4 but no Solonchak)	Sodic Phase (ESP >6 but no Solonetz)
Fluvisols	16 800	2 940
Gleysols	26 520	1 640
Regosols	845	165
Lithosols	10 805	0
Andosols	40	0
Vertisols	555	5 580
Solonchaks	--	4 095
Solonetz	9 295	--
Yermosols	19 260	2 760
Xerosols	29 080	17 560
Kastanozems	16 825	77 115
Chernozems	1 015	7 220
Phaeosems	620	1 045
Cambisols	4 995	350
Luvisols	80	13 740
Planosols	5 310	80
Histosols	2 385	0
TOTAL	144 430	134 290

Neither saline nor sodic phases have been mapped in Arenosols, Podzols, Acrisols, Ferralsols, Nitisols, Podzoluvisols, Greyzems, Rankers, and Rendzinas.

The distribution and nature of sodic soils will now be discussed on a continental basis. An attempt will be made to keep the discussion proportional to the relative importance of sodic soils on that continent. The focus of the discussion will be on environmental conditions and pedogenic processes involved in the formation of sodic soils.

The areas of sodic soils on each continent and in some countries where they form an important proportion of the soils are presented in Table 2.4. Australia accounts for the greatest area of sodic soils, followed by the former USSR.

2.4.2 Sodic Soils in Australia

Australia, which is often said to be the driest continent on Earth, has the largest areal extent of sodic soils of any continent (340 million ha) (Table 2.4) (FAO, 1988), of which an estimated 38 million ha are Solonetz (FAO, 1991). Generally, Australian landscapes show little relief, with many sodic soils being associated with late Cenozoic landscapes (Beckmann, 1983). The distribution of sodic soils (Fig. 2.3) is approximately related to the average annual rainfall according to Northcote (1988); however, this is not a universally accepted view (Isbell *et al.*, 1983). Soils that are sodic throughout the profile are generally found where average annual rainfall is less than 500 mm; those with only sodic subsoils generally occur where annual rainfall is < 900 mm (Chartres, 1993). Generally, sodicity increases with depth, often abruptly, and many soils with sodic subsoils are not sodic in their A horizons (Isbell, 1995b). However, many sandy A horizons can have ESP greater than 6 because their cation exchange capacity (CEC) is very low.

The most comprehensive estimate of the extent of sodic soils in Australia was published by Northcote and Skene (1972). They defined sodicity on the basis of ESP values anywhere within the upper 1 m depth; nonsodic soils were those with ESP < 6, sodic with ESP 6–15, and strongly sodic with ESP > 15. They presented the distribution of six mapping units (saline soils, alkaline strongly sodic to sodic clay soils, alkaline strongly sodic to sodic coarse- to medium-textured soils, alkaline strongly sodic to sodic duplex soils, nonalkaline sodic to strongly sodic neutral duplex soils, nonalkaline sodic to strongly sodic acid duplex soils) using the *Atlas of Australian Soils* (1:2 000 000) as a base (Northcote *et al.*, 1960–1968). Although Solonchak soils are not widespread, many of the areas with a high proportion (> 50%) of Solonetz (Fig. 2.3) have a salic phase (Fig. 2.1).

Although no improved version of Northcote and Skene's (1972) map, which overcomes the constraints to map production they encountered, is available, the knowledge on the distribution of sodic soils in each state in Australia has been updated (McKenzie *et al.*, 1993; Ford *et al.*, 1993; Naidu *et al.*, 1993b; Doyle and Habraken, 1993; Shaw et al., 1994; Cochrane *et al.*, 1994). Profile descriptions presented by Northcote and Skene (1972) show that sodic soils in Australia occur on a wide range of parent materials. In Queensland, Shaw *et al.* (1994) were unable to find a relationship between sodic soils and parent material composition beyond a reduced incidence of strongly sodic soils on calcic lithologies. In Tasmania, sodic soils which occur on lowland plains, river terraces, and valley floors, have formed mainly from Triassic and Permian mudstones and sandstones, Tertiary clays, and Quaternary deposits, but are also found on granite and basalt (Doyle and Habraken, 1993). In New South Wales, sodic soils are concentrated in cracking clays west of the Great Dividing Range (McKenzie *et al.*, 1993). Large areas of the Murray-Darling river basin, which covers much of southern Queensland, New South Wales, Victoria, and South Australia, are sodic. Little published information is available for Western Australia and the Northern Territory, but an estimated 3.5 million ha in the southwest of Western Australia, or 34% of the agricultural land, are

TABLE 2.4 World distribution of sodic soils [Massoud, *Proc. Int. Conf. on Management of Saline Water for Irrigation*, Texas Technical University, Lubbock, (1977)]

Continent	Country	Area of sodic soils ('000ha)
North America	Canada	6 974
	United	2 590
South America	Argentina	53 139
	Bolivia	716
	Brazil	362
	Chile	3 642
Africa	Algeria	129
	Angola	86
	Botswana	670
	Cameroon	671
	Chad	5 950
	Ethiopia	425
	Ghana	118
	Kenya	448
	Liberia	44
	Madagascar	1 287
	Namibia	1 751
	Niger	1 389
	Nigeria	5 837
	Somalia	4 033
	Sudan	2 736
	Tanzania	583
	Zambia	863
	Zimbabwe	26
South Asia	Bangladesh	538
	India	574
	Iran	686
North and Central	China	437
	USSR	119 628
Australasia	Australia	339 971

sodic (Tennant *et al.*, 1992). Most of the texturally contrasted soils of southwest Western Australia have sodic subsoils, small areas have sodic topsoils and, in the wheatbelt, hardsetting (Mullins *et al.*, 1990) is a widespread surface soil problem in which sodicity can play a part (Cochrane *et al.*, 1994).

Sodicity has often been implicated in crusting and hardsetting of surface soils. However, this behavior is also observed in Nonsodic Nonsaline (Sod_L Sal_L) soils that are mechanically dispersive (Rengasamy *et al.*, 1984b; Cochrane *et al.*, 1994; Chapter 1). The A horizons of many texturally contrasted soils with strongly sodic B horizons often have low ESP, and Isbell (1995b) suggests that where relatively thin A horizons overlie sodic B horizons, long-term cultivation may have led to mixing of the horizons. In northern Victoria, Queensland and New South Wales, land-levelling for irrigation may expose sodic subsoils that are more prone to crusting than the original A horizons (McKenzie *et al.*, 1993; Isbell, 1995a).

Rengasamy and Olsson (1991) suggest that two types of sodic soils occur in Australia: those in which the sodicity is a natural phenomenon related to the nature of the parent material and those in which sodification is secondary, arising from human activity. Irrigation without proper drainage can increase the SAR of the soil solution, exacerbate sodicity, and even render soils sodic (Rengasamy and Olsson, 1991, 1993). Large areas of irrigated soils in the Murray-Darling river basin are sodic. Therefore, management of irrigation is closely related with management of sodicity.

Tree clearing and other land management practices that alter the water balance in soils can lead to waterlogging and sodicity problems. For example, Fitzpatrick *et al.* (1994) demonstrated that changes in land management could induce sodicity-related environmental degradation in a toposequence of red, yellow, and grey duplex soils (Palexeralfs and Natraqualfs) in South Australia. Changes in catchment hydrology resulting from forest clearing in upslope positions created salt seepage zones, which resulted in sheet, rill, tunnel, and gully erosion in downslope positions. Fitzpatrick *et al.* (1994) highlight the sequential train of events resulting in salinization and sodification, which arise from the disturbance of natural ecosystems.

In Australia, the spatial distribution of sodic soils often coincides with that of alkaline duplex (texturally contrasted) soils (Northcote and Skene, 1972; Chittleborough, 1992; Chartres, 1993). However, is the duplex nature due to sodicity or *vice versa*? This proposition will now be discussed.

Oertel (1961) concluded that the clay profiles of six sodic Red-Brown Earths [according to the classification of Stace *et al.* (1968)] from South Australia were not the result of eluviation-illuviation processes, but rather that most of the clay in the B horizons had formed *in situ*. Similarly, Sleeman (1964) and Oertel and Blackburn (1970) demonstrated that the abrupt textural contrast in other sodic soils was due to lithologic discontinuities between the sedimentary layers of the parent material. Thus the textural contrast was not due to sodic soil genetic processes.

In a central Queensland catena, Gunn (1967) described Red and Yellow Earths [according to the classification of Stace *et al.* (1968)] on uplands, sodic and relatedsoils with

Figure 2.1 World distribution of saline and sodic soils

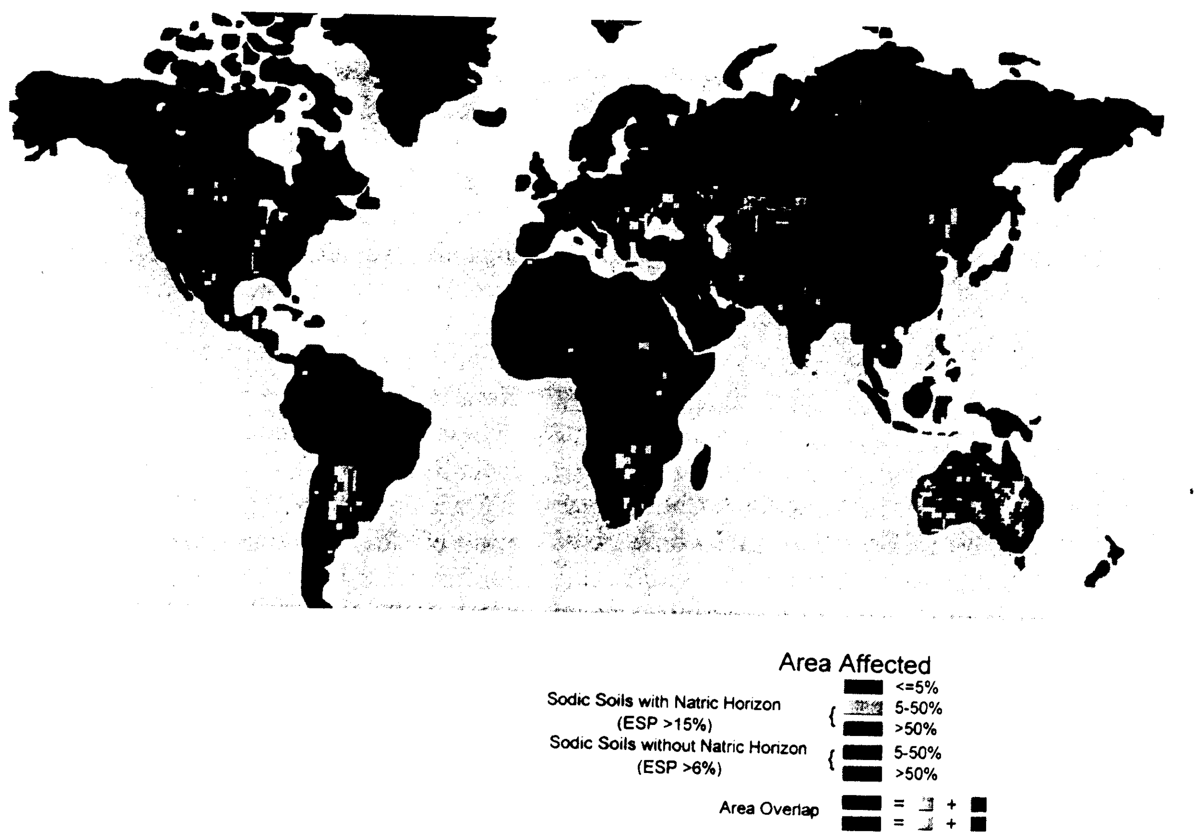

Figure 2.2 World distribution of sodic soils

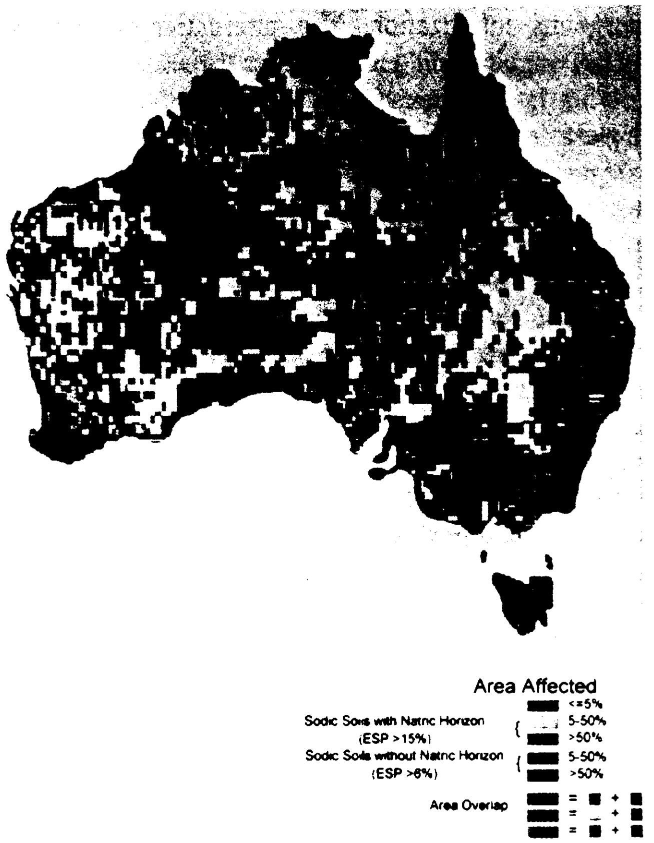

Figure 2.3 Distribution of sodic soils in Australia

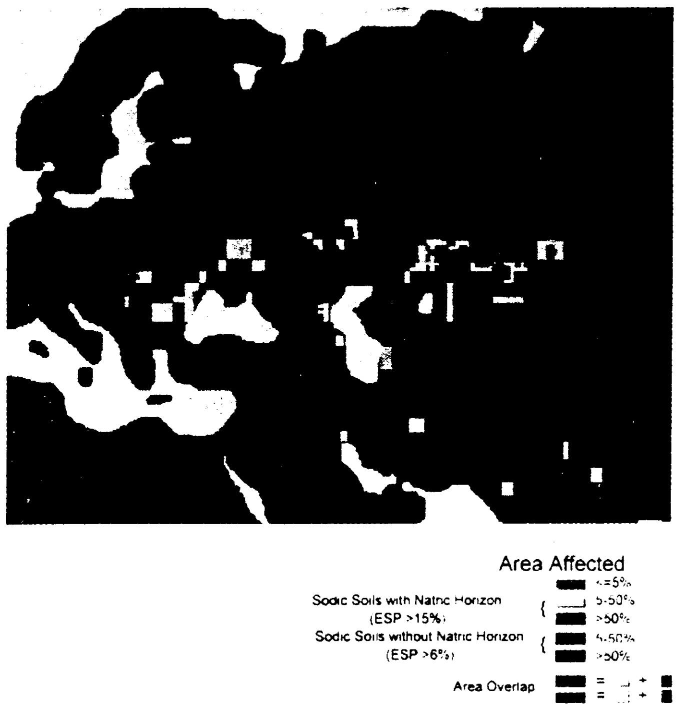

Figure 2.5 Distribution of sodic soils in Eurasia

Figure 2.4 Distribution of sodic soils in South America

Figure 2.6 Distribution of sodic soils in Africa

abrupt textural contrast on intermediate slopes in gently undulating land or below scarps on moderately sloping land (< 10%), and cracking clay soils, often sodic, with gilgai microrelief in the lower positions. Surface horizons of the duplex sodic soils ranged from sand to sandy clay loam in texture, with a thickness of a few centimeters to 0.6 m. Bleached A horizons were sometimes present. In B horizons with high clay content, Mg dominated the exchange complex with ESP between 15 and 30. The soluble salt content was low throughout the profiles. Gunn (1967) postulated that the textural contrast in these sodic soils developed in different cases as a result of soil genesis from weathering *in situ* or as a consequence of polycyclic deposition. This catena is very similar to that described by Bocquier (1964, 1968, 1971) in Chad in Section 2.4.6.

Hallsworth and Waring (1964) believed that, although the textural contrast in sodic soils developed on Jurassic sandstone alluvium in New South Wales formed during soil genesis, these soils did not reflect the classical Solodized Solonetz evolution and, in fact, were the normal soils found on coarse-textured parent materials in semiarid to subhumid, temperate to subtropical climates. Isbell *et al.* (1983) point to the widespread occurrence of sodic soils in South Australia which lack pronounced textural B horizons and are permeable on the one hand, and to soils with strong textural contrast that do not have impermeable saline and sodic B horizons on the other. These authors conclude that "[it is] unlikely that many of the present diverse and widespread varieties of sodic soils ever went through the complete classical sequence."

2.4.3 Sodic Soils in North America

In North America, most sodic soils occur in the Great Plains of western Canada and the northern United States under cold, semiarid to subhumid climates comprising about 11 million ha of Solonetz (FAO, 1991). Because many are developed on tills and other glacial deposits derived from saline shales (Munn and Boehm, 1983; Heck and Mermut, 1992a,b), the classical theory of Solonetz formation still holds much sway in Canada (Agriculture Canada Expert Committee on Soil Survey, 1987; Heck and Mermut, 1992a,b; Miller and Pawluk, 1994). However, Munn and Boehm (1983) showed that a classical catenary sequence Natrargid → Haplargid in Montana can be interpreted in two ways. Interpretation along the lines of the classical theory necessitates the presence of a shallow, saline water table, implying that the Natrargid soils formed under earlier, wetter climatic conditions and that the sequence is presently in disequilibrium with the climate and undergoing solodization. The alternative hypothesis suggests ongoing soil genesis under the existing climate involving lateral subsurface movement of salty, silica-rich water into the subsoils of the depressions. The lateral water movement is driven by matric suction and osmotic potential gradients from the moist subsoils of the Haplargid into the drier subsoil of the incipient Natrargid. As the proportion of Na in solution increases, Na replaces Ca and Mg on the exchange complex and dispersion of the subsoil proceeds. The dispersed zone expands, and *in situ* smectitic clay formation is enhanced due to high concentrations of silica and cations.

In the United States in general, a greater variety of environmental conditions has been shown to lead to sodic soil formation. For instance, some sodic soils have been shown to have formed on loess rich in Na-bearing minerals (Wilding *et al.*, 1963). The occurrence of ephemeral, perched water tables has been implicated in the current genesis of sodic soils on loess in Nebraska (Lewis and Drew, 1973). Differences in water movement with landscape position, and topography and permeability of the underlying parent material have been shown to be the driving forces in sodic soil genesis on glacial deposits in all cases (Wilding *et al.*, 1963; Lewis and Drew, 1973; Munn and Boehm, 1983; Seelig *et al.*, 1990; Richardson *et al.*, 1992). In addition, Whittig and Janitsky (1963, 1964) have demonstrated the role of sulfate (SO_4)-reducing microbes in biologically driving sodic soil genesis on the edge of wetland environments.

In the southeastern United States, large areas of mechanically dispersible soils, which would fall in the Nonsodic Nonsaline (Sod_L Sal_L) category (Chapter 1), have been identified (Miller and Baharuddin, 1986; Sumner and Miller, 1992). Although these soils would not fall in any classical sodic soil category, they exhibit many properties in common with soils containing higher levels of Na, such as crusting, hardsetting, and erodibility. This is particularly true in the topsoil where structural degradation due to loss of organic matter allows clay to become dispersed even at very low ESP (SAR) levels because the EC of the soil solution is exceedingly low (Miller, 1987; Miller and Radcliffe, 1992; Chapter 5). These soils are sensitive to even the slightest increases in Na levels (Chiang *et al.*, 1987; Miller and Scifres, 1988).

2.4.4 Sodic Soils in South America

South America has an estimated 34 million ha of Solonetz (FAO, 1991) and 25 million ha of sodic phases of other soil groups (FAO, 1988), mostly in the Argentinian and Paraguayan pampas and in northeastern Brazil (Fig. 2.4).

Argentina

In Argentina, sodic soils are dominant in the Pampa Deprimida and the Bajos Submeridionales regions with salt-affected soils also occurring in the Oeste Bonaerense. All three regions are on the periphery of the Pampean prairie and are used mainly for cattle grazing on native grasslands (Soriano, 1991).

In the Pampa Deprimida, an area of about 80 000 km^2 east of Buenos Aires Province, most soils have developed on loesslike sediments derived from the Andes Mountains under a subtropical to temperate, subhumid (west) to humid (coast) climate with unevenly distributed rainfall exhibiting no seasonality but cyclic variations. Droughts are common in the summer when evapotranspiration is high (Alconada *et al.*, 1993). The landform, which is extremely flat and at low elevation, has resulted in a lack of equilibrium with the present wet climate. As a result, a significant portion of the region is covered by permanent and temporary ponds generally connected by groundwater, resulting in frequent deep waterlogging of low-lying soils in the winter and spring for long durations. Floods that last several months and inundate millions of hectares with 1 m or more of water occur several times a century (Paruelo and Sala, 1990). Consequently, most soils have an aquic moisture regime. Salts move upward by capillary rise from the shallow fluctuating groundwater table driven by high evapotranspiration in the summer (Lavado and Taboada, 1988). Because much of the groundwater has a high pH and contains Na_2CO_3, sodic soils, mostly Natraqualfs, are abundant (Alconada *et al.*, 1993). Neither rainfall nor mineral weathering contribute significantly to soil salinity or sodicity (Lavado, 1983; Lavado *et al.*, 1983).

Most soils (80%) in the Pampa Deprimida have an aquic soil moisture regime with Natraquolls (28 000 km^2) and Natraqualfs (11 000 km^2) being dominant over continuous areas of hundreds of thousands of hectares. Natralbolls and Argialbolls are also present (INTA, 1990a). Large areas of soils with a mollic A and a natric B horizon occur in this region, but not under an aquic soil moisture regime. Because soil taxonomy does not cater adequately to such soils, Godagnone *et al.* (1991) have proposed a new Great Soil Group, Natrudolls.

The Bajos Submeridionales region occupies about 40 000 km^2 in northern Santa Fé and southern Chaco provinces. The northern part is characterized by subnormal to concave relief, with slope gradients between 0.1 and 0.2 %. Water flow to the Paraná River is impeded by the physiography which promotes periodic flooding (Morras and Perman, 1977). Parent materials vary from loesslike (west) to alluvial materials from the Brazilian shield (east) with sediments from the Andes in between. The monsoonal climate is subtropical and subhumid. The predominant soils are associations and complexes of Natraquolls and Natraqualfs, including Natrudalfs, Natralbolls, etc. Gley horizons occur frequently (INTA, 1990b). As in the Pampa Deprimida region, sodification arises from the discharge of very saline shallow groundwaters (Morras and Candioti, 1982).

The Oeste Bonaerense (several million hectares) located in the northwest of the Buenos Aires and parts of Santa Fé, Cordoba, and La Pampa provinces are characterized by a series of longitudinal dunes which impede the general drainage of the area. The soils, which have developed in the interdunal depressions, have a higher salt content than those described above. The soils have formed from loesslike material but coarser than that of the other two regions under a subtropical/temperate and semiarid climate with floods being more episodic (INTA, 1990a). Salt is supplied by deep thaptonatric horizons (Altamore *et al.*, 1983) and eolian sources in dry summers (Lavado and Reinaudi, 1988). Natraquolls, Natraqualfs, and some Salorthids occur in the depressions with Natrustalfs and Natrustolls on midslope positions (INTA, 1990a).

Brazil

In northeastern Brazil, sodic soils are widespread in Bahía, Ceará, and Pernambuco States (Fig. 2.4). Throughout northeastern Brazil, where the climate is semiarid and warm with a rainfall of 600–1100 mm, sodic soils have developed on Precambrian migmatites and gneisses, intruded by acid igneous bodies, on the Cambro-Ordovician Formaçao Estancia or in Holocene sandy clays in landforms with slightly undulating relief (EMBRAPA, 1977). A characteristic xerophytic vegetation formation of open scrubland to open woodland called *caatinga* generally coincides with the distribution of the semiarid climate and sodic soils.

Sodic soils (Solodic Planosols and others) also occur in the state of Matto Grosso under a seasonally contrasted, humid tropical climate on sandy to sandy clay Holocene alluvial deposits of the Paraguay River at a low elevation on subdued microrelief (2–3 m) subject to annual flooding (EMBRAPA, 1971).

Paraguay

Most of Paraguay is covered with sodic soils under a semiarid tropical (west) to subhumid subtropical climate (east) (Fig. 2.4). Solonetz soils derived from poorly consolidated clastic Cenozoic sediments, many with salic properties, occur over a large portion of the Chaco basin in western Paraguay (FAO, 1964). Low slope gradients and dense subsoil clay pans are responsible for seasonally perched water tables and waterlogging. These soils appear to be similar to those of the Oeste Bonaerense in northern Argentina. In eastern Paraguay, sodic soils developed from Permian shales and Triassic red bed sandstones only occur in topographic lows.

2.4.5 Sodic Soils in Eurasia

In Europe, there are 22 million ha of sodic soils (FAO, 1988), including 7 million ha of Solonetz (FAO, 1991) whereas Asia has an estimated 120 million ha of sodic soils (Abrol *et al.*, 1988), 30 million ha of which are Solonetz, mostly in central Asia (Figs. 2.2 and 2.5) (FAO, 1991). Eurasia is the landmass on which most anthropogenic salinization and sodification have occurred and where the reclamation of saline and sodic soils has been the focus of most research (Glazovskaya, 1984; Szabolcs, 1989). Because of the influence of Russian and central European pedologists, many of the models developed on soils in Eurasia are still used worldwide. Sodic soils occur over a range of climates in Eurasia.

Europe

Much research has been conducted on sodic soils (*szik*) in the Carpathian basin (mean annual temperature 10–11°C, mean annual precipitation 520–580 mm) in Hungary, Romania (Oprea *et al.*, 1971; Obrejanu and Sandu, 1971), Serbia (Adam *et al.*, 1988), and Slovakia (Hrasko, 1971). Most of the sodic soils formed in the Quaternary period in Hungary are found either in the Trans-Tisza region or in the Danube-Tisza interfluve at elevations above 100 m with microrelief of about 0.5 m (Tóth and Rajkai, 1994). In the Danube-Tisza rivers interfluve, mostly saline (Solonchak) soils have formed on calcareous sands of the Danube, while in the Trans-Tisza region, the dominant Solonetz soils have formed on sediments intermingled with loesslike material of silt or clay texture. In both areas, the dominant salt is Na_2CO_3, with accessory amounts of Na_2SO_4 and sodium chloride (NaCl).

Despite previous disagreements concerning the factors involved in the formation of sodic soils in the Carpathian basin (Jenny, 1941), the present consensus is that hydrological conditions, namely, groundwater level and composition, have played the dominant role in the genesis of these soils. The occurrence of salt-affected soils closely matches groundwater discharge areas, and capillary rise from saline groundwater seems to be the means by which salt accumulates. Three major sources of salts, (a) released by rock weathering (feldspars), especially volcanic tuffs, in the surrounding mountains and transported into the groundwater of the lowlands, (b) Pliocene evaporites from which salt seeps upward (Erdélyi, 1979), and (c) salt in surface waters, have been identified.

Catenary relationships in the sodic soils of Hungary were recognized early, giving rise to popular and scientific terms distinguishing soil categories according to topographic position (Treitz, 1924). de'Sigmond (1927a) and Magyar (1928) distinguished the dry (seldom waterlogged) and wet types of salt-affected soils while Kreybig and Endrédy (1935) demonstrated that salt-affected soils tend to occur at the same elevation at the same latitude. The sodic soils of the Danube-Tisza interfluve have the following catenary sequence downslope: Calcareous Meadow Soil → Sodic Meadow Solonetz → Sodic Solonchak → Solonetz → Peaty Meadow Soil (Rajkai and Molnár, 1981), while in the Trans-Tisza Region, the sequence is Meadow Chernozem (Haplustoll) → deep Meadow Solonetz (Natrustoll) → shallow Meadow Solonetz (Natrustalf) → crusty Meadow Solonetz (Natraquept) → Meadow Soil with saline subsoil (Haplaquoll) (Magyar, 1928; Bodrogközy, 1965; Tóth *et al.*, 1991; Tóth and Rajkai, 1994). The terms *deep*, *shallow*, and *crusty* describe the thickness of the eluvial A horizon, as in the Russian terminology. Quantitative prediction of soil properties can be made on the basis of vegetation (Tóth and Rajkai, 1994) and catenary relationships (Kertész and Tóth, 1994).

The genesis of Ukranian sodic soils is similar to that of the Carpathian basin. Around the Black Sea (mean annual temperature 7–8 °C, mean annual precipitation 500–550 mm), Solonetzic Soils, Solonetz, and, in closed depressions, Gleyic Solods occur while at Stavropol, Vertic Solonetzic Chernozems have formed on Tertiary marine clays (Hitrov, 1988).

Most of the Transcaucasian plain in Georgia and Azerbaijan (mean annual temperature 14 °C, mean annual precipitation 200–250 mm) is covered by sodic soils (Solonetz) with salinity increasing and alkalinity decreasing from northwest to southeast as precipitation decreases (Ostrikova, 1991).

Northern and Central Asia

Sodic phases of Kastanozems are commonly associated with Solonetz throughout the desert steppe region of central Asia under a climate characterized by low rainfall with cold winters and warm summers (FAO, 1978). An extensive belt of sodic soils occurs west of the Caspian Sea covering Kazakhstan, Turkmenia, Uzbekistan, Tadzhikistan, and Kirghizia (Figs. 2.2 and 2.5). Rozanov (1961) noted a genetic connection between Solonetz and weathering granite in the Tien Shan Mountains, which consist mostly of Precambrian to Devonian crystalline rocks, with a widespread occurrence of granitoids (FAO, 1978).

The Caspian lowland at the northern end of the Caspian Sea (mean annual temperature 6 °C, mean annual precipitation 150–250 mm) consists of Quaternary moraine deposits which together with rivers produce the salts. In Kazakhstan, sodic soils have formed on saline and gypsic Tertiary deposits with very little microrelief (0.3–0.5 m) (Eskov, 1991). Solonchak-Solonetz occur on microhighs with Solonetz on slopes and leached Meadow Chestnut Soils in depressions (Dementyeva and Motuzov, 1988).

South of the Tien Shan Mountains, in the basin comprising the Xinjiang-Gansu-Qinghai provinces in China (mean annual temperature 7–9 °C, mean annual precipitation <350 mm), which is hydrologically closed from the surrounding area, most of the soils are saline with SO_4 and Cl anions dominant but some Solonetz soils, including Mg-Solonetz, occur. On the Huang and Huai river plains in eastern China (mean annual temperature 12.5 °C, mean annual precipitation 580 mm), saline soils have developed on the alluvial sediments salinized by ground- andseawater (SO_4 and Cl) (Inanaga, 1991). Sodification can be observed (Renpei, 1988) in depressions where HCO_3^- accumulates with the vegetation pattern reflecting pH changes (Tóth *et al.*, 1994). In northeastern Manchuria (mean annual temperature 4 °C, mean annual precipitation 440 mm), sodic soils are found on the low river and lake terraces of the Amur River and its northeast-flowing tributaries. The dominant salts in the subsurface waters and soils are NaCl and Na_2SO_4.

The northernmost sodic soils in Eurasia are found in the Russian Republic of Yakutia (mean annual temperature -8 °C, mean annual precipitation 130–250 mm) on the Lena River plain in central Yakutskaya derived from saline Devonian, Cambrian, and Jurassic materials. The arid climate coupled with permafrost limits the migration of salts, which accumulate in depressions, giving rise to Solonchak and Solonetz soils containing $NaHCO_3$. At more elevated positions, solodized soils occur. The sodic soils of the west Siberian forest-meadow-steppe region (mean annual temperature -1.6 °C, mean annual precipitation 324–354 mm) consist of Peaty Solonchak soils on the flat plains, Na_2CO_3-rich Solonchak soils in depressions at slightly higher elevations, and Solonetz soils on the high ground (Bazilevich, 1965). The Solonetz soils encircle the ridges covered by leached Chernozems. Dominant anions in the sequence of soils from north to south are CO_3^{2-}, HCO_3^-, SO_4^{2-}-CO_3^{2-}, Cl^--SO_4^{2-}, and SO_4^{2-}-Cl^-.

Southern Asia

In the Middle East and southern Asia, under arid, semiarid, and subhumid climates, saline and sodic soils are widespread in poorly drained environments of the alluvial plains of the Euphrates, Indus, and Ganges rivers. Sodic soils have been described in Syria (Al-Saleh, 1991), Iraq (Kadry, 1969), Iran, Pakistan (Sandhu and Aslam, 1980), India (Kanwar, 1969; Bhargava, 1977, 1979; Bhumbla, 1977; Murthy *et al.*, 1982), and Bangladesh (Dent, 1992). The distribution of saline and/or sodic areas in the Indo-Gangetic alluvial plains is determined mostly by groundwater movement and climatic zonation (Bhumbla, 1977; Bhargava, 1979; Murthy *et al.*, 1982). Throughout India and the other areas, the increase in irrigated agriculture has caused salinization and/or sodification arising from (a) poor land preparation, (b) seepage from unlined canals, (c) over-irrigation and the subsequent percolation of water, (d) inefficient water management, (e) inappropriate cropping systems, (f) nonconjunctive use of surface and groundwater, and (g) impeded drainage and lack of outlets (Yadav, 1993). In Pakistan, tube well irrigation with sodic groundwater has contributed to an increase in sodic soils (Sandhu and Aslam, 1980).

2.4.6 Sodic Soils in Africa

In Africa, sodic soils, which cover 27 million ha (0.9% of the total land), occur under warm, semiarid to subhumid climates (FAO, 1991), including 13 million ha of Solonetz soils found mainly in Chad, Nigeria, Somalia, Sudan, coastal Tunisia, and the Kalahari basin. The Solodic Planosols mainly occur in Chad, Burkina Faso, Tanzania, and southern Africa, with minor areas in Senegal and Niger (Fig. 2.6).

West Africa

The geochemical evolution of surface and groundwaters and their effect on pedogenesis and mineralogy in the polders of Lake Chad can give rise to alkaline sodic soils (Cheverry, 1974). In the interdunal depressions bordering the lake, surface waters are concentrated by evaporation. While the surface waters are initially dilute but relatively high in Ca^{2+} and HCO_3^-, they become enriched in HCO_3^-, CO_3^{2-}, and Na as they are concentrated leading to precipitation of $CaSO_4$, Na_2SO_4, $CaCO_3$, and Na_2CO_3 (calcite, gaylussite, and trona) on the surface. Shallow groundwaters are relatively rich in SO_4^{2-} and Ca^{2+}. Bocquier (1964, 1968, 1971) described some typical catenas, incorporating sodic soils, developed on granitic rocks in semiarid West Africa between 14 and 10° N latitude. Essentially eluvial-illuvial, the downslope catenary sequence is: ferruginous leached soils → hydromorphic soils → Planosols → Solonetz → Vertisols. These soil types cover various proportions of the slopes according to latitude. Nevertheless, the actual soil pattern may differ widely from this classical sequence due to local conditions of drainage and parent materials. The Na input from weathering relative to that from other sources is unknown. Sodic soils also occur in the Sahelian Oudalan Province of northern Burkina Faso, where weathering *in situ* governs their development (ORSTOM, 1968; Boulet, 1970, 1978; Leprun, 1977; BGR, 1980; BUNASOL, 1991). The excess Na responsible for the sodification is derived from the crystalline bedrock, which has inclusions of calc-alkaline granite that vary in size and are irregularly distributed in the bedrock causing the distribution of sodic soils to be somewhat patchy and irregular (Ducellier, 1963; Hottin and Ouedraogo, 1975, BGR, 1980). As shown in Table 2.5, calc-alkaline granites have a rather high ratio of Na to Ca + Mg. As a result, despite the large areas of sodic soils shown on maps, they occur as a complex of individuals on a microscale, sometimes with similar morphology but with little or no Na influence. The remaining soils belong to the *sols bruns subarides* or *sols ferrugineux tropicaux* groups according to the French CPCS system (1967). Lateral water movement can spread Na from its original source to soils in lower slope positions where it accumulates by evaporation.

Southern Africa

Sodic soils are found throughout southern Africa occurring widely in the Republic of South Africa (van der Merwe, 1956; Beater, 1957, 1959,1962; van der Eyk *et al.* 1969; de Villiers, 1962; MacVicar *et al.* 1977; Schloms *et al.*, 1983), Swaziland (Murdoch and Andriesse, 1964; Murdoch, 1964), Lesotho, Botswana, and Zimbabwe (Blair Rains and McKay, 1968; Purves and Blyth, 1969; Thompson and Purves, 1978; Stocking, 1979; Verbeek, 1989) but are confined mainly to numerous scattered small localized areas, whereas in northern Namibia and southern Angola, there are much larger tracts covered by these soils (Cass, 1980). The regions where they occur seem to have a mean annual rainfall of less than 800 mm. However, the main factor responsible for their formation is the occurrence of parent materials with high amounts of Na-releasing weatherable minerals (Beater, 1957, 1959, 1962; van der Eyk *et al.* 1969; Thompson and Purves, 1978). Their most frequent occurrence, therefore, does not necessarily coincide with the regions of lowest mean annual rainfall. For example, sodic soils occur more extensively in the Zambezi Valley (Zimbabwe) and near Estcourt (South Africa), where the mean annual rainfall is appreciably higher than in the drier lowveld areas. In these higher rainfall areas, the sodic soils are formed even on uplands in undulating terrain and are developed from the Karroo formation members that are rich in Na-releasing weatherable minerals. In many parts of southern Africa, sodic soils are commonly found on granitic parent materials, but usually occur at the lower end of a catena where the surface horizons (A and E) are predominantly sandy. A very thin albic horizon (very pale, bleached) usually occurs between the A horizon and the underlying impermeable B horizon. The conditions leading to the formation of the abrupt, sharp-line nature of the upper boundary of the B horizon is brought about by lateral movement of water across the surface of the B horizons (Purves and Blyth, 1969). When there are low amounts of iron oxides and oxyhydroxides present (<1%), the clay fraction of the sandy granite-derived soils is easily dispersed at ESP values as low as 3 when these soils experience aquic conditions (Thompson and Purves, 1978). The albic horizon is diagnostic of a marked degree of lateral water movement and redoximorphic conditions. In effect, surplus soil water moving within the solum across the surface of the sodic horizons removes clay to give rise to what amounts to a subsurface erosion pavement (Thompson and Purves, 1978).

Thompson and Purves (1978) have noticed that there tends to be a correlation between the depth of sandy surface horizons and the degree of sodicity in the underlying impermeable horizons. Soils with an appreciable depth of surface sand tend to be weakly sodic, with ESP less than 15 in the sodic horizon, while those with the shallower surface sands tend to have strongly sodic subsoils. The pH values of the upper part of the weakly sodic horizons are not necessarily high if the exchange complex is not fully saturated; occasionally pH values as low as 6.0 are encountered. However, all the strongly sodic horizons are markedly alkaline in reaction, with pH values greater than 7.5.

Sodic horizons also occur in soils with appreciable clay contents, mainly on colluvia and alluvia (van der Eyk *et al.*, 1969). Where the clay content of the surface horizon is

TABLE 2.5 Ratios of Na and Na + K to Ca + Mg in various rocks of the Oudalan Province in Burkina Faso [Ducellier, *Mém. BRGM*, 10 Paris, (1963)]

Ratio	Alkaline granite	Calc-alkaline granite	Amphibole plagioclase granite	Amphibole schist
Na/(Ca + Mg)	6.7–10.3	1.5–4.9	0.21–0.76	0.13–0.56
Na+K/(Ca + Mg)	11.5–14.9	2.40–7.66	0.28–1.15	0.15–0.83

sufficient to give rise to sandy clay loams or heavier textures, the upper boundary of the underlying sodic horizon is almost invariably much less apparent, and the change may even be a gradual one.

Saline sodic soils are found mainly in areas of low rainfall in pans and in some of the more extensive diffuse drainage depressions, such as those that occur in part of the lower Sabi Valley (Zimbabwe) and Karroo (South Africa) and on eolian and lacustrine deposits around the Makgadikgadi salt pans (Blair Rains and McKay, 1968). Sodic soil phases are found in the clayey central depressions of sandy alluvial islands in the Okavango delta and in large duricrusted pans (e.g., Thale, Ngwako pans) in the sandveld (Verbeek, 1989). At its Quaternary maximum, Lake Palaeo-Makgadikgadi was second in size to Lake Chad (Thomas and Shaw, 1991) with obvious parallels in the genesis of saline and sodic soils in the two areas.

2.5 CONCLUSIONS

The preceding discussion suggests that sodic soils can occur over a wide range of climates, but generally under seasonally contrasted conditions. Among the environmental conditions that promote the genesis of sodic soils are the presence of shallow saline groundwater, textural discontinuities during the deposition of eolian, glacial, alluvial, or colluvial sediments, the occurrence of perched water tables within 1 m of the surface, low slope gradients, and endorheic or impeded drainage. Salts dissolved in groundwater as well as the weathering of Na-containing minerals, such as albite, in granitic or sedimentary deposits are the sources of Na. The classical theory of Solonetz formation is clearly limited in its applicability on a worldwide basis. More generally, it appears that restricted water movement and soil moisture dynamics that fluctuate between aquic and ustic or aridic, within 1 m of the surface, in a landscape where a source of Na exists, promote the formation of natric horizons or sodic properties. Soils can become sodic as a result of anthropogenic processes that change their water balance, such as irrigation and drainage of saline soils, and land clearing.

Many soils that would not fit classical sodic soil specifications exhibit sodic behavior and cover a large but undetermined area of the world. Because of their agricultural importance, more attention needs to be devoted to these soils in the future.