Agricultural Sciences, 2022, 13, 150-164
https://www.scirp.org/journal/as
ISSN Online: 2156-8561
ISSN Print: 2156-8553

Genesis and Behavior of Sodic Soils in Humid Climates

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How to cite this paper: Aide, M. (2022) Genesis and Behavior of Sodic Soils in Humid Climates. *Agricultural Sciences*, **13**, 150-164.
https://doi.org/10.4236/as.2022.132012

Received: January 13, 2022
Accepted: February 7, 2022
Published: February 10, 2022

Abstract

Sodic soils are typically located in semi-arid to arid climates. However, sodic soils in continental humid climates are rare. As with sodic soils in dry climates, sodic soils in wetlands pose management difficulties for agriculture, forestry, or wild-life habitat. The typical practice of gypsum application is problematic given inability to provide drainage. Natraqualfs located in southeastern Missouri present an acid argillic horizon superimposed on a natric horizon, where the exchangeable sodium percentage and an alkaline reaction are characteristic attributes. Ferrolysis is an active soil process that is slowly degrading the natric horizon because of exchangeable Al^{3+} and H^{+} generation and re-stabilization of the soil structure, permitting leaching of the sodium.

Keywords

Sodic Soil, Natric Horizon, Ferrolysis, Weathering, Aqualfs

1. Introduction

1.1. Saline and Sodic Soils: Similarities and Differences

Soil genesis involves evaluating the roles of: 1) parent materials, 2) climate, 3) organisms, 4) topographic position, and 5) time in the development of soils. Aridisols are soils developed in regions where the evapotranspiration exceeds the precipitation in seven out of ten years. These climatic conditions limit the percolation of water, resulting in the accumulation of soluble and difficulty soluble salts. In humid regions, water percolation through the solum typically removes soluble salts; however, some soils in humid climates do exhibit sufficient concentrations of soluble salt that alter the soil profile and its properties.

Saline, sodic and saline-sodic soils are typically located in semi-arid and arid regions; however, these soils are also less frequently located in humid regions

[1]. The exact definitions of saline, sodic, and saline-sodic soils are based largely on experimental protocols that reveal the intensity of soil properties associated with salt concentrations [2] [3] [4]. The exchangeable sodium percentage (ESP) is a measure of the sodium concentration associated with a soil horizon's cation exchange capacity. ESP is expressed as [Na] × 100/CEC, where all concentrations have units of centimole proton charge per kg ($cmol_{p(+)}/kg$), or in the older literature as milliequivalents/100g-soil (meq/100g). The sodium adsorption ratio (SAR) is generally a measure of the sodium concentration in water or saturated paste extracts. The SAR is expressed as $[\mathrm{Na}]\Big/\sqrt{\{[\mathrm{Ca}]+[\mathrm{Mg}]\}/2}$, where all concentrations are mole charge/liter. When the ESP is less than 50%, the ESP and SAR frequently exhibit a linear relationship; that is, ESP = K_G × SAR, where K_G is the Gapon constant [2] [3] [4].

Typically soils not considered sodic, saline or saline-sodic have water saturated electrical conductivity extracts (ECe) less than 4 $dS \cdot m^{-1}$ at 25˚C and saturated sodium adsorption extract ratios (SARe) less than 13. Saline soils have an ECe greater than 4 $dS \cdot m^{-1}$ and a SARe of less than 13. Sodic soils are soils exhibiting an ECe less than 4 $dS \cdot m^{-1}$ and a SARe of greater than 13. Typically, saline soils have an ESP of less than 15 and a pH less than 8.5, whereas sodic soils have an ESP of greater than 15 and a pH greater than 8.5. Saline-sodic soils generally exhibit an ESP of greater than 15 and a pH less than 8.5 [2] [3] [4].

The natric horizon, as defined in the "Keys of Soil Taxonomy" [5], requires "1) a thickness requirement based on soil texture and the presence or absence of lamellae, 2) evidence of clay illuviation (examples include clay bridging of sand grains, clay films lining pores, clay films on both vertical and horizontal surfaces of peds), 3) a greater clay content requirement than an overlying eluvial horizon (argillic horizons), 4) typically having columnar or prismatic structures, and 5) typically having an exchangeable sodium percentage (ESP) of 15 percent or more exchangeable magnesium plus sodium than calcium plus extractable acidity". The reader is encouraged to observe the "Keys of Soil Taxonomy" for a more rigorous and precise listing of the criteria for a natric horizon. The absence of a natric horizon should not infer that plant productivity or the soil's physical properties are not influenced by the presence of sodium, as sodium intolerant plants may be negatively impacted at an ESP of less than 15%. Therefore, Australia proposes an ESP greater than 6% as the significant onset for soil structure dispersion [6].

1.2. Sodium, Calcium and Other Minerals Appropriate to This Study

Calcite [$CaCO_3$], dolomite [$CaCO_3MgCO_3$], gypsum [$CaSO_4 \cdot 2H_2O$], and magnesite [$MgCO_3$] are abundant minerals in the soil environment and parent materials. However, based on the water status of the soils and the weathering of primary minerals, the following minerals may also be present: nahcolite [$NaHCO_3$], trona [$Na_3H(CO_3)_2 \cdot 2H_2O$], sylvite [KCl], halite [NaCl], kalicinite [$KHCO_3$], thermonatrite [$Na_2CO_3 \cdot H_2O$], pirssonite [$CaCO_3 \cdot Na_2CO_3 \cdot 2H_2O$], gaylussite [$CaCO_3 \cdot Na_2CO_3 \cdot 5H_2O$]. Albite, a sodium bearing silicate ($NaAlSi_3O_8$), is also present in many soils and parent materials.

1.3. Sodic Soils and Their Influence on Plant Growth

Sodium may negatively influence plant growth and development in several distinct domains: 1) degradation of the soil's physical properties, 2) supporting alkaline to extremely alkaline pH values, and 3) increasing chemical activities involving sodium, molybdenum, and boron to toxic levels [2] [3] [4] [6]. Generally, if as little as 10 percent of the cation exchange complex becomes composed of sodium, then the soil's physical properties are deleteriously affected.

Soil structures are complex flocculated and aggregated entities primarily composed of sand, silt, clay, and soil organic matter. An important soil physical property that is adversely affected by sodium is the wet aggregate stability. Divalent calcium exhibits stronger phyllosilicate adsorption, subsequently reducing the diffuse layer thickness and permitting greater soil structure strength. Conversely sodium exhibits weaker phyllosilicate adsorption, subsequently increasing the diffuse layer thickness and permitting substantially weaker soil structure strength. The resulting dispersion of the soil structure permits the textural separates to migrate and reduce the soil's pore space, resulting in reduced: 1) water infiltration and percolation, 2) root penetration, and 3) aeration and gaseous exchange. The diffuse double layer (DDL) theory can predict swelling pressures in smectite systems, particularly with montmorillonite [7] [8]. Swelling pressures are effectively repulsion forces, with Ca-Na systems showing greater macroaggregate inhibition with increasing Na saturation of the exchange complex.

A frequently disturbed chemical property in sodic soils is an excessively alkaline pH. Soil pH increases with increased sodium activity, presumably because exchangeable Na acts as a Lewis acid, fostering hydrolysis and ion exchange, resulting in the generation of exchangeable H^+ and increased solution activities of Na^+ and OH^- [2] [3] [6]. The hydrolytic behavior of Na rests with its small ionic radius and a large effective ionic radius, permitting Na^+ to be easily displaced from the diffuse layer by other common ionic species. Monovalent alkali cations display ionic radii patterns that support increased hydration spheres upon progression with atomic number. The hydration radius of ammonium is similar to potassium: Li < Na < K < NH_4 < Rb < Cs. Compared to calcium, magnesium has a greater hydration energy, supporting a larger hydration radius. The larger magnesium hydration shell supports soil structure dispersion, whereas calcium strengthens soil structure stability [6] [7].

The development of soil alkalinity reduces the plant availability of phosphorus, iron, manganese, copper, and zinc, potentially inducing plant nutrient deficiencies. Elemental toxicity may arise from pH-dependent plant availability of sodium, molybdenum, and boron. Boron toxicity arises from the development of soluble sodium metaborate, rather than the less soluble calcium metaborate.

Molybdenum typically has greater plant availability in alkaline soils.

Rice (Oryza sativa) and burmuda grass (*Cynodon dactylon*) are considered examples of plants that are tolerant of sodic soils. Semi-tolerant plants include wheat (*Triticum aestivum*), barley (*Hordeum vulgare*) and oat (*Avena sativa*), whereas cowpea (*Vigna unguiculata*), lentil (*Lens esculenta*) and Maize/Corn (*Zea mays*) are susceptible. Sensitivity varies because of growth stage, environment (rainfall, evapotranspiration, soil drainage, and irrigation water quality), varieties, and cultural practices such as tillage and mulching [6].

1.4. Soil Chemistry and Its Influence on Soil Properties

Carbon dioxide will interact with water to form carbonic acid (H_2CO_3). The equilibrium expression is:

$$CO_2(g) + H_2O = H_2CO_3 \quad \log K = -1.46$$

or

$$[H_2CO_3]/[P_{CO_2}] = 10^{-1.46},$$

where P_{CO_2} is the partial pressure of carbon dioxide, having a value of 413 ppm. The acid protonation reactions for carbonic acid are:

$$H_2CO_3 = H^+ + HCO_3^- \quad \log K_1 = -6.36$$

$$HCO_3 = H^+ + CO_3^{2-} \quad \log K_2 = -10.33$$

Substitution of the H_2CO_3 protonation reaction will provide a pH of 5.6. Rainfall, which has not been influenced by oxides of nitrogen and sulfur and other anthropogenic species, is acidic.

Weathering reactions are thermodynamic predictable reactions involving earth minerals. Congruent weathering involves the dissolution of solid minerals, an example being the dissolution of calcite to Ca^{2+} and bicarbonate, which is expressed as:

$$CaCO_3 + H_2O + CO_2 = Ca^{2+} + 2HCO_3^-.$$

Incongruent weathering involves the conversion of a mineral to another mineral. Important to this study is the incongruent weathering of albite [$2NaAlSi_3O_8(s)$]. Three examples of the incongruent weathering reactions involving albite include: 1) hydrolysis, 2) carbonation, and 3) oxalic acid, which is an example of an organic acid emanating by plant roots.

1) Hydrolysis

$$\begin{aligned}&2NaAlSi_3O_8(s) + 11H_2O\\&= 2Na^+ + 2OH^- + 4H_4SiO_4[\text{silicic acid}] + Al_2Si_2O_5(OH)_4(s)[\text{kaolinite}]\end{aligned}$$

2) Carbonation

$$\begin{aligned}&2NaAlSi_3O_8(s) + 2CO_2 + 11H_2O\\&= 2Na^+ + 2HCO_3^- + 4H_4SiO_4 + Al_2Si_2O_5(OH)_4(s)\end{aligned}$$

3) Albite weathering by oxalic acid (dicarboxylic acid):

$$2NaAlSi_3O_8(s)+H_2C_2O_4+9H_2O \\ =2Na^{+}+C_2O_4^{2-}+4H_4SiO_4+Al_2Si_2O_5(OH)_4(s).$$

In soil environments that experience leaching, soluble silicic acid may be removed from the system, supporting the weathering of albite to kaolinite. The influence of rainfall over protracted time periods supports congruent and incongruent weathering. Plant acids, particularly present in the root rhizosphere, similarly support weathering [6] [8].

1.5. Ferrolysis

First proposed by Brinkman [9], ferrolysis is mostly observed when seasonal wetting and drying cycles create alternating anoxic and oxic soil environments, which in turn, create sufficient acidity to degrade primary and secondary (phyllosilicate) minerals. In anoxic soil environments, carbon sources (CH_2O) and microbial populations respond with Fe-oxyhydroxides to produce ferrous iron (Fe^{2+}):

$$CH_2O+4Fe(OH)_3+7H^{+}=4Fe^{2+}+HCO_3^{-}+10H_2O.$$

Carbon sources include particulate soil organic matter, mineralized humus, microbial or plant exuded organic acids, and other compounds. Ferrous iron (Fe^{2+}) will adsorb onto the soil's cation exchange complex, displacing Ca^{2+}, Mg^{2+}, and K^{+}. Upon the establishment of an oxic soil environment, Fe^{2+} will oxidize to form Fe-oxyhydroxides, resulting in distinct zones of iron accumulation and depletion and the creation of soil acidity. The oxidation of Fe and creation of acidity may be represented as:

$$4Fe^{2+}+O_2+10H_2O=4Fe(OH)_3+8H^{+}.$$

The establishment of active and reserve acidity should accentuate incongruent weathering; however, incongruent weathering of one phyllosilicate (montmorillonite) to another (kaolinite) may not readily occur [10].

1.6. Purpose of Manuscript

The purpose of this manuscript is: 1) to present an in-depth review of sodium bearing soils in a humid continental climate (southeastern Missouri) and 2) to provide an assessment of the soil processes involved in sodic soil genesis.

2. Materials and Methods

2.1. The Geologic History of the Study Area

The study area comprises the southeastern portion of Missouri and the northeastern portion of Arkansas within the Mississippi Embayment (Middle Mississippi River Alluvial Valley). The geologic history of the study area is complex, with multiple episodes of Pleistocene-Holocene valley entrenchment and deposition [11]. The Advance lowlands occupy areas between the Ozark Border region and Crowley's Ridge in southeastern Missouri and northeastern Arkansas.

Within the Advance Lowlands, Roxanna loess (Altonian at 55,000 yr BP) and Peoria loess (Woodfordian at 20,000 yr BP) have been identified [12] [13] [14] [15] [16]. In Arkansas, West *et al.* [12] documented that Crowley's Ridge loess was a succession of Peoria loess, Roxana loess and Loveland loess. The younger Peoria and Roxana loess sheets had an eastern source area, whereas the older Loveland loess had its source area in the Advance Lowlands. Rutledge *et al.* [13] investigated silty braided stream terraces in the Advance Lowlands, documenting that Peoria loess was superimposed on Loveland loess. West and Rutledge [14] investigated several silty sites in the Advance Lowlands and determined the source materials to be alluvium.

In Arkansas, Saucier [11] proposed that the Advance Lowlands have Peoria loess superimposed on Roxana loess, presumably on early or middle Wisconsin valley train. Subsequently, Blum *et al.* [15] using similar transects reinterpreted the valley train ages from middle Wisconsin to late Wisconsin. Royall *et al.* [16] suggested that extensive river meandering during or around 12,000 yr BP produced extensive areas of backswamp. By 9000 yr BP, the Mississippi River occupied a position along Sikeston Ridge. Approximately 9000 yr BP, the Mississippi River diverted through Thebes Gap and flowed east of Sikeston Ridge, occupying its modern location [16] [17].

2.2. Climatic Evolution in Southeastern Missouri

Royall *et al.* [16] documented pollen assemblages in the Missouri Advance Lowlands. Between 14,500 to 18,000 yr BP, pollen assemblages indicate a boreal forest consisting of spruce (Picea) and northern pine (Dploxylon Pinus), fir (Abies) and minor stands of Tamarack (Larix laricina). Broadleaf representation consisted of oak (Quercus) and willow (Salix). With warming conditions (9500 to 14,500 yr BP), the pollen assemblages indicate a large oak, hickory (Carya) and hornbeam (Carpinus) population increase, suggesting the conversion of a boreal forest to a mixed conifer-northern hardwood forest. With continued warming (4500 to 9500 yr BP), oak and ash (Fraxinus) populations increased and the first recognized presence of bald cyprus (Taxodium distichum). The fine-grained sediments also indicated that silt and clays were being deposited from the Salem Plateau by flooding rivers. Willow, elm (Ulmus), sweetgum (Liquidambar), red maple (Acer rubrum) and locust (Gleditsia) dominated the landscape between 4500 yr BP to the present and oak declined in importance.

Currently, the mean annual temperature is 13˚C (56˚F), and mean annual precipitation is 1118 mm (44 inches). Approximately 53% of the rainfall occurs from April to September. The average winter temperature is 4.4˚C (40˚F) and the average summer temperature is 26˚C (79˚F). The average daily summer maximum is 33˚C (91˚F) [18].

2.3. Sodic Soils in Missouri

Of the many soil series within the study area, the emphasis will be placed on three aqualfs. The Overcup series (fine, smectitic, thermic Vertic Albaqualfs) consists of very deep, poorly drained, very slowly permeable soils that formed in fine-textured alluvium. These soils are on broad low-lying terraces in the Advance Lowlands. The horizon sequence is Ap (ochric) - Eg (albic) - Btg (argillic) - Cg. The Foley series (fine-silty, mixed, active, thermic Albic Glossic Natraqualfs) consists of very deep, poorly drained, very slowly permeable soils that formed in silty terraces. The horizon sequence is Ap (ochric) - Eg (Albic) - B/E (B is argillic) - Btng (natric) - BCng (natric). The Lafe series (fine-silty, mixed, active, thermic Glossaquic Natrudalfs) consists of very deep, somewhat poorly drained, very slowly permeable soils that formed in silty Pleistocene terraces. The horizon sequence is Ap (ochric) - Eg-BE (Albic) - Btng (natric) - BCng (natric) [19]. The important phyllosilicates in the clay separate are smectite (montmorillonite), followed by hydroxy Al-interlayered vermiculite, hydrous mica (Illite), and minor quantities of kaolinite [1]. The Foley series spans 133,950 ha across the states of Arkansas, Missouri, and Louisiana, with Arkansas having the largest areal extent. In western Dunklin County, Missouri, the Foley series spans 982 ha and the Lafe series spans 170 ha. Correspondingly, the Overcup series spans 6615 ha.

2.4. Laboratory Methods

Soil pedons were sampled in excavated pits and the soil profile descriptions were according to US Department of Agriculture criteria [20]. Soil pH in water, NH_4-Acetate (pH 7) exchangeable cations (Ca, Mg, K and Na), and $BaCl_2$-triethanolamine (pH 8.0) acidity are routine soil characterization procedures (Carter, 1993). Soil organic matter by loss on ignition, Bray-1 phosphorus, and 2M KCl extractable SO_4-S were also determined by the University of Missouri Soil Testing Laboratory. The clay, silt, and sand fractions were fractionated by Na-saturation of the exchange complex, washed with water-methanol mixtures, dispersed in Na_2CO_3 (pH 9.2), followed by centrifuge fractionation and wet sieving [21].

An aqua regia digestion was employed to obtain a near total estimation of elemental abundance associated with all but the most recalcitrant soil chemical environments. Aqua-regia does not appreciably degrade quartz, albite, orthoclase and other minerals; however, anorthite and phyllosilicates are partially digested. Homogenized samples (0.75 g) were equilibrated with 0.01 liter of aqua-regia (3 mole nitric acid: 1 mole hydrochloric acid) in a 35˚C incubator for 24 hours. Samples were shaken, centrifuged and filtered (0.45 μm), with a known aliquot volume analyzed using inductively coupled plasma emission - mass spectrometry. Selected samples were duplicated, and known reference materials were employed to guarantee analytical accuracy.

3. Results

All pedons exhibit an ochric - albic - argillic or natric horizon sequences. The argillic horizons for all pedons exhibit medium to course, moderate subangular blocky structures. Munsell soil colors (low chroma) indicate gleyed (g) soil conditions. The expression of Fe-oxyhydroxide accumulations and depletions and the presence of glabules (Fe and Mn concretions) indicate seasonal and fluctuating water tables. The clay percentages abruptly increase from silt loam to silty clay loam on transition from the albic to argillic or natric horizons (**Table 1**). The natric horizon in the Foley pedon exhibits smaller clay percentages than the overlying argillic horizon, which is not in accordance with the definition for natric horizons. The usage of natric horizon remains appropriate because clay illuviation appears to be supported by dispersion of the thick E and EBg horizons.

The ochric epipedons range from strongly acid to moderately acid for the Overcup pedons and have neutral pH values for the Foley and Lafe pedons (**Table 2**). The upper argillic horizons range from moderately acid to extremely acid for the Overcup pedons and extremely acid for the Foley pedon and moderately acid for the Lafe pedon. The deeper portions of the argillic horizons range from neutral to mildly alkaline for the Overcup pedons and range from alkaline to very strongly alkaline in the Foley and Lafe pedons, respectively. The cation exchange capacities (CEC) in the eluvial horizons of the Overcup pedons range from low to moderate, whereas the illuvial horizons generally express high cation exchange capacities. The eluvial horizons of the Foley and Lafe pedons demonstrate low to moderate cation exchange capacities, whereas the illuvial horizons range from moderate to high. In all pedons, the CEC values parallel clay contents. The exchangeable sodium percentages (ESP) are greater in the illuvial horizons and are greatest for the Lafe pedon, corresponding with the most alkaline pH values. The exchangeable Ca/Mg ratios are greatest in the eluvial horizons, with the Foley argillic horizons having the smallest ratios.

It is important to document that each pedon has a portion of its argillic horizon that has an acidic reaction, yet exhibits an elevated exchangeable sodium percentage. Each of these sodium rich and acidic Bt horizons transition to a deeper portion of the argillic horizons with greater ESP values and an alkaline to strongly alkaline reaction. It is suspected that the considerable presence of Al^{3+} and H^{+} on the cation exchange complex offsets the dispersive capacity of sodium, supporting the downward migration of soluble anions that promote an acidic pH in the upper Bt horizons.

The aqua regia digestion was performed for the Overcup #1 pedon and the Foley pedon. For reference purposes 1000 mg Na kg^{-1} from the aqua regia digestion corresponds to 4.35 cmol Na kg^{-1} if all the aqua regia digestion sodium values were converted to an exchangeable sodium basis. The aqua regia digestion will to a very limited extent degrade albite, thus if albite remains in the soil environment, then any sodium present in the lattice of albite will not be quantitatively detected. The relationship between exchangeable sodium and aqua regia digestion sodium for the Foley pedon is highly significant (**Figure 1**). Additionally,

Table 1. Selected soil chemical properties.

Horizon	Depth (cm)	Texture	Clay (%)	Silt (%)
		Overcup #1		
Ap	18	silt loam	15	76
Eg	25	silt loam	20	68
Btg1	43	silty clay	41	57
Btg2	71	silty clay	40	56
Btg3	99	silty clay loam	36	59
Btg4	129	silty clay loam	31	63
Btg5	157	silt loam	25	71
BCg	200	silt loam	18	77
		Overcup #2		
A	10	silt loam	12	70
E	31	silt loam	14	69
BE	46	silt loam	17	67
Bt1	61	silty clay loam	32	57
Btg2	76	silty clay loam	31	56
Btg3	94	silty clay loam	33	54
Btg4	112	silty clay loam	37	58
Btg5	153	silty clay loam	29	61
		Foley		
Ap	18	silt loam	11	57
Eg	30	silt loam	13	57
EBg	51	silt loam	15	62
Btg1	76	silty clay loam	34	52
Btg2	91	silty clay loam	31	51
Btng1	109	silt loam	24	58
Btng2	135	silt loam	26	66
Btng3	178	silt loam	27	67
		Lafe		
Ap	5	silt loam	14	80
Eg	21	silt loam	21	73
BEg	30	silt loam	36	61
Btng1	61	silty clay loam	39	56
Btng2	101	silty clay loam	33	64
Btng3	142	silty clay loam	43	53
Btng4	157	silty clay loam	62	38

Table 2. Selected soil chemical properties.

Horizon	pH	CEC	BS %	ESP %	Ca/Mg
			Overcup #1		
Ap	5.4	8.2	82	1.0	2.6
Eg	6.2	8.4	83	3.5	2.5
Btg1	4.2	23.9	39	3.3	2.2
Btg2	4.1	25.5	39	5.7	1.9
Btg3	4.7	21.6	58	9.5	1.7
Btg4	7.1	19.8	87	13.8	1.7
Btg5	7.5	15.0	100	14.2	1.7
BCg	7.1	13.4	100	13.3	1.7
			Overcup #2		
A	6.0	15.1	57	0.8	2.6
E	5.1	12.8	46	0.7	2.3
BE	5.2	14.8	29	2.1	1.0
Bt1	5.6	20.4	31	6.7	1.0
Btg2	5.1	29.4	58	9.8	1.5
Btg3	5.4	24.9	80	13.8	1.8
Btg4	6.5	21.0	100	18.3	2.1
Btg5	7.3	21.3	100	16.3	1.5
			Foley		
Ap	6.6	10.5	100	1.3	2.7
Eg	6.5	8.4	100	2.0	2.2
EBg	5.5	10.5	82	4.6	1.2
Btg1	3.7	24.2	41	5.0	0.6
Btg2	4.6	24.0	51	9.8	0.3
Btng1	6.3	17.2	84	19.1	0.3
Btng2	7.7	16.0	100	24.2	0.2
Btng3	7.9	15.5	100	24.8	0.3
			Lafe		
Ap	7.3	10.4	99	5.0	1.3
Eg	4.9	12.1	98	7.4	1.5
BEg	4.8	13.5	73	18.9	1.1
Btng1	5.9	25.3	98	37.6	1.0
Btng2	8.3	26.2	100	36.0	1.1
Btng3	8.6	26.8	100	35.1	0.9
Btng4	9.7	36.8	100	35.7	1.0

CEC is cation exchange capacity (cmol charge/kg), BS % is percent base saturation, ESP % is exchangeable sodium percentage.

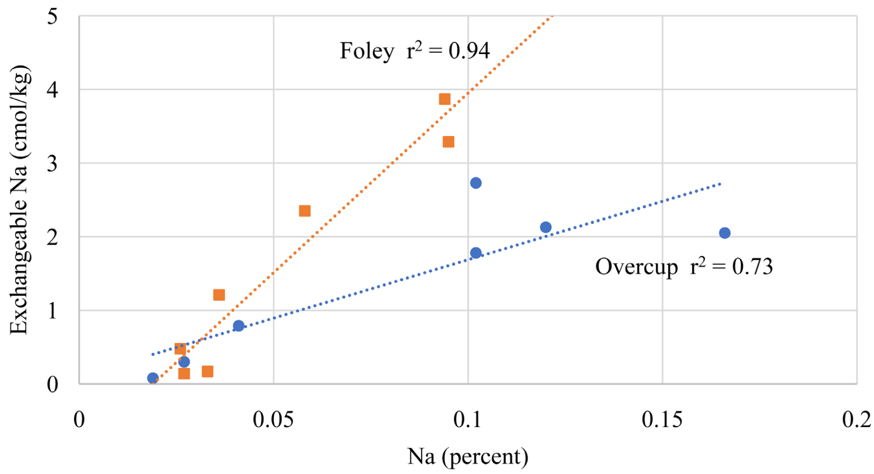

Figure 1. Relationship involving exchangeable sodium and aqua regia digestion sodium.

the sodium content measured from the aqua regia digestion is roughly equivalent to the exchangeable sodium content across the horizons of the soil profile. The relationship involving the Overcup pedon is less precise, suggesting that a minor percentage of sodium may exist in an aqua regia digestible mineralogy in addition to the sodium allocation as exchangeable sodium.

For reference purposes 1000 mg Ca kg^{-1} from the aqua regia digestion corresponds to 5 cmol Ca kg^{-1} if all the calcium was converted to an exchangeable calcium basis. The calcium aqua regia digestion concentrations range from equivalent to slightly greater than the experimental determined exchangeable calcium concentrations, suggesting that some calcium-bearing crystalline material exists. The aqua regia digestion will partially degrade anorthite ($CaAl_2Si_2O_8$); however, anorthite is rare and exists largely in mafic Precambrian rocks. More likely, some small percentage of the calcium may exist in a few, small microenvironments as calcite, gypsum or calcium phosphate.

4. Soil Genesis of Sodium Bearing Soils

It is commonly acknowledged that soil evolution may be predicated on correctly ascertaining the specific attributes of five soil forming factors: 1) parent material, 2) climate, 3) organisms, 4) topography, and 5) time. If soils are commingled across the landscape, then in many circumstances, some of the soil forming factors are more important in predicting differences in soil profile appearances and soil behavior.

Soil mapping reveals that the Overcup-Foley-Lafe soils form a mosaic across the landscape. The Foley series is slightly more elevated in the landscape (commonly 5 to 15 cm). Regardless, much of the landscape has been precision land graded for furrow or flood irrigation. Thus, the limited landscape topographic differences do not effectively support soil divergence in their genesis. Similarly, climate and organisms do not appear to be the dominate soil forming factors that reveal soil profile evolutionary differences. All soils have thermic temperature regimes; thus, temperatures differences are not sufficiently different to foster evolutional differences. It should be noted that ancestral forest growth is an unknown influence; in that, the depth to the fluctuating water table and the thickness of the rooting zone would be tree species dependent and influenced by the depth to the upper portion of the natric horizon [6]. The Lafe and Foley pedons have tongues of albic materials degrading the uppermost portion of argillic horizons. Given the slight elevation differences and the tongues of albic material infer that these pedons occupy older silty terrace positions and the Crowley pedons occupy lower topographic silty terraces [18]. Currently, the entire forest cover has been removed because of crop production [18] [22]. The study area has been artificially drained by a series of water diversion structures and drainage ditches [22].

The influence of parent material is integral to the discerning soil profile differences. The Overcup series has a fine-textured control section, whereas the Foley and Lafe soil series have a fine-silty control section. Thus, for the Overcup and Foley/Lafe soils, either the textural composition of the alluvium is different, or the alluvium depositional environments are different. The timing of the depositional environments is also relevant. All the investigated soils have well developed argillic horizons, whereas soils east of Crowley's Ridge lack argillic horizons. As previously noted, the ancestral Mississippi River abandoned the Advance Lowlands to begin entrenchment and sedimentation east of Crowley's Ridge [11] [12] [13] [14] [15]. Thus, these soils in the Advance Lowlands are older than the Morehouse Lowland soils east of Crowley's Ridge, with a time differential to permit argillic horizon development [18].

It is probable that the fine-silty alluvium in the Foley and Lafe was deposited as terrace material, with the fine-textured material in the Overcup deposited as backswamp. The fine-silty alluvium originated from stream transported from erosion of the thick loess mantles of the Salem Plateau, possibly co-mixed with areal deposition of loess [18]. Conversely the fine textured alluvium likely had its source from the ancestral Mississippi River.

5. Ancestral and Contemporary Soil Processes That Contribute to Soil Profile Expression

The soils are aqualfs, thus these soils are poorly drained or somewhat poorly drained, slowly permeable, and exhibit seasonal episodes of suboxic to anoxic reduction. Soil profile redoximorphic features include Mn- and Fe-oxyhydroxide accumulations and depletions, presence of glabules, and low chroma soil colors (gleyed). Given seasonal oxidation and reduction episodes, leaching and ferrolysis are active soil processes. Ferrolysis is involved in creating Mn- and Fe-oxyhydroxide accumulations and depletions, displacement of Ca, Mg, K, and Na from cation exchange sites, and the development of soil acidity.

The Ca/Mg ratio is smaller in the Foley and Lafe pedons than for the Overcup pedons, indicating than soil structure degradation because of dispersion is favorable (**Table 2** and **Table 3**) [2] [4] [6]. The presence of greater ESP values for the Lafe and Foley pedons further suggest enhanced soil structure degradation, dispersion, and water percolation restrictions. Soil acidification supports the incongruent weathering of albite to montmorillonite and ultimately to kaolinite, providing a source of sodium from albite and a source of aluminum and magnesium from phyllosilicates.

The Foley genesis sequence involves poorly-drained alluvial deposition where: 1) seasonal anoxic conditions orchestrate Fe-oxyhydroxide accumulation and depletion, gleyed soil conditions and cation leaching, 2) ferrolysis contributes to the acidic soil regime, and 3) clay eluviation-illuviation creates argillic horizons. Sodium accumulation because of mineral weathering supports 1) an alkaline pH and 2) an elevated exchangeable sodium percentage, 3) soil structure dispersion, and 4) natric horizon formation. Continued ferrolysis encourages soil acidification and sodium displacement from the exchange complex and reduction of the exchangeable sodium percentage, and because of increased Al^{3+} and H^{+} re-constitution of the soil structure. Thus, the acidic upper portion argillic horizon represents degradation of the natric horizon to non-sodic argillic horizon.

The Overcup series did not have sufficient albite to create natric horizons, except for the lower most horizons of the Overcup pedon, which shared similar alluvium with the Foley pedons. The Lafe series lags behind the Foley series in the reduction of the natric horizon to a non-sodic argillic horizon.

Table 3. Selected aqua regia digestion alkaline earth and alkali elements.

Horizon	Calcium	Magnesium	Potassium	Sodium
	mg·kg^{-1}			
		Overcup (#1)		
Ap	1100	1400	1300	190
Eg	1200	1500	1200	270
Btg1	1200	2400	1700	410
Btg3	1400	2700	1900	1660
Btg4	2300	4300	2300	1020
Btg5	3400	4300	2200	1200
BCg	3100	3800	1900	1020
		Foley		
Ap	5100	2900	1900	270
Eg	3100	3000	2100	330
EBg	2200	2400	1700	260
Btg1	1300	3500	2600	360
Btng1	600	4000	2900	580
Btng2	700	5900	3800	950
Btng3	1600	6500	3700	940

6. Soil Behavior

The dominant row crops in the study area are rice (Oryza sativa) and soybeans (Glycine max). Rice is not affected by the presence of natric horizons because of the shallow root systems. Conversely, in some instances soybeans are severely impacted when their root systems encounter natric horizons, particularly for the Lafe soil series. Regardless, excessive water during the growing season is a serious agricultural issue.

7. Conclusions

This study was conducted to present an in-depth review of sodium bearing soils in a humid continental climate and to describe soil processes involved in sodic soil evolution. Sodic soils having natric horizons exist in alluvial basins commingled with other Aqualfs. The source of the sodium presumably is the weathering of sodic plagioclase minerals. Subsequent soil structure dispersion limits sodium leaching.

Seasonal water table fluctuation is involved in creating redoximorphic features and gleyed soil conditions associated with Fe-oxyhydroxide migrations to create zones of Fe-accumulation and Fe-depletion. Ferrolysis supports the creation of soil acidity, responsible for reducing the soil's base saturation and facilitating soil structure stability, a process that converts the natric horizon to a non-sodic argillic horizon.

Conflicts of Interest

Author has no conflict of interest.

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