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The effect of parent material and soil development on nutrient cycling in temperate ecosystems

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Abstract. The parent material of a soil determines the original supply of those nutrient elements that are released by weathering and influences the balance between nutrient loss and retention. Organic acids and exudates produced by microorganisms and plants enhance the weathering of minerals and the release of nutrients. Nutrients may be stored in organic cycles or as ions adsorbed to clay and organic matter. Nutrients are lost mainly by leaching, both as dissolved ions and when associated with soluble organic components. Soil formation evidently affects these processes and modifies the environment at different depths as soil horizons develop. Strong interactions between mineral and organic colloids occur where most residues are added below ground, as in grasslands, or mixed with mineral soil by faunal activity, as in some forests. These systems tend to be nutrient conserving. The addition of organic residues to the soil surface often results in slow decomposition, the tie-up of many nutrients in biologically resistant humic materials, and the generation of organic acids that are active in leaching and chelation. These soils tend to lose nutrients by leaching and become strongly acidic with time. Leaching is strongest in uplands with net downward flows to deep water tables, and may be dampened or obviated in lowlands with strong upward fluxes due to artesian pressure or capillary rise from a water table that is close to the surface. Pedogenic features such as clayey B horizons or duripans may alter water flow. Simonson's concepts that all basic soil-forming processes occur to some degree in all soils are critical to developing models describing soil formation and nutrient cycles.

Introduction

Soil science as a discipline within the natural sciences began with the work of earth scientists such as Dokuchaev (1883) who determined that soils were natural bodies with distinctive, repetitive and predictable properties that were the result of the conditions of their formation. This early work considered that the factors most important to the formation of soils were: the nature of the original geological material or parent material, the current and past climates and vegetation, the effects of other organisms, relief or topo-

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graphy, and time. These ideas hold today, conditioned by refinements of scientists who were able to study soils in greater detail with more exact technologies of measurement. A short but by no means complete list includes the following citations. Jenny (1941, 1980) described soils as systems and studied their properties with systematic and holistic methods, establishing functional relationships between soils and their environment. Nikiforoff (1959) reminded us of the need to study soils in a fundamental rather than pragmatic way and presented an apt metaphor of soils as a turn-stile through which the nutrients for life pass again and again. Simonson (1959)

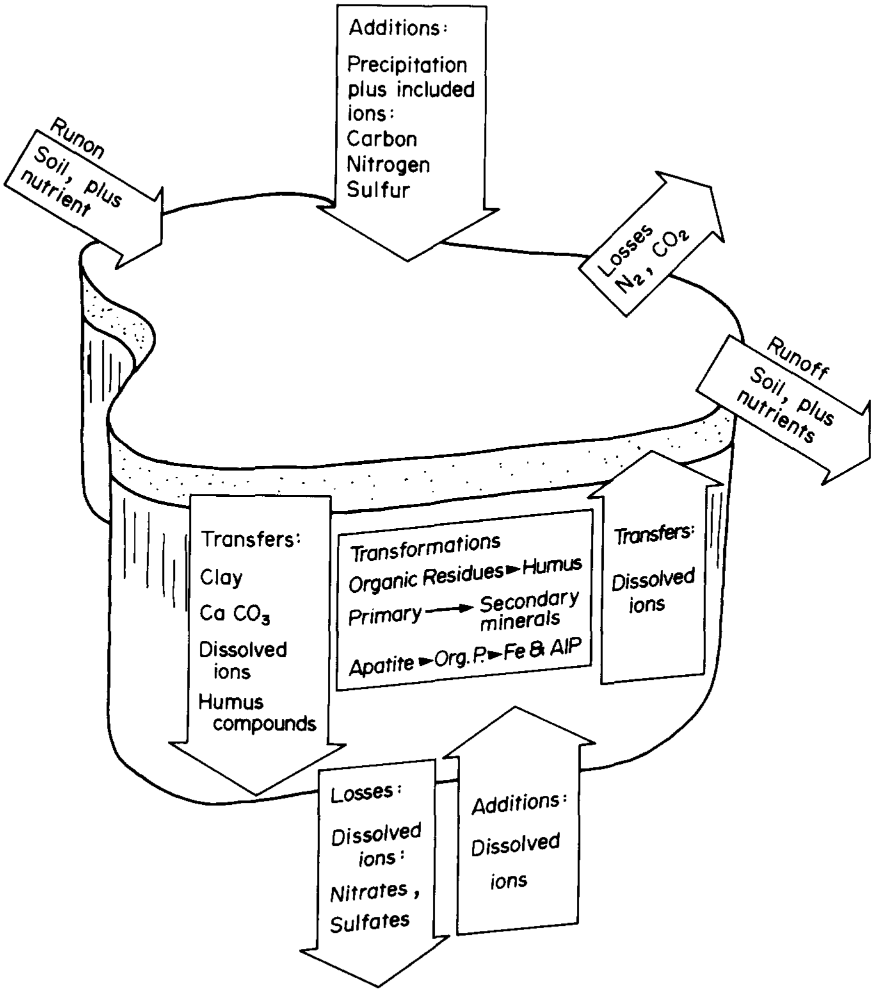

Fig. 1. Soil forming processes, based on the concepts of Simonson (1959) and adapted from Birkeland (1974) & Dijkerman (1974).

removed some of the mystery from soil-forming processes with his recommendation that soils be considered to form in two stages, the accumulation of the parent material and the differentiation of horizons. The basic processes by which soils form are additions, removals, transformations and translocations (Fig. 1). In addition, the same processes are active in all soils to some degree. It is the balance of the processes that determines the nature of the soil. This is an important concept, particularly when one develops conceptual and operational models of soil systems. Crompton (1962) pointed out that the soil-forming factors do not form soils, they shape the largely internal processes by which soils form. The work of Walker, his associates and others showed the considerable importance of soil formation to nutrient supply, particularly phosphorus (Walker & Syers 1976; Smeck 1985).

It is evident that the processes that form soils are the same as those that determine the supply of nutrients to the biota in and on the soil (Fig. 2). This simplified depiction of the many and varied reactions that occur in the soil (Trudgill 1977) will serve as an outline for the discussion to follow. The primary emphasis of the discussion is to deal with the supply of nutrients by parent materials, a supply that is affected not only by the original content

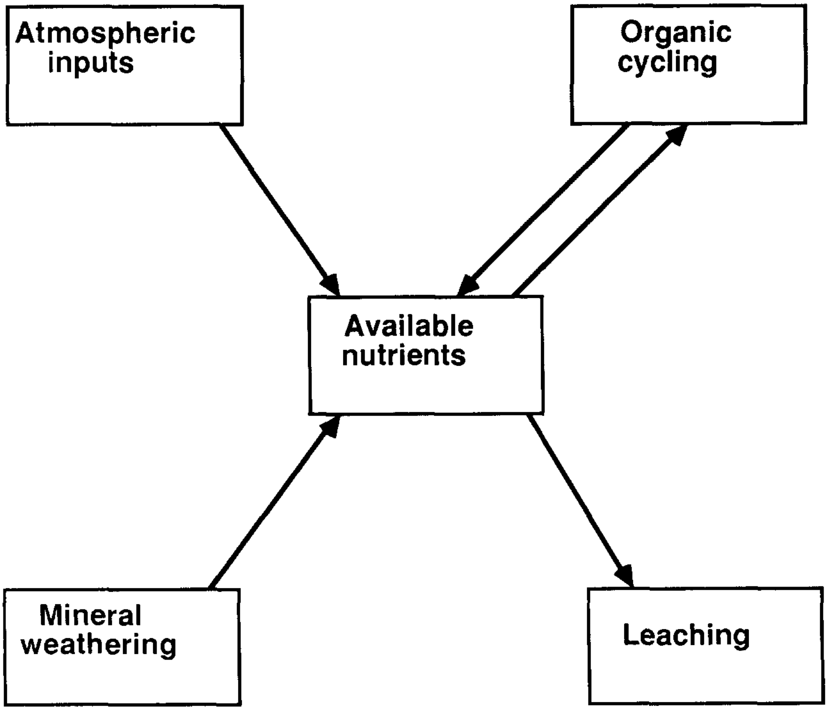

Fig. 2. Simplified depiction of the processes affecting nutrient supply in soils (Trudgill 1977).

in the material, but the rates of release of nutrients by weathering, their fixation as new minerals are formed, their potential loss by leaching and the reactions of the organic cycles which act as both barriers and mechanisms for these losses depending upon soil environment. Considerations of elements originating in the atmosphere are included because the kind of parent material and soil formation affects their storage in the soil. Sulfur may be supplied mainly from atmospheric sources in some soils, while other soils have ample supplies of mineral sulfur. Even carbon, an element originating in the atmosphere and entering the soil in organic form, may become a mineral constituent in caliche layers (Schlesinger 1982) that can profoundly affect subsequent processes in the soil, becoming a barrier to root growth and the movement of water.

Parent material and weathering effects

Physical properties of the parent material

The physical and lithological character of the parent material has a considerable influence on the nature of soil-forming processes and the resultant soils. Most soils in temperate climates have formed on unconsolidated sediments or on soft rocks. Rates of soil formation on hard rocks may be so slow in comparison to erosion rates that significant depths of soil may never develop. A generalized rock-stability ranking for soil formation, from more to less stable, is quartzite, chert > granite, basalt > sandstone, siltstone > dolomite, limestone (Birkeland 1974).

The texture of the parent material is a factor of importance. Clayey soils, particularly those with a high content of smectite minerals, often are unstable. Slope failures may occur where these materials occur on steep slopes, removing the soil that has formed up until that time. Vertisol soils develop where clayey deposits occur on level land under a climate with a marked dry season (Ahmad 1983). Vertisols undergo substantial changes in volume with change in moisture content, resulting in deep and wide cracks upon drying and strong internal forces resulting from expansion on re-wetting (Ahmad 1983). The soils are mixed to depths of up to two meters and lack the horizons and distribution of organic matter that is characteristic of less clayey soils (Mermut & Acton 1985). Water infiltration is mainly via cracks, resulting in spatially variable moisture contents (Lewis 1977).

Texture also affects the infiltration of water, the amount of water that can be stored in unit depths of soil and, therefore, the depth of leaching. Sandy soils are more readily leached and affected to greater depths compared with more clayey soils, given equivalent water for leaching (Jenny 1941; Hole &

Campbell 1985). Therefore it can be expected that sandy soils will not only have a reduced supply of nutrients in the original material, as discussed later in this paper, but will be subject to greater nutrient losses as soil formation proceeds. The periods during which water-mediated processes can occur are generally limited in sandy soils in comparison to soils with more clay. Proportionately large amounts of water may move right through sandy soils to the water table, and uptake by plants rapidly uses up stored moisture. This may not be the case in semi-arid regions, in that infiltration is the key factor where precipitation usually is not sufficient to use the whole moisture storage capacity of sandy soils.

The amount of organic matter stored in the soil is affected by the clay content of the soil. Jenny (1941) reports findings that show an increase in the organic carbon content and narrowing of the C:N ratio with increase in clay in a group of related soils of Iowa. More recent work, based on the evaluation of a large number of soils in the southern Great Plains, indicates that clay content was the factor most strongly correlated with the organic carbon content of soils (Nichols 1984). A later study, however, found significant relationships between clay and organic carbon only for soils of mesic (> 8 °C mean annual soil temperature) temperature regimes (McDaniel & Munn 1985; Sims & Nielsen 1986). Soils of colder temperature regimes appear to have high organic carbon contents because of reduced rates of decomposition in unfavorable environments. Clay-humus complexes, however, may still affect the nature of humic materials in these soils, maintaining a pool of more labile, nutrient-rich materials of importance to the medium term cycling of nutrients and carbon (Bettany et al. 1979; Anderson & Paul 1984).

Soils that contain aproximately equal proportions of sand, silt and clay have adequate clay to acquire the positive characteristics such as cation exchange and moisture storage capacities without the negative elements of site instability, erodibility and slow permeability of more clayey soils. In addition, they do not have the production-limiting features of sandy soils such as low nutrient concentrations in original materials, insufficient nutrient and moisture storage, and high potential for loss of nutrients by leaching. The response to soil texture varies, however, with environment. Where infiltration rather than moisture storage becomes a critical factor, in areas with limited precipitation but a high frequency of intense storms, sandy soils may perform better than those with more clay (Aandahl 1982).

Weathering and nutrient processes

Chemical weathering is one of the most important sources of inorganic nutrients on mineral (excluding organic deposits) soils under natural conditions. The elements of greatest concern are calcium, magnesium, potassium, sodium, silicon, iron, aluminum and phosphorus, all of major significance in plant nutrition or in soil development (Trudgill 1977). Other elements released by chemical weathering include the trace elements of manganese, copper, zinc, molybdenum, boron, chlorine and cobalt. Sulfur may be supplied from both mineral and atmospheric sources and is therefore central to both weathering processes, mostly in soils of semi-arid regions, and organic cycling.

Mechanical or physical weathering will not be considered in detail in this discussion, but is of considerable significance. Physical processes of abrasion by glaciers, water and wind have formed most of the unconsolidated sediments on which the great majority of soils in temperate climates have formed. Sorting by these same agents has been a major factor in determining the texture of deposits and, therefore, the water-holding and transmitting properties of soils as well as the surface areas for chemical reactions.

The input of nutrients released by weathering depends upon their original content in the parent material, and the stability of the minerals in which they are contained. Weathering within the soil profile is the response of minerals or assemblages of elements to an environment different from that under which they formed (Ollier 1984). Minerals may be arranged in sequence of their resistance to weathering (Ollier 1984), and considerable research has dealt with the nature of crystal structures and bonding that determine a mineral's resistance, particularly for silicate minerals (Crompton 1962; Allen & Fanning 1983). Minerals formed in the soil environment such as the secondary clay minerals are stable under that particular environment, but conditions at different depths in the soil change as soil development proceeds. Bases are translocated downward by leaching and acidity increases with time. Pedogenetic features such as clay-enriched argillic horizons or indurated layers such as fragipans or duripans may restrict the downward flow of water and alter redox conditions. Many soil profiles present a wide

Table 1. Average composition of major nutrient elements in sedimentary and igneous rocks (Ronov & Yaroshevsky 1972).

	SiO_2	Al_2O_3	Fe_2O_3	FeO	MgO	CaO	K_2O	P_2O_5	S^n
	%								
Sedimentary	49.90	12.97	2.99	2.80	3.06	11.70	2.04	0.16	0.18
Granitic	69.94	15.18	2.00	2.86	2.21	3.98	3.29	0.20	0.04
Basaltic	58.23	15.49	2.86	4.78	3.85	6.05	2.58	0.30	0.03

range in weathering environments, from calcareous C horizons with alkaline reactions to E horizons that are moderately acidic, and subject to wide swings in redox potential (Arshad & St. Arnaud 1980).

Many elements of biological importance occur in several minerals, often of varying degrees of susceptibility to weathering. Calcium, for example, is contained in gypsum, calcite and dolomite, amphiboles and pyroxenes, and in calcium feldspars. The significance of these minerals to calcium supply depends upon the soil environment. The dissolution of gypsum or calcite is a probable source of calcium in young soils in semi-arid to sub-humid climates, but is of no significance in more strongly weathered soils where calcium is derived from more resistant minerals such as feldspars.

The average composition of the major nutrient elements in generalized groupings of rock types indicates a considerable range in nutrient content (Table 1). Sedimentary rocks are enriched in calcium and sulfur but somewhat lower in phosphorus and potassium. "Granitic" or more acidic igneous rocks have more potassium but much less phosphorus and calcium than basic "basaltic" rocks. These are generalizations, and variations in composition within groups can be very substantial. Sedimentary rocks, for example, may range from 3.24% K_2O for shale, to 1.31 for sandstone and 0.33 for limestone (Pettijohn 1957). Phosphorus contents are shale 0.075%, sandstone 0.035% and limestone 0.018%.

Plants, microorganism and mineral weathering

The presence of living organisms in the weathering zone has profound effects on weathering processes. Soil formation without the biota's presence is largely a question of academic interest (Nikiforoff 1959), occurring only in harsh environments such as polar deserts or in fresh volcanic deposits. The role of plants in weathering includes the mechanical processes of plant roots breaking rocks apart by expansion while growing in fissures, and the stabilizing effect of vegetation in reducing erosion and lengthening the time for soil formation.

Plants, however, have direct influences on chemical weathering. Hydrogen or hydronium ions and the carbon dioxide released by plant roots make substantial contributions to the acidic environment favoring the hydrolysis of carbonates and silicate minerals (Boyle & Voigt 1973). Plant roots actively produce exudates (chiefly sugars and proteins) which are substrates for microorganisms in the rhizosphere. These organisms enhance weathering by the production of organic acids, promoting hydrolysis reactions. Many of the organic acids act as chelates, complexing polyvalent cations and thereby reducing their concentration in ionic form and actively translocating them to different depths in the soil. Chelates are thought to be active agents in the translocation of iron and aluminum in Spodosol (podzolic) soils and, perhaps, in far-reaching transfers involving ground and surface waters and many other elements.

Plants reduce the concentration of weathering products at reaction sites by removing elements for their nutrition (Trudgill 1977). This promotes further release of elements by weathering. Incorporation into plant or microbial tissue acts to retard the loss of soluble constituents by leaching, a feature of organic cycling that is discussed later.

Leaching and nutrient loss

Water in soil brings reactants to the sites of weathering reactions, transports weathering products back to roots, or removes them from, or redistributes them within, the soil profile. Mobile ions such as sodium are more likely to be removed completely while less mobile ions such as phosphate may only be moved to lower depths (Trudgill 1977). Leaching occurs primarily by the flow of gravitational water in the larger pores of soil, but flow in water films at lower water contents is also significant.

There are several factors that determine the effectiveness of precipitation in leaching. The total amount, and the size and frequency of precipitation events are important. The concentration of precipitation into less frequent but heavier rains makes a given amount of precipitation more effective in leaching, providing that infiltration is not limiting (Trudgill 1977; Howitt & Pawluk 1985). Periods between intense rains with relatively low water contents in the soils allow for longer reaction times and the build-up of solutes which may be then leached as a pulse or flush following saturation of the soil layer by heavier rains. Snow accumulation and melting over short periods of time provides large quantities of water, but the effectiveness of this water in leaching may be considerably reduced where soils are frozen.

Vegetation influences leaching in both positive and negative ways. Canopy interception may reduce the amount of precipitation reaching the soil and reduce the leaching potential (Sanborn & Pawluk 1983). In other instances, however, the reduced evaporation potential due to the presence of forest or shrub vegetation coupled with more even and slower melting of snowpacks results in higher soil moisture levels in spring (de Jong & MacDonald 1975) and a greater potential for leaching. Litter horizons in forest have high moisture capacities, and limit the amount of water reaching the mineral soil (Sanborn & Pawluk 1983; Howitt & Pawluk 1985).

The removal or absence of vegetation profoundly reduces water uptake and results in more frequent instances when the soil is saturated and water

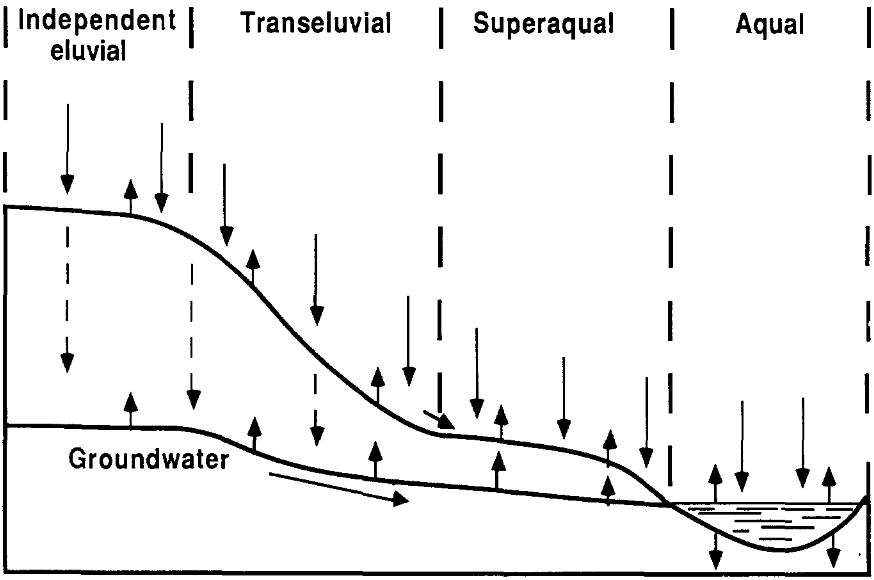

Fig. 3. Elementary landscapes according to Polynov (1951) and illustrating leaching and upward fluxes.

moves downward by gravitational flow resulting in greater leaching potential. This occurs in clear-cut forest land (Likens & Bormann 1975), and under bare summerfallow in semi-arid regions where increased leaching is thought to have resulted in the enhanced transfer of soluble components from uplands to saline lowlands (Ferguson & Bateridge 1982).

Soil structures resulting from pedogenesis influence leaching and residence times for solutes in the soil. Clayey but well structured horizons may allow reasonable rates of conductance, mainly through fissures between structural aggregates. Other clay-enriched layers, such as argillic horizons, or indurated pans can severely alter water flow. Water flows laterally through sandy layers on the surface of clay-enriched, Bt horizons formed in glacial till (Kachanoski & de Jong 1982). Slowly permeable B horizons result in the saturation of lower A and E horizons in some Alfisol soils, resulting in enhanced weathering and the reorganization of weathering products into structures such as iron-manganese concretions (Arshad & St. Arnaud 1980). Indurated pans that form by silica cementation at lithological discontinuities result in a dominance of lateral flow of water within the soil (Olson & Hupp 1986). These pans effectively reduce the rooting and water storage volumes of soils, and alter the composition of the plant community.

The position of a soil within local or regional landscapes determines its leaching characteristics to a considerable degree. Upland regions with deep water tables have a net transfer of constituents downward, and leaching is

Table 2. A migration series for elements in landscapes (Polynov 1951).

Migratory class of elements	Order of migration	Index of size of migration
Energetically removed	Cl (Br, I) S	2n × 10
Readily removed	Ca, Na, Mg, K	n
Mobile	SiO_2 (silicate), P, Mn	$n.10^{-1}$
Inert (slightly mobile)	Fe, Al, Ti	$n.10^{-2}$
Practically immobile	SiO_2	$n.10^{\infty}$

not restricted except by slowly permeable layers within the soil. These are the eluvial landscape elements described by Polynov (Fortescue 1980). Upward movement of water due to capillary rise or artesian pressure may occur in adjacent lowlands, in superaqual landscape elements. Saline or sodic soils result where the water contains dissolved salts and net upward fluxes are further augmented by evaporation from the soil surface under semi-arid climates (Henry et al. 1985). Upward fluxes may also slow the leaching of nutrient elements such as calcium, magnesium and potassium. The close juxtaposition of soils with lower horizons enriched in $CaCO_3$ (calcic soils) on micro-knolls and strongly leached Albaqualf soils in micro-depressions is thought to have resulted from differences in the lateral flow of water and resulting effects on leaching (Sobecki & Wilding 1983). Runoff from the micro-knoll to the micro-depressions increases the potential for leaching in the latter. This results in more moist and strongly leached soils under the micro-depression, and sets up lateral flows from moist to dry soil, thereby concentrating $CaCO_3$ under the micro-knoll.

Elements differ in their mobility or solubility. Polynov (1951) provided a classification of elements in landscapes by comparing their composition in igneous rocks with their concentration in drainage waters (Table 2). The anions of chloride and sulfate are most mobile, followed by cations of calcium, sodium, magnesium and potassium. Phosphate was considered of equivalent mobility to silicate silica, while iron and aluminum and quartz silica are described as inert to practically immobile. Nitrogen is not included in this list, although there is little doubt that it is as mobile as chloride or sulfate when in the nitrate form.

Soil formation and vegetation can also act as a barrier to leaching, primarily by the biocycling of bases, the development of cation exchange sites within organic and mineral layers and by increasing the water-holding capacity of surface horizons, as mentioned earlier (Fig. 4).

Cation exchange sites within both organic and mineral layers are undoubtedly of importance in nutrient retention. Cation exchange capacity (CEC) is influenced by the kind and amount of clay minerals that are present, and

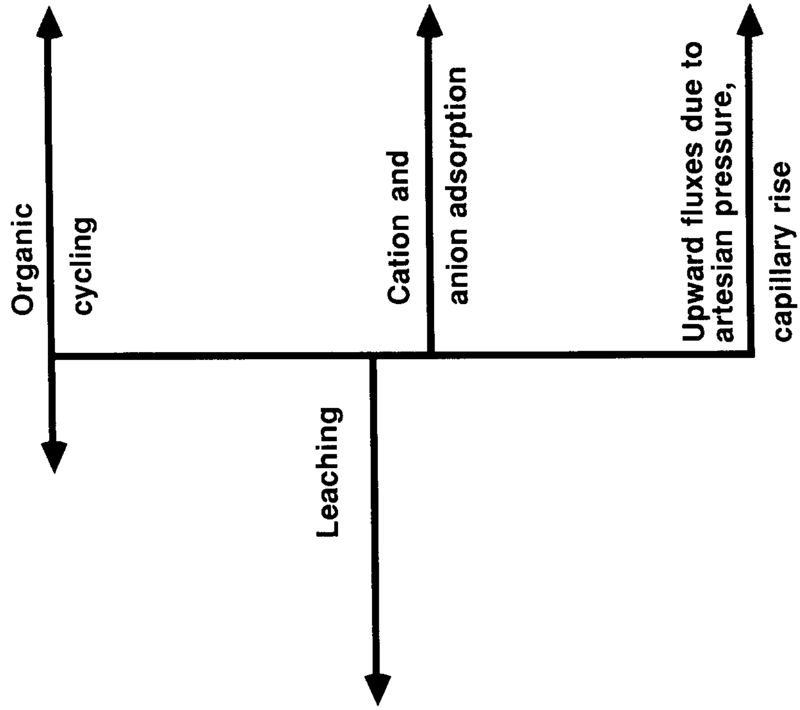

Fig. 4. Schematic depiction of leaching and forces counteractive to leaching in soils.

the organic matter content. CEC increases as organic matter is added to the soil (Anderson 1977) and decreases in surface layers as clay is weathered and leached to greater depths. St. Arnaud (1986) reports calculations based on a pedogenic index (relating current concentrations of elements to the index mineral, quartz) that indicates that surface layers of a Boralf soil have lost about one-quarter of their potential CEC, primarily by loss of clay. Some of this clay is retained in illuvial B horizons, but the net effect is that important surface layers have fewer sites for retaining nutrient cations.

Weathering/leaching ratio

Crompton (1960) points out the significance of the weathering/leaching ratio to the nature of minerals formed in soils. This ratio relates the intensity of weathering, determined chiefly by the climate and the weatherability of the parent material, to the leaching potential as affected by the precipitation/evapotranspiration balance and the permeability of the soil profile. Under rich weathering, i.e. the rapid release of constituent ions from primary minerals and low leaching intensity, the released ions have the opportunity to react and form new minerals. Calcium carbonate, for example, forms in soils where weathering releases calcium but leaching does not remove it completely from the soil profile. In soils with slightly stronger leaching, weathered aluminosilicate constituents and polyvalent cations have the opportunity to react to form secondary 2:1 lattice clay minerals (Borchardt 1977). A recent study of Alfisol soils under generally similar weathering intensities (climates) indicated maximum formation and illuvial accumulation of primary smectite clays in soils where leaching was reduced by the permeability of parent materials (Santos et al. 1985). A rich weathering environment is characteristic of the E horizon of a Solodized-Solonetz (Natriboroll) soil. This is due to strong potentials for both hydrolysis and oxidation-reduction, coupled with minimal leaching because of the impermeable nature of the underlying natric horizon. The presence of both secondary smectite and authigenic zeolites (calcium aluminum silicates) in the E horizon indicates that elements released by weathering have the opportunity to react and form new minerals (Spiers et al. 1984).

Organic cycling

The incorporation into organic cyles of the nitrogen and sulfur added to soil from the atmosphere is an important and self-renewing mechanism by which these elements build up substantial pools. This assures constant and generally enhanced levels of supply of these elements to the biota. Organic cycling, however, is of considerable importance to elements derived from the weathering of parent materials. Nikiforoff (1959) stressed the significance of the incorporation of mobile ions into organic tissues, thus protecting them against leaching or dissemination into space. Fortescue (1980) terms the humus layer in forests, particularly those that occur in strong leaching or eluvial landscapes, as a biogeochemical barrier to the loss of elements by leaching.

The significance of the biocycling of bases to the productivity of ecosystems increases as the degree of weathering or pedogenesis advances, even though smaller relative amounts of bases are recycled in highly weathered soils (Simonson 1970; Miller 1984). Most effective organic cycling or biocycling occurs when the vegetation present has a high requirement for bases, such as most deciduous species, and weatherable minerals are still present within the root zone. Poplar species return leaf litter with high concentrations of calcium, magnesium and potassium (Sanborn & Pawluk 1983), particularly when growing on calcareous parent materials.

The high uptake of bases, particularly calcium, by aspen increases the base content and pH of litter horizons, but may reduce exchangeable calcium and pH in the mineral soil (Alban 1982). The magnitude of this affect may depend upon the nature of weatherable minerals within the root zone. Where easily weatherable minerals are present, base supplies in the mineral soil could be maintained despite major transfers to the vegetation and forest floor.

The organic cycling of carbon, nitrogen, phosphorus and sulfur is the dominant process determining the supply of these nutrients in nearly all natural (not intensively fertilized) soils. Interactions among these cycles and the mineral portion of soils has been discussed earlier in this paper, pointing out that interactions among mineral colloids, organic matter and adsorbed or exchangeable cations are important to the storage and cycling of these elements. Studies of both native radiocarbon (Anderson & Paul 1984) and radioactive tracers (Christensen & Sorensen 1985) indicate the considerable importance of adsorption or protection by clay to this cycling. The amount of added ^{14}C retained in humic materials after incubation for five to six years increased with the clay content of soils (Christensen & Sorensen 1985). The effectiveness of different types of clay minerals in bonding organic polymers has been investigated in model systems (Greenland 1965), but it is difficult to apply these findings to the complex environments of soils. There appears to be only small differences in the capacity to adsorb organics among montmorillonite, illite, vermiculite and other mica (2:1 lattice) type minerals. Adsorption is affected by the density of charges on surfaces, but the surface area available for adsorption may be a more critical factor. With minerals of net negative charge, intermediary or cationic bridges are important bonding mechanisms (Greenland 1965). The nature of the cations vary with type of soil, with calcium dominant in less weathered soils such as Mollisols, and iron and aluminum of greater significance in highly weathered soils or soils formed on volcanic ash. Kaolinite and related minerals are different, with positive charges at the edge of kaolinite lattice enabling these clays to complex with anionic compounds.

A recent review concluded that organo-mineral complexes have a major role in pedogenesis (McKeague et al. 1986). A wide range of organics is involved, from simple organic acids to complex, high molecular weight polyelectrolytes such as humic acids. Similarly, a wide range of reactions occur. Some processes that involve simple organic acids or chelates make mineral soil components more soluble and mobile. Organo-mineral complexing appears to stabilize labile humic components and build up pools of importance to the medium-term cycling of nutrient, (Anderson & Paul 1984), whereas slightly different reactions result in the complexing of highly resistant humic materials in forms of limited biological significance.

These differences in type of reactants and reactions or processes may be demonstrated by considering those that occur in soil horizons and profiles of different environments (McKeague et al. 1986). Below ground additions of organic residues are dominant in Mollisols, decomposition is relatively rapid, humic constituents are of high molecular weight, rich in nutrients and complexed with mineral colloids by a variety of sorption reactions. These constituents are considered non-mobile and the translocation of organic matter is minimal. Processes are much different in Spodosol soils. Organic horizons develop on the soil surface, decomposition is relatively slow and low-molecular weight humic materials form. These simple constituents move to the mineral soil and are active in weathering, chelation and transport of elements. It appears that a key factor is the degree of association of organic materials with inorganic colloids during decomposition. Where close and intimate association results, whether as a result of addition below ground or mixing by soil fauna, organic matter and nutrient-rich horizons develop that are of considerable importance to nutrient cycling. In contrast, where decomposition occurs separate from mineral soil, as in the litter horizon of many forest soils, mobile and more soluble humic materials form that are active in the weathering and leaching of nutrient elements.

Continuing decomposition and the biological utilization of the more energy- and nutrient-rich humus results in the build up of strongly decomposed, highly resistant materials of limited biological importance. This is a long-term sink for any nutrients that remain complexed within these humic components. Strongly decomposed surface organic layers that build up in the cold environments of tundra soils, and the more humus layers of Spodosols, tie up an inordinate proportion of the nutrient capital present within those ecosystems (Everett & Brown 1982).

Phosphorus and pedogenesis

Phosphorus has received the most attention of the nutrient elements that are derived almost wholly from parent materials. This is probably a consequence of its low concentration within the lithosphere in comparison to plant requirements, and the complex and sequential nature of phosphorus reactions in soil.

Phosphorus makes up about 0.08% ($800\,\mu g\,g^{-1}$) of the lithosphere, but varies considerably with lithology. A detailed study of subsurface horizons in the humid tropics (Le Mare 1981) indicated average phosphorus contents of $263\,\mu g\,g^{-1}$ for acidic rocks, $164\,\mu g\,g^{-1}$ for intermediate crystalline rocks, $808\,\mu g\,g^{-1}$ for basic igneous rocks and $150\,\mu g\,g^{-1}$ for sedimentary rocks.

These values are lower than typical contents for these rock types on a world scale and appear to indicate some loss of phosphorus during the weathering of the rock to form the saprolite parent material of the soils, and weathering of the sedimentary materials prior to erosion and deposition.

The phosphorus contents of the unconsolidated parent materials of various origin in the glaciated parts of North America are generally in the range of 300 to 800 $\mu g\ g^{-1}$ P (Dormaar & Webster 1963; Runge & Riecken 1966; Smeck & Runge 1971; Roberts et al. 1985). Analyses of unpublished data at the Saskatchewan Institute of Pedology indicate a phosphorus content of 300 $\mu g\ g^{-1}$ for sandy parent materials, about 400 to 600 for medium textures and 800 $\mu g\ g^{-1}$ P for clayey sediments. A Spearman correlation of the clay and phosphorus contents of subsurface horizons (Roberts et al. 1985) gave a significant correlation ($r = 0.62$), but this is a small number of samples and may represent a negative correlation to sand content. An evaluation of size fractions of a sandy loam glacial till parent material indicates highest phosphorus concentrations in the coarse silt and fine clay fractions (Santos 1984). The mineralogical nature of this phosphorus is not known, but references to work on similar soils suggests that the sand and silt material is primary HCl-soluble calcium phosphates (apatite) and the fine clay material may be weathered or organically complexed forms of phosphorus formed in soils of a previous geological period that were incorporated into the till. Mineralogical analyses of sand and silt fractions of these parent materials indicates considerable weathering in an earlier soil or geological period (Mermut & St. Arnaud 1986). A concentration of total P and organic P in the clay fractions of soils in New Zealand (Syers et al. 1969), and a dominance of secondary forms of P indicates pre-weathering of the alluvial parent materials in a previous soil prior to erosion and subsequent deposition.

The progressive changes to phosphorus with weathering and leaching have been well documented (Walker & Adams, 1959; Smeck & Runge 1971; Walker & Syers 1976; Tiessen et al. 1984; Smeck 1985). With progressive weathering and leaching (at least in eluvial landscapes) phosphorus is converted from primary forms, such as calcium phosphates or apatite, to organic forms, iron and aluminum-based compounds or minerals of greater stability in soil environments. There are progressive reductions in total phosphorus as phosphorus is removed from the root zone by leaching (Walker & Adams 1959). This redistribution with depth because of biocycling and leaching results in pronounced eluvial zones, usually in the lower A and upper B, and illuvial phosphorus horizons deeper in the B or upper C horizons (Runge & Riecken 1966; Smeck & Runge 1971). The mechanism for phosphorus translocation is not completely understood. Complexing with iron has been suggested as a mechanism for retaining phosphorus in illuvial (B) horizons, with calcium – phosphorus complexes acting similarly in C horizons (Smeck & Runge 1971). Some phosphorus probably moves with the fine clay, since concentrations are highest in the fine clay fractions, but more soluble forms undoubtedly are involved. A comparison of grassland (Boroll) and forest (Boralf) soils on glacial till in Saskatchewan indicates essential differences in phosphorus transformations and translocations, that depend upon the relative degrees of weathering, the importance of organic cycling and the intensity of leaching (St. Arnaud 1986). Quantitative evaluations indicate that the Boroll has lost little phosphorus during its formation, although there has been a marked transformation to organic forms, and a concentration in the A horizon. Forty percent of the phosphorus originally present in the E and Bt horizons of the Boralf has been lost, with some small gains in lower horizons. These findings are consistent with the essential differences in organic complexes discussed by McKeague et al. (1986).

The mechanism by which phosphorus moves in soil requires further study. Research in high rainfall forests in Washington indicates that phosphorus moves mainly by the flushing effect of heavy rainfall following periods of decomposition during the warm and dry season (Riekirk 1971), probably in the form of simple organic (fulvic) acids. Phosphorus contents of fulvic acids are higher than other humus components (Batsula & Krivonosova 1973). Solubilization of organic nitrogen, mostly as fulvic acids, is a critical transport process for this element in soils under lodgepole pine (Fahey et al. 1985). The translocation of phosphorus and sulfur by the leaching of fulvic acids is a significant process in grassland and forest soils in Saskatchewan (Schoenau & Bettany 1987). Organic cycling, although a biogeochemical barrier to the loss of nutrients such as nitrogen, phosphorus and sulfur by leaching, may also be a process contributing to losses (Fig. 4). These losses occur mainly during critical periods when these nutrients are associated with soluble organic components and the soil is flushed by a heavy rainfall.

Research has indicated a considerable translocation of phosphorus within an Illinois landscape segment on Peoria loess about 20 000 years old (Smeck & Runge 1971). The landscape segment was 43 m long and decreased in elevation from the highest to the lowest position by only 6 cm. Surface water flow carrying phosphorus solubilized from organic residues was considered the most likely mechanism for the translocation. The lowest site gained 0.5 kg m^{-2} of phosphorus while the uppermost site lost 0.15 kg m^{-2}. Markedly higher concentrations of phosphorus, iron and manganese in a lowerslope soil as compared to a soil higher in a toposequence was considered to have resulted from the flow of dissolved constituents in water moving laterally on the surface of dense subsoils, by a process termed interpedon translocation (Schlichting & Schweikle 1980). Application of Simonson's (1959) postulate of the universality of processes within soils points to the possibility of phosphorus translocations within larger landscapes. Polynov (1951) listed phosphorus as a mobile element in a group with silicate SiO_2, that are less than one-tenth as mobile as sodium or potassium. Phosphate is a minor constituent of groundwater, with a concentration usually less than $0.1\,mg\,L^{-1}$ (Fortescue 1980). Thomas (1970), quoting from work done in 1921 prior to major pollution of surface waters, observed that the phosphorus content of surface and groundwaters ranged from 0.07 to $0.22\,mg\,L^{-1}$ and could be related to the phosphorus content of parent materials in the watershed.

The uptake of water and nutrients from deep capillary zones has been well documented (Fox & Lipps 1960), although the relative contribution of soil- and water-derived nutrients was not determined. A substantial contribution of water-derived nutrients would depend upon relatively high concentration of nutrients in the water, and a large uptake of water by the roots. Transfers of nutrients from one landscape element to another generally has not been considered a significant process in nutrient cycling, but this appears to be a hypothesis worth considering. Anomalously fertile soils on coastal lowlands may be receiving nutrients in groundwater flows (Liebhardt et al. 1976). These sandy and seemingly infertile soils generally do not show increased yields when potassium or phosphorus fertilizers are applied, and have high available potassium levels in early spring that decrease over the growing season. A net leaching regime in the soils may not be a reason to discount significant upward fluxes for short periods, particularly considering the sandy nature of materials and the dynamic nature of flows. Many of these soils show evidence of high watertables in their profiles (Daniels et al. 1971), although the soil properties examined most closely are clay mineralogy, iron oxides and mottling rather than those directly affecting nutrient supply.

Sulfur and pedogenesis

Sulfur minerals are of greatest importance in soils where their concentration is high and associated with undesirable soil properties. These include the acid sulfate soils where the oxidation of pyrite (iron sulfide) minerals results in high sulfate concentrations and extremely acid reactions. High concentrations of highly soluble or moderately soluble sulfate salts of sodium, magnesium and calcium occur in many saline soils. These soils have generally developed on gypsiferous parent materials originating as marine sedimen-

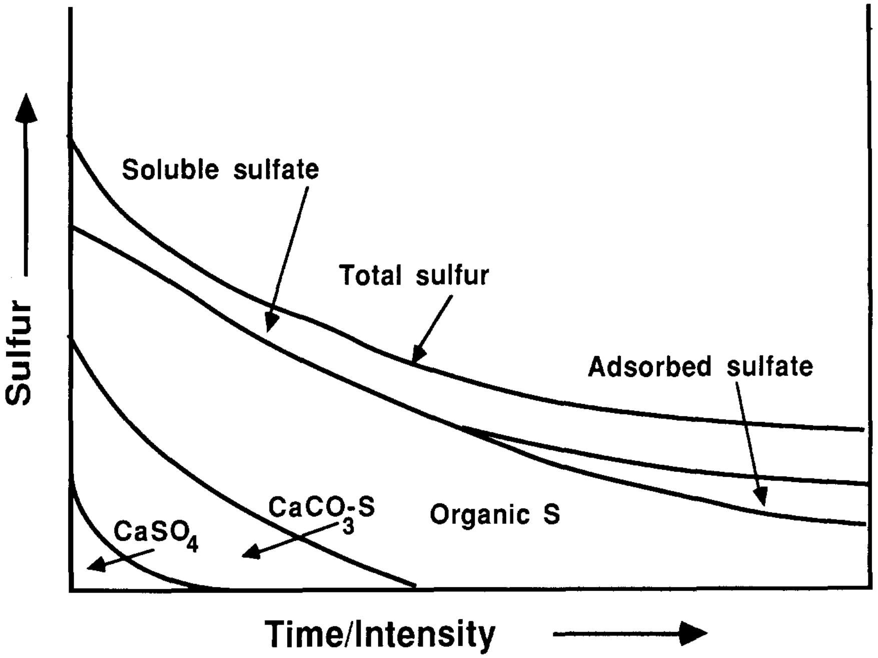

Fig. 5. Generalized sulfur forms with advancing soil formation, assuming constant and small atmospheric additions.

tary rocks (Nettleton & Peterson 1984), where gypsum-rich dust blows off playas or where sulfate is added by regional groundwater flows.

Mineral or inorganic forms of sulfur are of minor importance in most strongly leached, neutral to moderately acidic soils where organic cycling of sulfur is of much greater significance (Fig. 5). Adsorption by iron and aluminum oxides in soils of strongly acidic reaction, is an important means of sulfur retention in strongly weathered soils (Fuller et al. 1985). Other researchers, however, have presented evidence that sulfate is retained by precipitation reactions in the presence of aluminum at low pH, forming aluminum-hydroxy-sulfate minerals such as basaluminate and alunite (Hue et al. 1985). It appears that, regardless of the mechanisms, increased acidity and the presence of amorphous iron and aluminum promotes the retention of sulfate in strongly weathered soils.

There are, however, a range of moderately leached soils of sub-humid to semi-arid climates where both inorganic and organic cycling of sulfur is important (Roberts & Bettany 1985). Many of these soils have formed on calcareous parent materials of mixed mineralogy, and sulfate present as a co-precipitated minor component of $CaCO_3$ minerals makes up an important reserve, accounting for about 40% of the sulfur in subsoils. The less strongly leached soils of semi-arid regions contain high soluble-sulfate contents, probably as a result of the presence of partially soluble gypsum (Bettany et al. 1983). Gypsum occurs in the deeper subsoil of many of these soils and may be an important source of sulfur to crops late in the growing season. The amount of sulfur released by the weathering of the sulfur that is co-precipitated with $CaCO_3$ is determined by the sulfur content of the parent material and the intensity of weathering. More soluble forms such as gypsum are strongly influenced by the degree of leaching and the magnitude of any upward fluxes that may keep sulfate within the root zone. Secondary accumulations of gypsum (gypsic horizons) are largely a result of the weathering of sulfur minerals higher in the profile and the translocation of sulfate downward and precipitation of gypsum in the subsoil. The large amount of gypsum that is present in many subsoils in superaqual lands suggests that dissolved sulfate has been moved there by hydrological flows from adjacent eluvial landscape elements. Sulfate is not usually mineralized in excess of plant requirements (Maynard et al. 1985). An atmospheric origin via organic pathways is probably of minor significance for the sulfur present in gypsic horizons.

Sulfur deficiencies are most common in strongly leached soils low in organic matter, particularly those of neutral to weakly acidic reaction. Most hypotheses concerning loss of sulfur from these soils have implicated the leaching of sulfate anions, a method not completely consistent with low sulfate concentrations in natural (not cultivated) soils. Recent studies in Saskatchewan suggest that leaching in organic form, primarily as sulfur-rich soluble fulvic acids, may be a major factor in sulfur translocation in soils (Roberts 1985; Schoenau & Bettany 1987). Most of the sulfur in the fulvic acids found at depth was organic sulfate, accounting for nearly 100% of the organic sulfur in subsoils of a forest soil where no gypsum was present.

Aggrading and degrading soils

Jenny (1984), in discussing the long-term development of soils in relation to the ecosystem that the soil supports, said:

> On soft rocks the several dozens of time sequences so far on hand suggest that in high rainfall regions and in the absence of catastrophes, such as earthquakes and severe erosion episodes, the production of organic matter as biomass rises from near zero at the beginning of the sequence to a maximum in a few thousand years, and then very slowly declines because the endless water infiltration under high rainfalls leaches out the nutrients of the

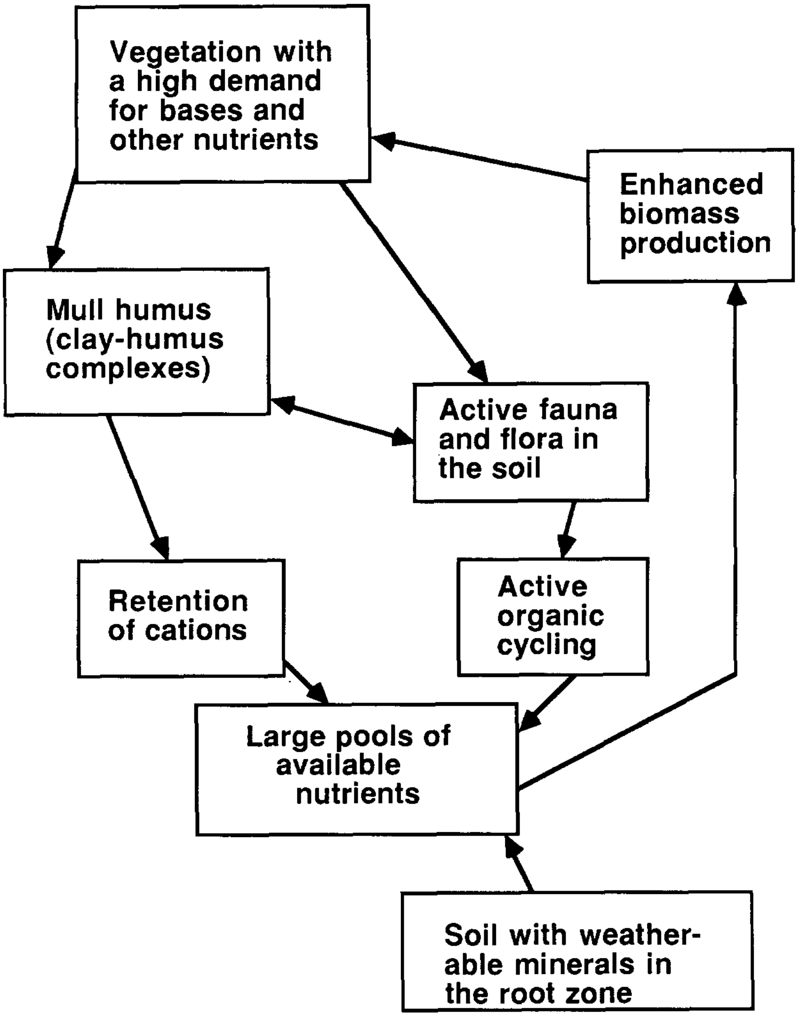

Fig. 6. The role of positive feedback in aggrading or stable soil systems.

soil, raises the acidity, and may establish hardpan and claypan horizons that curtail root growth.

This statement succinctly describes the aggradation and degradation of soils on eluvial landscapes where leaching potential is high. In aggrading stages there are initially the effects of the biota in stabilizing the soil against erosion, and providing many of the acidic biochemicals that promote the release of nutrients by weathering. Organic matter builds up in the soil, increasing the pool of organically bound nutrients, providing exchange sites for cations and enhancing the physical structure of the root zone. A response by which the completion of a process adds to controlling variables or forces, thereby amplifying the process, may be termed positive feedback (Torrent & Nettleton 1978). Additions of organic matter promote infiltration and moisture storage, enlarge nutrient pools and impart resiliency to the soil (Fig. 6). This in turn leads to greater organic production and a further improvement to the soil. Vegetation with strong requirements for nutrients and the high capacity to recycle bases is usually characteristic.

Degradation may be defined as the deterioration of a soil ecosystem, as it becomes less productive or less resilient. These processes may be very slow, or quite rapid in instances where a change in climate results in a major change in vegetation. The forest invasion of grasslands results in a change from well-structured and generally neutral or weakly acidic soils to more strongly leached and acidic soils with a deteriorated root zone because of the development of clayey, Bt (argillic) horizons (Geis et al. 1970; Severson & Arneman 1973). The dominant additions of organic residues to the soil surface rather than below ground changes organic matter processes, reducing the pool of organically bound nutrients, the fertility of the site and the capacity of the soil to retain exchangeable cations. The result is a gradual degradation in the quality of the soil as a medium for the biota.

In other situations the degradation of soils may be so slow so as to be insignificant and soils may be considered to be mature or at equilibrium. This is characteristic of ecosystems where subsoils with a variety of weatherable minerals maintain the supply of nutrients and bases, organic cycles that usually involve strong interactions between organic and mineral colloids (usually abetted by faunal mixing) are efficient and minimize the loss of nutrients by leaching, and a rich flora includes nitrogen-fixing species.

Negative feedback occurs when a process carried through to completion decreases the level or dampens the effectiveness of a variable controlling the process. Once degradation begins it appears that negative feedback is an important process. Slightly lower fertility and increased acidity renders the site less suitable for plants with stringent edaphic requirements. This permits greater competition from those plants that are able to grow in less fertile, acidic soils. The residues of these plants, however, are less rich in bases and nutrients and may decompose more slowly but release more organic acids. This results in a further decrease in fertility and greater acidity, thereby making the soil more suitable for the species that have started the downslide.

Not all landscape elements are equally susceptible to soil degradation, in that leaching potentials vary. Strongly convex and sloping surfaces lose both water and soil in runoff, leaching is reduced and soils remain weakly developed and in early stages of aggradation (King et al. 1983). Lowlands, in the superaqual elemental landscape (Polynov 1951), may be influenced by upward fluxes due to capillary rise from water tables or artesian pressure.

This dampens leaching at minimum, and adds to the content of bases and, perhaps, nutrients in the soils. The extreme examples of these processes occur where high evaporation from the soil surface and minimum precipitation results in the undesirable buildup of soluble salts and sodium in lowland soils. Increased leaching in many lowland soils, usually a consequence of the collection of extra moisture due to the configuration of the land surface, results in the aggradation of saline soils in that the undesirable salts are moved deeper into the soil and out of the root zone. This is characteristic of the classical sequence of development of salt-affected soils through saline/sodic (solonchak), solonetz, solodized-solonetz to deep solod soils (Joffe 1936).

Concluding discussion

Soil formation occurs in an open system in which the environment (factors) and intensity of processes vary in three dimensions. Pedologists have structured their studies of soil formation and classification by selecting as their object of interest a volume of soil termed the pedon, with lateral dimensions of about one metre and vertical dimensions from the surface to the depth of soil formation. The different nature and varying intensity of soil-forming processes with depth results in the formation of soil horizons. Horizons can be considered to be the functional portions of a complex system, akin to the organs of an organism (Nikiforoff 1959). Continuous performance of these functions imparts to each horizon its individual chemical and morphological character. Horizons and particular arrangements of horizons can be viewed as an integration of soil-forming processes over time. It is, however, difficult to interpret this record in terms of process. Most studies of soil development have a first step of detailed characterization of the morphology (arrangement and character of horizons), micromorphology, and chemical and physical properties of the pedon. Essential subsequent steps are the interpretation of properties in terms of process and the extension of the findings based on pedons to the soil landscape or continuum (Brewer & Sleeman 1970). A goal of modelling at ecosystem, region or global levels is to generalize these findings to real portions of the terrestrial surface.

Soil profiles, in essence, are a composite of individual profiles or curves of the various properties with depth and, by extension, the intensity of the reactions imparting the properties. This brings us to an interesting quandary in modelling soil systems. Should we recognize horizons *a priori*, that is model or vary the nature and intensity of processes with depth based on known characteristics of the soil profile; or is it better to vary the intensity of reactions or processes systematically with depth and use the nature of the horizons developed as a natural test of the model's appropriateness? The second alternative appears more suitable, but may not be practical in terms of slow processes such as mineral weathering where the time dimension is long and only known in relative terms.

Another precept requiring mention here is Simonson's (1959) postulate that all soil-forming processes are active to some degree in all soils and it is the balance of the processes that determines the ultimate nature of the soil profile. This implies that models should not be required for the myriad of kinds of soil, just one model based on sound principles and sensitive to the driving variables that direct and energize soil-forming processes. This is a tall order but it does focus our task. The integration of the processes at any point in space or time, or the soil profile, becomes a validation of the model for a particular group of variables. Soils at the extreme ends of spectra may be as important as more common soils, in that they are tests where certain processes or variables become strongly dominant. An example of this is the organic matter model developed by Paul & van Veen (1978), applied to boreal, temperate and tropical climatic regimes. Its performance under these extremes demonstrated that it was based on sound principles of process. I am confident that the number of scientists now considering more general models at global scales can use the same principles to evaluate their own efforts.

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