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Soil chronosequences, soil development, and soil evolution: a critical review

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Abstract

Soils chronosequences are valuable tools for investigating rates and directions of soil and landscape evolution. Post-incisive chronosequences are the most common type of chronosequence. They are found in many landscapes, including sand dunes, glacial moraines, landslide scars, old pasture, burnt landscape patches, old mining areas, lava flows, alluvial fans, floodplains, river terraces, and marine terraces. They register pedogenic change over time-scales ranging from years to millions of years. Soil chronosequences help in testing rival theories of pedogenesis. Traditional soil formation theory sees a soil developing progressively under the influence of the environmental state factors until it is in equilibrium with prevailing environmental conditions. This developmental view of pedogenesis is supported by the classic soil chronosequence studies. A new evolutionary view of pedogenesis, which was prompted by the omnipresent inconstancy of environmental conditions and the notions of multidirectional changes and multiple steady states (as predicted by non-linear dynamics), proposes that environmental inconstancy and non-linear behaviour in soil-landscapes lead to soil evolution, rather than to soil development. Soils 'evolve' through continual creation and destruction at all scales, and may progress, stay the same, or retrogress, depending on the environmental circumstances. Some recent soil and vegetation chronosequence investigations support an evolutionary view of pedogenesis. It is concluded that soil chronosequences are still potent instruments for pedological investigations and that they have a starring role to play in the testing of pedological theories. © 1998 Elsevier Science B.V. All rights reserved.

Keywords: Chronosequence; Pedogenesis; Soil chronosequence; Soil development; Soil evolution

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1. Introduction

Soil chronosequences are genetically related suites of soils evolved under similar conditions of vegetation, topography, and climate (Harden, 1982). They translate spatial differences between soils into temporal differences. The translation hints at the way that soils and soil properties in given regions change through time (cf. Vincent et al., 1994). Soil chronosequences were once relatively rare, but the number of well-documented and reliably dated examples is mounting very fast. Most of them show an exponential (or sometimes linear) increase or decrease in soil properties with time, as would be expected from the laws of chemical kinetics. Soil chronosequences are excellent indicators of the rate and direction of pedogenic change, and they provide invaluable information for testing theories of pedogenesis. Also, they are central to much soil–geomorphic research (Birkeland, 1990, 1992), and they may be used (with caution) to date a range of Quaternary landforms, including stream terraces.

Several excellent reviews of soil chronosequences are available (Jenny, 1941, 1980; Burges, 1960; Rode, 1961; Walker, 1966; Stevens and Walker, 1970; Vreeken, 1975; Yaalon, 1975; Bockheim, 1980; Birkeland, 1990). The present review focuses on three things. First, it briefly considers the construction and classification of soil chronosequences. Second, it describes studies of historical, Holocene, and Quaternary soil chronosequences, mainly to illustrate the wide range of settings in which chronosequences are now investigated. Third, it considers two rival theories of pedogenesis—the developmental and the evolutionary—and briefly explores the evidence for them in chronosequence investigations.

2. Constructing and classifying soil chronosequences

One of the most significant discoveries made in pedology was that soil profiles record their own history (Yaalon, 1983, p. 233). However, the pedological 'historical record' is normally incomplete and ambiguous, and changes in soils are therefore difficult to reconstruct. Soil chronosequences greatly aid the reconstruction process. Most soil chronosequences are established using the comparative geographical technique (Rode, 1961). This involves arranging soils of different age, and so from different locations, into a time sequence. As a technique, it rests upon assumptions that are normally unstated (cf. Vreeken, 1975). A central assumption is that the soils in the identified sequence represent successive stages of one or several pedogenic processes. Furthermore, it is assumed that the soils pass through stages characterized by some preceding member of the successional sequence (cf. Rode, 1961, p. 28). These assumptions underpin two different methods of constructing soil chronosequences. One method draws upon the traditional technique for identifying successional sequences in vegetation. It involves looking for the various stages of a developmental soil sequence in modern soil–landscapes. By identifying the different stages and placing them in a supposed chronological order, a chronosequence is inferred. A well-known sequence of this kind is the development of a lithosol formed in marly limestone, through a rendzina, brunified rendzina, calcareous brown soil, and calcic brown soil, to a lessived brown soil. This method rests on very shaky foundations and is no longer widely used. The chief weakness is that the age of different soils in the assumed sequence is at best educated guesswork. In addition, it supposes that, for example, rendzinas will evolve into brown soils under all circumstances. This supposition is suspect because rendzinas on steep slopes may be roughly in balance with local soil-forming factors and 'progress' no further. For these reasons, and others that will be elaborated later, strict adherence to a monosequential notion of soil chronosequences is unrealistic (cf. Vreeken, 1975). As Rode sagely said, ''the bulk of pronouncements on soil evolution [*qua* development] advanced by the geographical method alone have to be considered as rather more or less probable hypotheses which require the application of other methods for rigid proof in their support'' (Rode, 1961, p. 30). This admonitory statement is as relevant today as it was nearly 40 years ago.

A far securer way of constructing geographical soil chronosequences is to use soils that have developed on surfaces of known age, and that either have persisted through to the present day or else have been buried beneath a sedimentary cover. Sequences of alluvial fans, alluvial terraces, coastal sand dunes, lava flows, and moraines have proved particularly fruitful sites for this purpose; abandoned pasture, earthflows, mudflows, fire-cleared areas, landslide scars, historically created polders, loess deposits, strandlines, and other datable landscape features are also usable.

Geographical soil chronosequences dominate the literature on the subject, but other time sequences of soils are possible. Vertical chronosequences (Stevens and Walker, 1970), for instance, consist of buried soils sandwiched between successive sedimentary formations. Vreeken (1975) did pedology an enormous service by identifying four principal types of soil chronosequence. He argued that, if different soils should have evolved for different lengths of time, then they must have started evolving, or stopped evolving, or both, at different times. Soils that started evolving at the same time possess isochronous incipience; soils that started evolving at different times have time-transgressive incipience. Similarly, the times when soil evolution stopped may be isochronous or time-transgressive. Additionally, pedogenic start and stop times may, or else may not, overlap historically in different soils. These various possibilities produce the four principal kinds of soil chronosequence. First, post-incisive sequences occur where the start times are time-transgressive but the stop times are isochronous (and are often the present day). The term 'incisive' is used here to signify the geomorphic or human 'incisions' in the landscape that bury older surfaces, or create of new surfaces, or both. Post-incisive sequences contain soils that have evolved in sequence at successively later times. They are by far the most commonly studied kind of chronosequence, and result from post-incisive events producing a sequence of progressively younger surfaces in which soil evolution may begin. An example is soils formed in alluvial terraces. Commonly, alluvial terraces from a staircase within a river valley. In stepping down the staircase, soils become progressively younger. The soils forming in each tread form a chronosequence; at least, they do if it is assumed that the soils on the younger terraces will evolve into the soils on the older terraces. Second, pre-incisive sequences occur where the pedogenic start times are isochronous but the stop times time-transgressive. They contain soils that started to evolve at the same time, but which have been selectively and successively buried by pre-incisive events. An example would be soils evolved in a newly exposed glacial till that has been gradually covered by another deposit, so stopping pedogenesis and burying soils at different stages of evolution. Third, fully time-transgressive sequences with partial historical overlap occur where the pedogenic start and stop times are both time-transgressive but coeval in part. They consist of a mixture of buried and relict soils produced by erosion and deposition. An example is a complex of buried and surface soils in lateral moraines, Bugaboo Glacier area, British Columbia, Canada (Karlstrom and Osborn, 1992). And four, fully time-transgressive sequences with no historical overlap occur where the soils in question were never coeval. They are found in vertical sequences of soil–landscape units, such as those found between successive sedimentary units. In addition, the ‘geological palaeosols’ dating back to Precambrian times form a very disjointed chronosequence of sorts (e.g., Retallack, 1990, 1992).

Chronosequences may also be classed according to the time resolution on which they are based. At one extreme, the land surfaces (present ground and buried) on which the soils are evolved are not well known and are given relative ‘ages’ by applying the principle of superimposition. These may be thought of as ‘ordinal’ chronosequences, by analogy with ordinal data—the sequence of events is known (or at least guessed at), but the timing is not. An example is work on Holocene fan and floodplain deposits in Gandak megafan and adjoining Middle Gangetic Plains, India (Mohindra and Parkash, 1990). Clay minerals in these deposits reflect the duration of pedogenesis, but time is resolved on an ‘ordinal’ scale—young soils (active floodplain and young plain of the Gandak), older soils (older Gandak Plain), and still older soils (oldest Gandak Plain). At the other extreme lie ‘ratio’ soil chronosequences where the age of the landforms in which the soils have evolved is established by geochronometric techniques. Between these two extremes lie chronosequences calibrated using more sophisticated relative dating techniques. These methods rely on indices of change in parent materials (commonly sediments) after deposition. The degrees of rock surface weathering and of soil development are widely used as indicators of age. Relative dating has had some successes, but it should be treated guardedly. In glacier forelands, for example, environmental and sedimentological factors, which can influence commonly used relative-dating variables, may exhibit systematic variations in parallel with, but independent of, surface age, and so invalidate the assumed rates of soil change (McCarroll, 1991; see also Kroonenberg et al., 1990).

The building and interpreting of soil chronosequences are hampered by several well-known problems (e.g., Birkeland, 1990; Gerrard, 1992). A major difficulty is holding all soil-forming factors constant except time. In particular, climate is highly unlikely to have held steady, even for short periods, and topography and vegetation are unlikely to have remained unchanged for millennia or more. If topography should change, then it may or may not be true that a chronofunction (a soil property plotted against soil age) reflects a single pedogenic process acting without interruption from geomorphic processes. In some locations, notably in arid environments, soils form chiefly in aeolian sediments and evolve as dust accumulates. At the same time, the dust deposits tend to fill in topographic lows, so reducing the local relief. Soil chronosequences can be established in such environments. In any environment, mass movements remove and bury pre-existing soils and reset the chronosequence clock to zero. Pedogenic thresholds create problems as they may produce soil profile characteristics that are very like soil profile characteristics created by climatic change. Only in closely dated chronosequences is it possible to untangle the two sets of effects. Another point to remember is that not all changes in soil processes nor all events in soil history are recorded a soil profile—a chronosequence is only a partial record of the past. And, it may be a biased record, leaving more evidence of resistant soil constituents, such as duricrusts, than of rapidly changing soil properties such as pH and nitrogen content (cf. Yaalon, 1971). A practical difficulty lies in finding pedons on dated surfaces that are suitable for chronosequence work. Magnetic susceptibility measurements may be helpful in assessing the uniformity of pedogenesis and thus indicate pedons that might be used in chronosequence construction (Fine et al., 1992). Magnetic susceptibility measurements may also be used to estimate soil age, at least under certain climates (Singer et al., 1992). A final difficulty is that traditional forms of soil survey (including mapping, profile description, and analysis by horizon), in conjunction with simple transect or random sampling approaches, are inappropriate for the detailed quantitative investigation of soil chronofunctions. Most soil surveys focus on agricultural properties of soils, which are usually uninformative about long-term soil evolution. Seeking the environmental factors that control or influence rates of soil development requires a non-traditional approach. One suggestion is to use stratified sampling of the best developed soils within time zones and topographic site-types, followed by soil property analysis on samples collected at specified depths (Messer, 1989).

Despite the problems involved in their construction, there is no doubt that soil chronosequences are immensely powerful tools for probing the rate and direction of soil evolution (e.g., Walker and Syers, 1976; Crews et al., 1995; Schaetzl et al., 1994). Indeed, they are the only way of establishing how pedogenesis operates over centuries and longer periods. Well-dated chronosequences are therefore a boon to pedologists. They are also invaluable to geomorphologists, for, once a soil chronosequence is established, it may be used to investigate other landscape processes. A podzol chronosequence in the Scottish Highlands has furnished information on saturated hydraulic conductivity changes in each horizon over the last 13,000 years; this information can be used in interpreting changing runoff process and slope stability (Brooks and Richards, 1993). Two alluvial fan chronosequences in the Negev Desert have yielded information on the gravel shattering process in reg soils (Amit et al., 1993). In some cases, soil chronosequences may be used to date land surfaces—known relationships between soil properties and time are used to gauge the age of landforms. This is probably a reasonable practice in cases where geochronometric ages cannot be ascertained. But it is a relatively crude tool—soil property estimates of Quaternary deposits and faulting events give errors of ±50%, or even more (Birkeland, 1990). The problem of using soils as a geochronometric tool is also demonstrated by a study of spatial soil variability in the well-dated Cajon Pass chronosequence, southern California (Harrison et al., 1990). It was found that the influence of aeolian silt on pedogenic rates meant that the sequence is not strictly a chronosequence. Furthermore, the evidence for a pedogenic threshold in these soils indicates that the soils do not develop monotonically with time and that soil development cannot be defined by a continuous univariant chronofunction. The discrete nature of the data from a chronosequence and the complex nature of soil development are better analysed by multivariate statistical procedures. Of course, where soil–time relationships are used as a crude dating tool, the dated surfaces cannot then be used to estimate rates of pedogenesis.

3. Studies of soil chronosequences

Soil chronosequences record pedogenic change over several time-scales—years to centuries, millennia, hundreds of thousands of years, and even millions of years. Chronosequences evolved during the last millennium or so might be called historical chronosequences to distinguish them from older Holocene and Quaternary chronosequences. The classic work on soil development on moraines left in the wake of retreating glaciers and on coastal sand dune systems established historical chronosequences. More recent work on historical chronosequences uses a much wider range of dated surfaces. Landslide scars, old pastures, mined areas, and burnt landscape patches have yielded information on various aspects of short-term pedogenesis. During the Holocene and Quaternary, geomorphic change has produced a selection of datable surfaces that form a basis for chronosequence construction. Lava flows, a range of fluvial landforms (alluvial fans, terraces, and floodplains), and old coastal sand dunes have been of great service to soil chronosequence builders. This section takes selected examples to illustrate the full sweep of soil chronosequence investigations carried out today (see also Table 1).

3.1. Glacial moraines

Glacier retreat in historical times has led to many fine soil chronosequences evolving in moraines. A classic study is the 220-year chronosequence (and related vegetation succession) in Glacier Bay, National Park, Alaska (Crocker and Major, 1955; Olson, 1958). Neoglacial moraine ridges in southern Norway have provided several suitable sites for soil chronosequence investigations (e.g., Mellor, 1987; Matthews, 1992).

3.2. Sand dunes

Coastal sand dunes commonly comprise a set of dune ridges separated by slacks. The dunes often lie roughly parallel to the coast, the youngest lying nearest to the sea. They thus provide a sequence of dated surfaces suitable for chronosequence work. Indeed, a sand dune sequence on the Lancashire coast, England, was used in a classic study of a soil (and vegetation) time sequence (Salisbury, 1925). Many recent soil chronosequence studies also employ sand dune systems. For instance, a soil chronosequence evolved in late Holocene dunes along Lake Huron, south-western Ontario, Canada, displayed progressive features of soil weathering (VandenBygaart and Protz, 1995). The plainest indications of progression were an increasing solum thickness and a darkening of chroma in B horizons. Total organic matter in the profiles increased logarithmically with soil age, the fastest change occurring in the first 2000 years or so. The depth to, and thickness of, the B horizons, and the depth of $CaCO_3$ leaching, all increased linearly with increasing soil age. Soil pH decreased linearly with soil age for the first 2900 years, but after that time, spatial differences in vegetation appear to have influenced the pH and thus pedogenesis.

A variation on the sand-dune chronosequence theme comes from Late Pleistocene sand dunes at Tomago, on the east coast of Australia, that have been rehabilitated after sand mining (Prosser and Roseby, 1995). The rehabilitation involved spreading stock-piled A1 horizon material over mixed A2 and B horizon materials from the original humus podzols. A four-stage chronosequence of 1, 5, 11 and 17 years since soil rehabilitation was established. Eighty-one percent of the leaching occurred between 1 and 5 years after soil rehabilitation, at a mass loss rate of 3.0 t ha^{-1} yr^{-1}. Such rapid leaching led to thicker A2 horizons than before mining, which fact was attributed to physical destruction of the indurated B1 horizon and its homogenization with A2 and B2 material to form a permeable mass containing easily translocated forms of iron and aluminium.

3.3. Landslide scars

Landslides strip the soil leaving patches of regolith within which pedogenesis starts anew. Where landslide scars can be dated, a soil chronosequence can be established. For example, a soil chronosequence is formed in landslide scars, ranging in age from 1 to 55 years, in the Luquillo Experimental Forest, Puerto Rico (Zarin and Johnson, 1995). The chronosequence shows that the base saturation index in surface mineral soil (0–10 cm) increases during primary succession; that the base saturation index and major nutrient cation concentrations are extremely low on new landslide scars; that, when initial conditions are oligotrophic, both nutrient cation pools and the base saturation index can increase in the surface mineral soil during early pedogenesis; and that the production and decomposition of soil organic matter is the dominant process controlling capture, retention, and within-ecosystem cycling of nutrient cations in the forests.

3.4. Old pasture

Pasture that has been abandoned for varying periods provides a ready-made chronosequence for rapidly changing soil properties, such as carbon and nitrogen levels. An example of this is a study of net nitrogen mineralization and net nitrification along a tropical forest-to-pasture chronosequence in the western Brazilian Amazon Basin state of Rondonia (Piccolo et al., 1994). Present forest and pasture of three different ages—3, 9, and 20 years—were used. The natural abundance of ^{15}N in soil profiles along two chronosequences was investigated. One chronosequence consisted of forest and 3-, 5- and 20-year-old pasture, the other of forest and 8- and 20-year-old pasture. Pasture surface soils were 1–3 per thousand depleted in ^{15}N compared with forest soils. The $\delta^{15}N$ values in 20-year-old pastures were consistent with greater cumulative inputs of ^{15}N-depleted atmospherically-derived nitrogen, fixed by free-living bacteria associated with planted pasture grasses in older pastures, or differential plant utilization of soil inorganic nitrogen pools with different δ^{15}N values.

Table 1
Some recent soil chronosequence studies

Site characteristics	Location	Main soil changes studied	Reference
Years to centuries			
Forest and old pasture	Rondonia, western Brasilia	Soil nitrogen	Piccolo et al. (1994)
Current and old pasture	Sevilleta National Wildlife Refuge, New Mexico, United States	Soil carbon and respiration	Kieft (1994)
Clear-cut mixed-conifer stands	Sierra Nevada, northern California, United States	Soil nitrogen mineralization	Frazer et al. (1990)
Mown grasslands (unfertilized for 2, 6,9, and 45 years)	Anloébrdiepje, The Netherlands	Nitrogen mineralization	Olff et al. (1994)
Forelands of Athabasca glacier	Canada	Soil nitrogen	Kohls et al. (1994)
Sand dunes	Westhoek Nature Reserve, Belgium	Horizon thickness, litter content, humus content	Ampe and Langohr (1993)
Holocene			
Andesitic ocean beach-ridge sediments	Costa Rica	Weathering and neoformation of minerals	Nieuwenhuyse et al. (1994)
Beach-ridge plain	Moruya Heads, New South Wales, Australia	Horizon thickness, chroma, pH, depth to leaching front, acid-extractable aluminium, calcium, iron, magnesium, manganese, and sodium	Bowman (1989)
Alluvial fans	Negev Desert, Israel	Gravel shattering by salts	Amit et al. (1993)

River terraces	Western Cairngorms, Scotland	Exchangeable calcium, magnesium, sodium, and potassium; base saturation; clay type	Bain et al. (1993)
Quaternary			
Alluvial terraces	Appalachian Highlands, south-eastern United States	Clay content, rubification index, iron oxide content, elemental ratios	Leigh (1996)
Alluvial terraces	Cowlitz River, south-west Washington, United States	Profile morphology and thickness; dithionite-extractable iron, pedogenic clay	Dethier (1988)
Alluvial surfaces	Inner coastal plain, central Virginia, United States	Soil type, duripans, incipient plinthite, ferricrete, weatherable minerals	Howard et al. (1993)
Marine terraces	California, United States	Dithionite- and oxalate- extractable iron and aluminium	Aniku and Singer (1990)
Alluvium	Rock Creek, south-central Montana, United Sates	Clay mineralogy	Reheis (1990)
Coastal dunes	Cooloola and North Stradbroke Island, southern Queensland, Australia	Podzol morphology, organic matter composition, elemental composition, (C, Si, Fe, Mn, P, Ti, Zr)	Thompson (1992); Skjemstad et al. 1992)
Volcanic rocks	Hawaii	Soil phosphorus	Crews et al. (1995)
Volcanic rocks	Hawaii	Nitrogen	Kitayama et al. (1995)
Volcanic rocks	Islands in south-western Pacific	Ferralitization; silica–alumina ratio	Zamotayev and Targulian (1994)

3.5. Burnt patches

Fire creates burnt patches that are open to vegetation colonization and renewed surface-soil evolution. Repeated fires within an area produce patches of varying age, so creating a chronosequence. For example, the effect of recent fire history and successional stage were evaluated in soils from a steep semiarid shrubland chronosequence in south-east Spain (Carreira et al., 1994). A single fire significantly increased soil mineral nitrogen availability and net nitrification. An increasing fire frequency in the last few decades was associated with a sharp decrease in surface soil organic matter and total nitrogen concentrations and pools, and with changes in the long-term nitrogen dynamic patterns.

Another study investigated forest-floor regeneration after fire in Catalonia, Spain. (Ferran and Vallejo, 1992). The area considered was a holm-oak (*Quercus ilex*) forest frequently suffering wildfires. Bulk samples from the L, F, and H layers were taken in five burned plots, aged from 0 to 35 years. They were analysed for dry standing weight, and organic carbon and nitrogen content. Within 2 years of a fire, plant cover reached almost 100%. Shrubs and herbs dominated the cover for 20 years, after which time holm-oaks became dominant. The litter decay coefficients were relatively high, allowing for a rapid structuration and formation of the L and F layers after the fire. Indeed, 95% of the maximum steady standing weight accumulated in 8–9 years.

3.6. Old mining areas

There are instances where past mining activity has left a series of land surfaces of different ages, in each of which soil genesis has proceeded. An example, is the chronosequences produced by phosphate mining on the island of Nauru (Manner and Morrison, 1991). This island, which at 21 km^2 is the world's smallest republic, lies halfway between Australia and Hawaii. A central plateau is rich in phosphate deposits. Mined areas of phosphate ranged from less than 1 year old to 55 years old. Soil carbon and soil nitrogen increased from 0.41–0.48 to 4.56 and from 0.03–0.04 to 0.32%, respectively. The final figures are comparable to concentrations in nearby undisturbed soils. Soils evolved faster in unconsolidated sands and limestone rubble in mining pit bottoms than they did on dolomitic limestone pinnacle surfaces.

3.7. Lava flows

Many volcanoes obligingly produce lava flows in discrete episodes throughout their active phases. The dates of these flows are often known for historical times, or can be dated with a high degree of precision. Lava flows around a particular volcano thus enable a reliable chronosequence to be constructed. An example is the weathering of volcanic pumices on Mont Pelée, Martinique, in the Caribbean (Quantin et al., 1991). The chronosequence comprises three main deposits, dated at 48, 650, and 1670 years, covering the mountain massif. The initial pumices are essentially glassy, rich in silicon and aluminium, calcium and sodium. Within the period covered by the chronosequence, the weathered horizon reached a depth of 30–50 cm, and the median size of particles decreased from approximately 2 to 0.2 mm.

3.8. Fluvial landforms (fans, floodplains, and terraces)

Several fluvial landforms tend to form episodically and to produce surfaces of differing age. These landforms provide fertile hunting grounds for seekers of soil chronosequences. Investigations of alluvial fans, floodplains, and river terraces have all proved especially rewarding in the search for suitable time sequence.

Flights of river terraces provide many soil chronosequences. In the Reefton area of New Zealand, a sequence of dated river terraces has produced a chronosequence with soils ranging from a Dystric Fluvisol on the youngest surface, through Dystric Cambisols on middle terraces, to Gleyic Podzols on the higher terraces (Dawson et al., 1991). Silicon, titanium, and vanadium (extracted by hydrofluoric–perchloric acid digestion) have accumulated in the soils over 130,000 years (on a mass/volume basis), as would be expected given their slow loss during weathering. With the exception of titanium, all the elements have become depleted by over 50% of the original mass within 100,000 years.

Four soil chronosequences developed in gravelly alluvial fans in the southern Great Basin, United States, were examined to quantify and help understand soil development during the Quaternary (Harden et al., 1991). The four soils are formed in granite–gneiss, granite and basalt, limestone, and siliceous volcanic rocks. The ages of the soils were approximated from several radiometric and experimental techniques, and rates were assessed using a conservative mathematical approach. Holocene soils in all areas appear to have developed at similar rates, and Pleistocene soils at two of the sites may differ by only a factor of two to four. A preferred model for the age curves over long time intervals is not linear, but may be exponential or parabolic, with rates decreasing with increasing age. It was deduced from these preliminary results that the geographical variation in soil development rates within the southern Great Basin–Mojave region may be much less significant than temporal variation. The reasons for temporal variation in rates are linked to climatic change and related changes in water and dust, erosional history, and internally driven chemical and physical processes.

3.9. Marine terraces

Quaternary marine terraces may be suitable for constructing soil chronosequences. In northern California, United States, a chronosequence was built from six soil profiles formed in unconsolidated, sandy-marine, and aeolian parent material deposited on bedrock marine platforms that range from a few years old to 240,000 years old (Merritts et al., 1992). Soil evolution has been dominated by a depletion of silicon, calcium, magnesium, potassium, and sodium; by an enrichment of phosphorus in surface soil horizons; by a relative immobility of iron and aluminium; and by a transformation of iron, silicon, and aluminium in the parent material to secondary clay minerals and sesquioxides. Net mass losses of bases and silicon have been generally uniform with depth, and in some cases have approached 100%. However, the loss rate of each element is markedly different, so that the rank order according to relative abundance shifts with time.

4. Theories of pedogenesis and chronosequence studies

Empirical investigations in science normally rest upon a theoretical base. New observations sometimes call for a change in the theory. This interplay of theory and observation is how science works. Commonly, the big theories (megatheories) become entrenched in the lore of a discipline and are enormously difficult to budge—they become ruling theories or paradigms. In pedology, soil-formation theory is a well-established paradigm that arose in the closing decades of the nineteenth century. It originally postulated that soil genesis is a product of essentially downwards acting processes that lead to two sets of interrelated layers—the A horizons and the B horizons, which together constitute the solum. Eluviation washes solutes and fine-grained materials out of the A horizons and deposits them in subjacent, illuvial B horizons. Continued eluviation and illuviation produce coarse-textured residual A and E horizons over heavier-textured B horizons. Under some conditions, organic matter accumulates as distinct O horizons that lie on top of the uppermost A horizon. Later, it was realized that some soil processes mix soil materials and in doing so tend to destroy soil horizons. Soil-formation theory was then modified to include the effects of horizon creation (horizonation) and horizon destruction (haploidization) (Hole, 1961). According to soil-formation theory, the nature and rate of pedogenic processes are regulated by 'factors of soil formation'—climate, organisms, relief, parent material, and time (Jenny, 1941). This factorial–functional approach to soil genesis, which had a far-reaching impact in many environmental sciences, was the ruling theory until recently (see Johnson and Hole, 1994). However, soil-formation theory is now challenged by an evolutionary view of pedogenesis.

In its traditional version, soil-formation theory assumes that a soil forms or develops progressively under the influence of the environmental state factors. The developmental sequence continues until the soil is in equilibrium with prevailing environmental conditions. Once equilibrium is achieved, the soil will be a mature (or normal), zonal soil (e.g., a podzol or a chernozem) and will change no more (or at least until interrupted by geomorphic processes). This idea was borrowed by Marbut from Davis's 'geographical cycle' concept (Davis, 1909), in which the landscape develops progressively from 'youth' to 'maturity' (and ultimately 'senility') (see Jenny, 1941). The same notion found expression in the developmental view of plant succession as proposed by Cowles (1899) and Clements (1916), in which new surfaces will be colonized in a definite sequence until a climatic climax vegetation is created that endures indefinitely.

Two recent developments have undermined the hegemony of the developmental view, both in pedology and in vegetation science. First, empirical work on environmental change shows that inconstancy, not constancy, of environmental conditions is the norm (Huggett, 1997). Considering this fact, it is improbable that a developmental soil sequence will ever run its full course under a constant environment.

Second, it has been found profitable to regard all ecospheric systems (including soils) as dissipative structures forced away from equilibrium states by driving variables. Such structures are dynamical and non-linear. In dynamical systems, there is a turnover of materials through ongoing additions, loses, transfers, and transformations (cf. Simonson, 1959, 1978). In addition, state often changes owing to adjustments between inputs, outputs, and storage. Net loses, net gains, and steady states of soil nitrogen exemplify such state changes. Two remarkable properties arise from the non-linearity of dynamical soil systems—depending on internal conditions and external forcing, soils may exhibit stable, periodic, or chaotic behaviour; and they may display self-organizing characteristics. Self-organizing characteristics involve change spatially from a uniform (undifferentiated) state to an increasingly non-uniform (differentiated or segregated) state, largely in response to dynamical instabilities (Phillips, in press). Many soil (and geomorphic) systems have two modes of behaviour: first, a stable, non-chaotic, non-self-organizing mode; and second, an unstable, chaotic, self-organizing mode (Phillips, 1995b). Chemical weathering transforming rock into saprolite epitomizes stable mode behaviour. Overall, the weathering process is effectively irreversible, monotonically progressing to a single end state. Progressive pedogenesis typifies an unstable mode behaviour—an undifferentiated regolith (the product of weathering) is transformed to an increasingly differentiated and organized soil profile. Now, a soil in a stable, non-chaotic mode evolves towards (or stays in) a single, predetermined, steady-state condition. No matter what the starting conditions, and regardless of any disturbances, the outcome of pedogenesis is always the same. This is mode of pedogenesis envisaged in the classic, developmental view of soils. However, a soil in an unstable, chaotic mode may evolve along any of several evolutionary pathways and at any particular time may exist in several possible states. In this mode, the state at any time is unique and depends upon initial conditions and historical happenstance (small disturbances may be significant), and the soil changes through a series of largely unpredictable states within the bounds set by the local attractor (e.g., Phillips, 1995a, 1997). This mode of pedogenesis is captured in the evolutionary view of soils. It is supported by numerical models of such processes as humus carbon dynamics (Ryzhova, 1996) and soil thickness change (Arlinghaus et al., 1992).

Environmental inconstancy and non-linear dynamics mean that, although some soils and soil processes may stick to the predestined developmental mode, others adopt the far less predictable evolutionary mode (Huggett, 1995, 1997; cf. Johnson and Watson-Stegner, 1987). This line of thinking has led to the developmental view of pedogenesis, as interpreted from the classic chronosequences, being questioned (Johnson and Watson-Stegner, 1987; Johnson et al., 1990). It was anticipated by Jenny (1980) (p. 241) on his reading about the bold challenge to the climatic climax concept in ecology by Drury and Nisbet (1973). (Jenny's state-factor approach to soil genesis applies both to the developmental and the evolutionary view of soils, but in the evolutionary view it is associated with a variety of evolutionary pathways or multidirectional succession).

Soil chronosequences are investigative pedological tools. As such, they may be used to test hypotheses of pedogenesis, and seem ideally suited to evaluate the developmental vs. the evolutionary view of soils. It should be possible using chronosequences to see if pedogenesis is unidirectional or whether it multidirectional (that is, displays a degree of evolutionary divergence). It may be wondered why, given that many chronosequences have been established, no signs of multidirectional evolutionary pathways have been reported until recently. However, the interpretation of chronosequences is to an extent preconditioned by theoretical predilections. It is often the case that a ruling theory is so ingrained in researchers' minds that they unwittingly make 'the facts fit the theory'.

Thus, while the developmental view prevailed, researchers generally sought evidence for unidirectional pedogenic changes leading to a single steady state. It did not occur to anyone to look for multidirectional changes or multiple steady states, although some botanists have never been keen on the idea of a climatic climax vegetation, favouring instead an individualistic interpretation of succession as prosecuted by Gleason (1926).

Some recent work on chronosequences supports an evolutionary view of pedogenesis by showing that unidirectional progression towards a single soil type is just one of several evolutionary pathways. A chronosequence formed in terraces of the Almar River, Spain, involving Xerorthents (Holocene), Haploxeralfs (Upper Pleistocene), and Palexeralfs (Middle Pleistocene) all formed in granite, displayed several trends in chemical and physical properties and in mineralogical components (Dorronsoro and Alonso, 1994; see also Dorronsoro, 1994). The horizon development indices and the soil development indices relate to soil age, the rate of 'development' declining most strongly in the oldest soils. But interestingly, in the great majority of cases, the properties and development indices continue to evolve through the chronosequence without reaching a steady state. Similarly, in an alluvial soil chronosequence from the inner Coastal Plain of central Virginia, where ages range from 60,000 to 1,600,000 years, not all soil properties showed unidirectional development, a steady state of pedon development was not observed, and the transition from one phase to the next was marked by a change in rate, or sometimes a reversal in the direction, of soil evolution (Howard et al., 1993). A new investigation of the classic chronosequence at Glacier Bay, Alaska, compared the inferred primary vegetation succession with reconstructions of stand development based on tree-ring records from 850 trees at ten sites of different age (Fastie, 1995). It revealed three spatially and temporally segregated pathways of vegetation change. The conclusion was that communities of different age at Glacier Bay do not constitute a single chronosequence. The differences among the pathways influence soil evolution. In particular, the long-term accumulation of soil nitrogen becomes spatially differentiated according to the chance location of nitrogen-fixing Sitka alder (*Alnus sinuata*) shrubs. Moreover, where alder shrubs compete with black cottonwood (*Populus trichocarpa*) trees, the black cottonwoods tend to oust the alder and so retard the long-term accumulation of nitrogen at those sites. By altering litter and soil chemistry, black cottonwood could also affect succession to conifers. Other work in Glacier Bay shows similar spatial differentiation of soil properties by tree species (Bormann and Sidle, 1990). The O horizon at a Sitka alder site contained greater concentrations of most extractable macronutrients and micronutrients than at a Sitka spruce (*Picea sitchensis*) site. The chemical differences probably result from more rapid soil weathering, vegetative uptake, and cycling back to the O horizon under alder. The soils under Sitka spruce experienced rapid podzolization.

5. Conclusions

Soil chronosequences are valuable tools for pedological research. Classic chronosequence studies were made on sand dunes and glacial moraines. The number of well-dated chronosequences, most of them post-incisive, is growing rapidly. Sequence lengths have been extended to millions of years. The original work on soil (and vegetation) chronosequences seemed to support the traditional developmental theory of pedogenesis (soil formation theory). A new evolutionary view of pedogenesis, which parallels a new evolutionary view of vegetation change, is supported by some modern soil chronosequence investigations. Soil chronosequences remain potent instruments for probing the pedological past, and for helping to test pedological theories.

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