exemplar to all in recognizing and utilizing the interrelation between his "first love", Quaternary Geology, and the practice of Civil Engineering.

References

Antevs E., 1951, Glacial clays in Steep Rock Lake, Ontario: Geol. Soc. America Bull., v. 62, p. 1223.

Boswell, P.G.H., 1961, Muddy Sediments: Cambridge, W. Heffer & Sons Ltd., 140 p.

Crawford, C.B., 1961, Engineering Studies of Leda Clay: in R.F. Legget, Soils in Canada: Royal Soc. Canada, Spec. Publ. 3: University of Toronto Press, 240 p.

Dreimanis, A., 1976, Tills, Their Origin and Properties: in R.F. Legget, ed., Glacial Till: Royal Soc. Canada, Spec. Publ. 12: University of Toronto Press, 412 p.

Fisk, H.N. and B. McClellend, 1959, Geology of Continental Shelf off Louisiana; its influence on offshore foundation design: Geol. Soc. America Bull., v. 70, p. 1369.

Goldberg, J.M., F.S. Fosberg, M.H. Sachet and A. Reimer, 1965, World distribution of soil, rock and vegetation: United States Geol. Survey Report TE1 - 865, 33 p.

Hack, J.T.,1957, Submerged River System of Chesapeake Bay: Geol. Soc. America Bull., v. 68, p. 817.

Harrison, G., 1958, Marginal Zones of various Glaciers reconstructed from the preconsolidation pressure values of over-ridden silts: Jour. Geology, v. 66, p. 72.

Karrow, P.F., R.J. Hebda and E.W. Presant, 1978, Interstadial (Middle Wisconsinian?) Paleosol and Fossils from Guelph, Ontario: Geol. Assoc. Canada, Toronto Meeting Program, p. 432.

Kenney, T.C., 1964, Sea-Level movements and the geological histories of the post-glacial marine soils at Boston, Nicolet, Ottawa and Oslo: Geotechnique, v. 14, p. 203.

Legget, R.F., and W.R. Schriever, 1960, Site Investigations for Canada's First Underground Railway: Civil Engineering and Public Works Review (London), v. 55, p. 73.

Legget, R.F., 1961, Soils in Canada: Royal Soc. Canada, Spec. Publ. 3: University of Toronto Press (Revised Edition) 240 p.

Legget, R.F., 1976, Thomas Roy (?-1842) an early Engineering Geologist: Geosci. Canada, v. 3, p. 126.

Legget, R.F., 1979, Geology and Geotechnical Engineering (the 13th. Terzaghi Lecture): Proceedings of the American Society of Civil Engineers, v. 105 GT3, p. 339.

Lyell, C., 1845, Travels in North America in the years 1841-2 with geological observations in the United States, Canada and Nova Scotia: New York, Wiley and Putnam, 2 Vols., 251 and 231 p.

McClintock P., 1958, Glacial Geology of the St. Lawrence Seaway and Power Project: New York State Museum and Science Service (Albany), 26 p.

Rominger, J.F., and P.C. Rutledge, 1952, Use of soil mechanics data in correlation and interpretation of Lake Agassiz sediments: Jour. Geol., v. 60, p. 160.

Rominger, J.F., 1954, Relationships of Plasticity and Grain Size in Lake Agassiz sediments: Jour. Geol., v. 62, p. 537.

Roy, T., 1837, On the Ancient State of the North American Continent: Proceedings of the Geol. Soc. London, v. 2, p. 537.

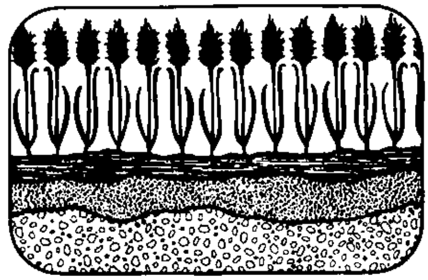
Sherlock, R.L., 1931, Man's Influence on the Earth: London, Thornton Butterworth Ltd., 256 p.

Skempton, A.W., 1944, Notes on the Compressibility of Clays: Quarterly Jour. Geol. Soc. London, v. 100, p. 119.

Skempton, A.W., 1953, Soil Mechanics in relation to Geology: Proceedings of the Yorkshire Geol. Soc., v. 29, p. 33.

Upson, J.E., E.B. Leopold and M. Rubin, 1964, Postglacial change of sea-level in New Haven Harbour, Connecticut: American Jour. Sci., v. 262, p. 121.

MS received November 2, 1981



Late Cenozoic Geology and the Second Oldest Profession

Ward Chesworth
Department of Land Resource Science
University of Guelph
Guelph, Ontario N1G 2W1

Abstract

All soils that are now farmed have been formed or modified by late Cenozoic events. Where these events have been dramatic with glaciers and plate tectonic processes actively intervening, old soils have been obliterated and replaced by newer, inherently more fertile materials. In more placid regions, soils that originated on Tertiary and even Mesozoic landscapes persist, and continue to evolve towards states of low fertility. The inherent fertility of soil, a renewable resource, is largely ignored in modern mechanised agriculture in favour of chemical fertilizers largely mined from non-renewable deposits. A saner attitude once existed, still exists in at least part of the Third World, and should be re-examined as a possible basis for future strategies.

Introduction

The production of an agricultural surplus frees part of the population from the need to grow food. This has enabled the human race to sustain cities and to invent the cultures we call civilised.[1] It depends directly on two things, climate and soil. About the former we can do little in the way of control or amelioration, but in the interests of large crops and short term profits, we have learned to manipulate the latter to a high degree.

In manipulating the soil, human beings constitute a potent geological force. We are not simply figures in the landscape but shapers of the landscape. Landscapes unmodified by human activities scarcely exist in the old world outside of the high latitudes and the high mountains. Even landscapes once thought to be natural, such as those of moorland Britain, are now seen as resulting from

0315-0941-82-01/054-061 $01.00/0

the activities of Neolithic farmers using fire to clear the land of trees (Dimbleby, 1962).

The literature concerning this aspect of farming as a geological activity is voluminous and goes back at least to Plato. Here I wish to look at the reverse relationship, and to consider to what extent geology has influenced the pattern of farming. In other words, from a geological perspective I will examine the question: why are the earth's most productive farmlands where they are (Fig. 1)?

A Conceptual Look at Soil

As a start, I review some elementary notions about the nature of soil. Unfortunately no generally accepted definition of soil exists. This slightly desperate semantic state led one eminent pedologist to coin what he called a nonsense definition: 'soil is anything so-called by a competent authority' (Fitzpatrick, 1971). In the absence of clearer guidance I take soil to be the loose, horizonated, plant-bearing material of the land surface of the earth, formed by weathering, a complex set of interactions between lithosphere, hydrosphere, atmosphere and biosphere[2].

In this zone of interaction at the earth's surface pedologists from the time of Dokuchaev, have recognized a number of environmental factors as being important in the formation of soil, for example parent material, topography, climate and organisms (see Fig. 2). All of these can be modified gradually or abruptly by geological events, and each modification if pronounced, leads to a change in kind of soil.

A non-environmental factor of great importance is time. The influence of parent materials is most clearly seen in young soils (Chesworth, 1973). With time this influence weakens and the effect of climate, hence of vegetation becomes dominant. Thus a comparison of soil and bedrock maps of Canada shows a marked congruity between soil and rock boundaries, while soils developed on the very much older landscapes of Africa clearly follow the climatic zonation of that continent.

Table I shows characteristics of the important soil orders.

Geological Determinants in Agriculture

In Beverley Township, Ontario, an irregular topography dominated by drumlins, gives way to a lacustrine plain (Karrow, 1968). A fine clay-rich sediment has collected in depressions between drumlin clusters, thereby impeding drainage and causing swamps to form. The whole landscape is a sermon in geological determinism. The swamps are left unfarmed, the steeply sloping drumlins are used as pasture, and the plain, amenable to the work of machines, is cropped. The same dictates are at work on a larger scale in the interior of the continent, in determining that much of the Prairies will be cropped while the Foothills will in general be grazed. Landform and soil texture are seen as the two supremely important geological factors in modern industrialized agriculture.

In many of the developed countries of the world, heavy textured soils have been made amenable to cropping, by artificial drainage. The northern Ontario claybelt is currently being opened up to the farming of small-grain crops in this way. An irregular landform however, at least in industrialized North America, is seen as a considerable barrier to cropping. Terracing, the age-old solution to this problem, is seen as too labour intensive for our form of economy.

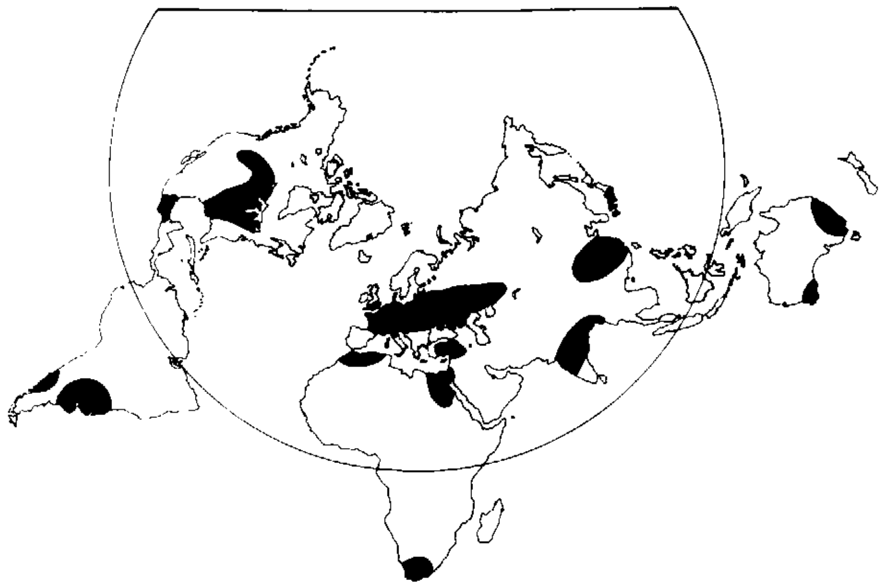


Figure 1 *The world's major croplands on Fitzpatrick's (1971) projection. Based on productivity data in Jones (1972).*

The emphasis laid on geomorphological and textural considerations can be seen by examining any of the schemes used in developed countries to classify land in terms of its suitability for agriculture. For example in Canada, the best agricultural soil (class 1) is defined as being on level to gently sloping landforms, with a deep profile and a texture that allows a good water holding capacity without impeding drainage too much (Environment Canada, 1976). The inherent fertility of the soil is not specifically considered though in class 2 it receives a mention where low fertility is stated to be a limitation that is readily correctable.

This lack of emphasis placed on natural fertility by the modern agriculturist is in marked contrast to the forester's attitude. Until comparatively recently, before the introduction of rapidly maturing tree-crops, the forester had not considered the necessity of artificially fertilising soils. Consequently in grading soils for forestry a naturally high fertility is an important attribute of the best soils (Environment Canada, 1972). In stressing this factor the forester finds common ground with the subsistence farmer in the third world as well as with the Neolithic ancestor of all farmers. Ten thousand years ago when the life-style of the hunter-gatherers was giving way to a settled agriculture, a good soil was one that was inherently fertile. The best soils had their fertility maintained, as in the ancient river-valley civilizations, by annual increments of river sediment rich in nutrients. Elsewhere, a shifting, slash and burn cultivation was necessary as over-used soils became exhausted. Slowly, by trial and error over thousands of years, a homeostatic farming evolved, wherein the fertility of soil was maintained by manuring and by the rotation of crops. British agriculture in the eighteenth and early nineteenth centuries, represents a high point of this development. Since that time, when farming was as close to an ecological equilibrium as it has ever been, there has been a shift in industrialized countries to a greedier style, where for convenience crop rotation has given way to monoculture, and where soil fertility is largely maintained by the addition of chemical fertilisers. In this new agriculture, the inherent fertility of soil, one of the most

Table I
Soil Orders *(from Smith, 1978, with additions).*

U.S. nomenclature[a]	Canadian equivalent[b]	General nature
Alfisols	Luvisolic Solonetzic (in part)	Soils with grey to brown surface horizons, medium to high base supply, with horizons of clay accumulation: usually moist, but may be dry during summer.
Aridisols	Chernozemic (in part)	Soils with pedogenic horizons, low in organic matter, and usually dry.
Entisols	Regosolic	Soils without pedogenic horizons.
Histosols	Organic	Organic soils (peats and mucks).
Inceptisols	Brunisolic	Soils that are usually moist, with pedogenic horizons of alteration of parent materials but not of illuviation.
Mollisols	Solonetzic (in part)	Soils with nearly black, organic-rich surface horizons and high base supply.
Oxisols	none	Soils with residual accumulations of inactive clays, free oxides, kaolinite and quartz; mostly tropical.
Spodosols	Podzolic	Soils with accumulations of amorphous materials in subsurface horizons.
Ultisols	none	Soils that are usually moist, with horizons of clay accumulations and a low supply of bases.
Vertisols	Chernozemic (in part)	Soils with high content of swelling clays and wide deep cracks during some seasons.
	Gleysolic[c]	Dark coloured and/or prominently mottled. Developed under wet conditions with Fe permanently or periodically reduced.

[a]Soil Survey Staff (1975)
[b]Agriculture Canada (1976)
[c]Not recognized as a separate order in the U.S. System.

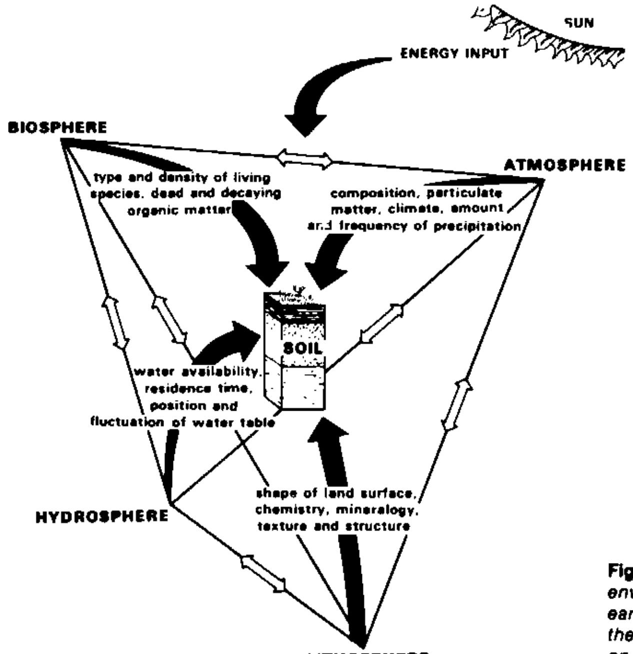


Figure 2 *The environment at the earth's surface, showing the formative influences on soil.*

important, renewable resources we have, is ignored.[3]

The Inherent Fertility of Soil

With the notable exception of nitrogen, which for the most part is present in soil as a consequence of biological fixation from the atmosphere, plant nutrients are provided by weathering (Clayton, 1979). Physical weathering comminutes rock and mineral fragments, and increases the surface area open to chemical attack. Chemical weathering releases ions into aqueous solution, where a proportion is used to feed plants, while some is lost to the agricultural system by leaching. Generally speaking good agricultural soils have a high capacity for storing ions in loosely held form on the charged surfaces of clay sized particles. The presence of such minerals as the 2:1 clays smectite, vermiculite and to a lesser degree illite, or of the amorphous phase allophane, are good qualitative measures of this capacity (Fig. 3).

These phases that are important to the fertility of soil tend to be more common in younger than in older soils, since the continuous loss by leaching of a finite balance of the ions released by weathering, results in the simplification of the oldest soils into compositions made up largely of some combination of SiO_2, Al_2O_3 Fe_2O_3 and H_2O. The mineralogy of such soils tends to be dominated by oxides, hydroxides and/or 1:1 sheet silicates (Chesworth, 1977), none of which is compatible with a high capacity to store nutrient ions.

No matter what degree of weathering has been reached in a soil, a well balanced natural ecosystem tends towards a climax vegetation, where a virtual steady state is maintained as far as input and output of nutrients are concerned. A balance then exists between weathering, atmospheric additions, cycling and leaching. Removal of an agricultural crop from the soils makes a natural balance of this sort impossible, and the use of fertilizers, manures or sewage sludges is an attempt, invariably imperfect, to maintain the balance artificially.

Geochemically, farming is a kind of rape, with annual harvests removing plant nutrients one or two orders of magnitude faster than weathering can replace them.[4] Only N, P and K are routinely replaced as fertilizers, so that it would not be unreasonable, especially under monoculture as practiced here to expect many trace element deficiencies to be appearing. In fact, surprisingly few show up. In Ontario and adjacent parts of the United States for example, Co, Zn, Cu, Mo and B are the best known. The fact that deficiencies in most trace elements

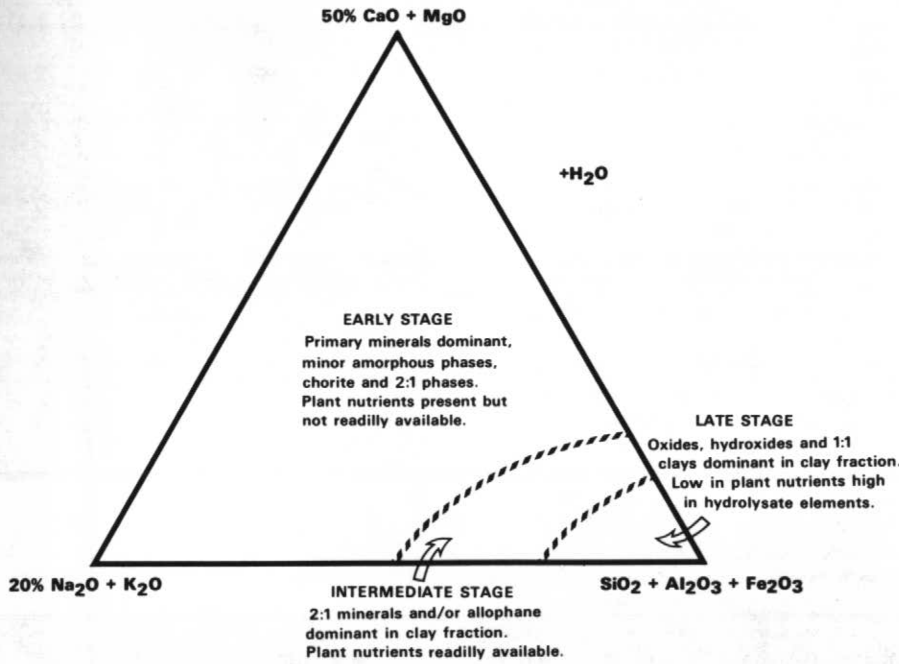
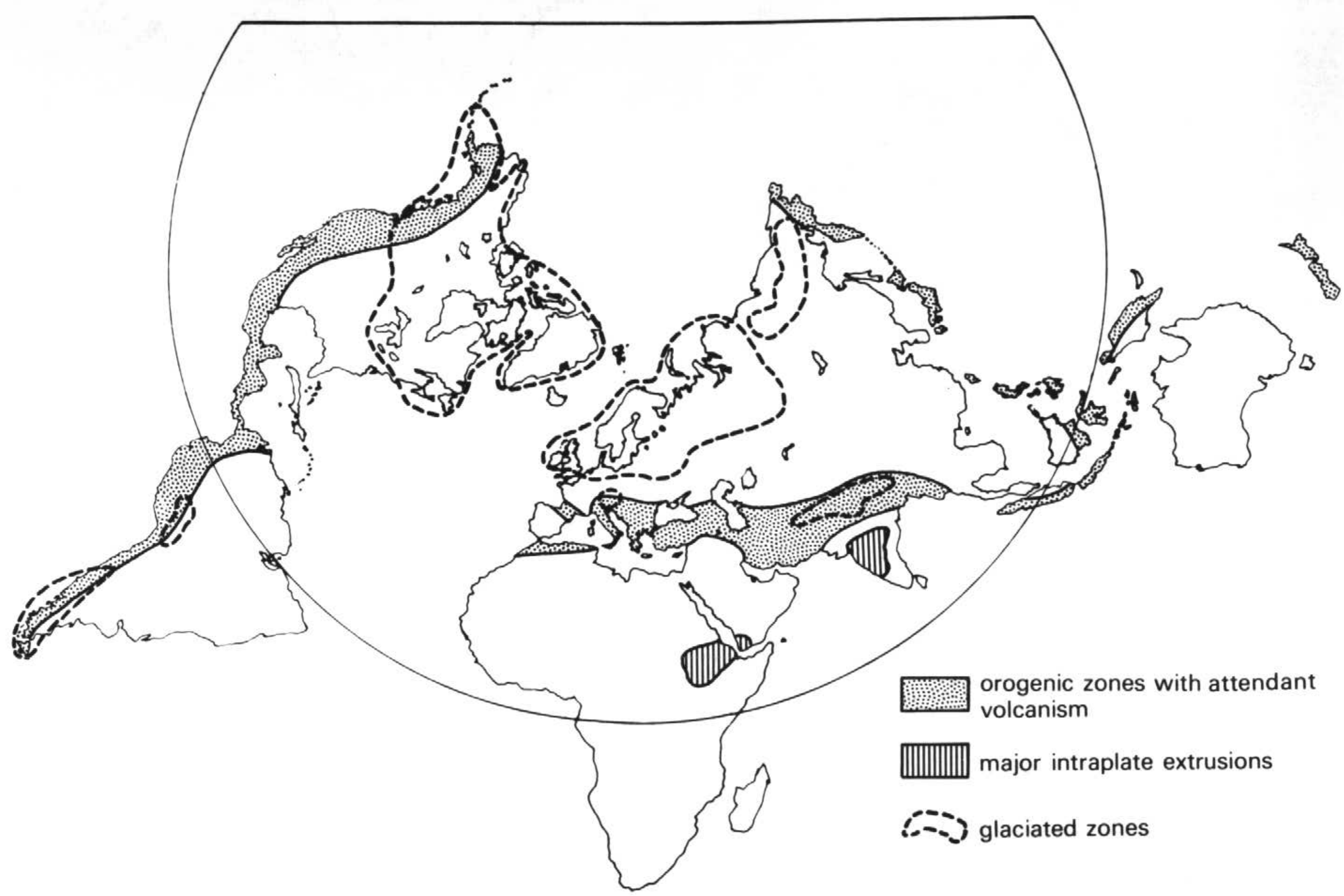


Figure 3 *Three gradational stages in the weathering of igneous rock. The intermediate stage is the stage of highest inherent fertility.*

are not found may be partly due to their inadvertent addition in manures or as impurities in fertilisers, but without doubt, another important source is air-borne material. Industrial and urban pollution of the atmosphere probably plays a more significant role in maintaining soil fertility than is generally recognized (Davies, 1980). It is noteworthy that Australia, one of the least industrialized of developed nations, and one that starts with the disadvantage of having soils of naturally low fertility anyway, is reputed to be the country with the commonest and most numerous trace element deficiencies (Papadakis, 1969). Similarly the republic of Ireland is worse off in this regard than the more industrialized countries of western Europe (Fleming, 1968), and central Canada seems to have more problems than Ontario (Doyle, 1977).

Late Cenozoic Events and Soil Fertility
Decreasing fertility and ultimately barreness, are the inevitable consequences of prolonged weathering (Chesworth, 1975). This trend is counteracted by any process that exposes and distri-

Figure 4 *Zones of the earth where geological processes produced or exposed fresh rock to the weathering regime during the Cenozoic.*



butes new rock to the weathering regime. The major processes are: (a) igneous activity, (b) orogeny, (c) glaciation, (d) sedimentary redistribution, and (e) surface-water level changes (Fig. 4 and 5). Provided that sufficient weathering has taken place under a favourable climate, the most productive agricultural soils on earth are found where these processes have been recently active.

Igneous activity, particularly basic and intermediate volcanism, is continually bringing new, nutrient-rich material from the mantle and lower crust. In late Cenozoic times volcanic rock has been added along most currently active converging and diverging plate boundaries, as well as at intraplate locations such as Hawaii, central France, central Europe and East Africa. No better illustration of the potential of volcanic rock to support a crop exists than the island of Lanzarote in the Canaries (Fig. 6). There, Quaternary scoria directly supports crops of onions, grapes and figs without the aid of artificial fertilizers (Dinkins, 1969). In this case, the agricultural potential of the material is not simply a function of its inherent fertility. Being porous, the rock also conserves moisture well, an important consideration in a place where the only reliable source of free water is dew. A second illustration is provided by Java, where soils developed largely on Quaternary volcanic rocks support a population density of 500 people per square kilometre, a marked contrast to Borneo, where the weathered land surface is older and therefore less fertile and supports less than 10 people per square kilometre (Fyfe, 1977). Finally the Tanzania-Canada wheat project which has put approximately 17,000 hectares of 'new' land in Tanzania into cultivation in the last 12 years, has relied completely on the inherent fertility of the soil, much of it deriving from volcanic sources. The oldest farm, started in 1968, has never employed artificial fertilizer and its present wheat yield (1.7 tonne/ha) is slightly better than the average yield from Saskatchewan farms (Pat Kirkwood, Agriculture Canada, pers. commun., 1981). In view of such examples the conclusion reached by Cook *et al.* (1981) that the Mount St. Helen's ash would make no

Figure 6 *The island of Lanzarote in the Canaries showing the characteristic depressions excavated in scoria to grow the grape vine. Each depression is planted with one vine, and the shape aids in water conservation.*

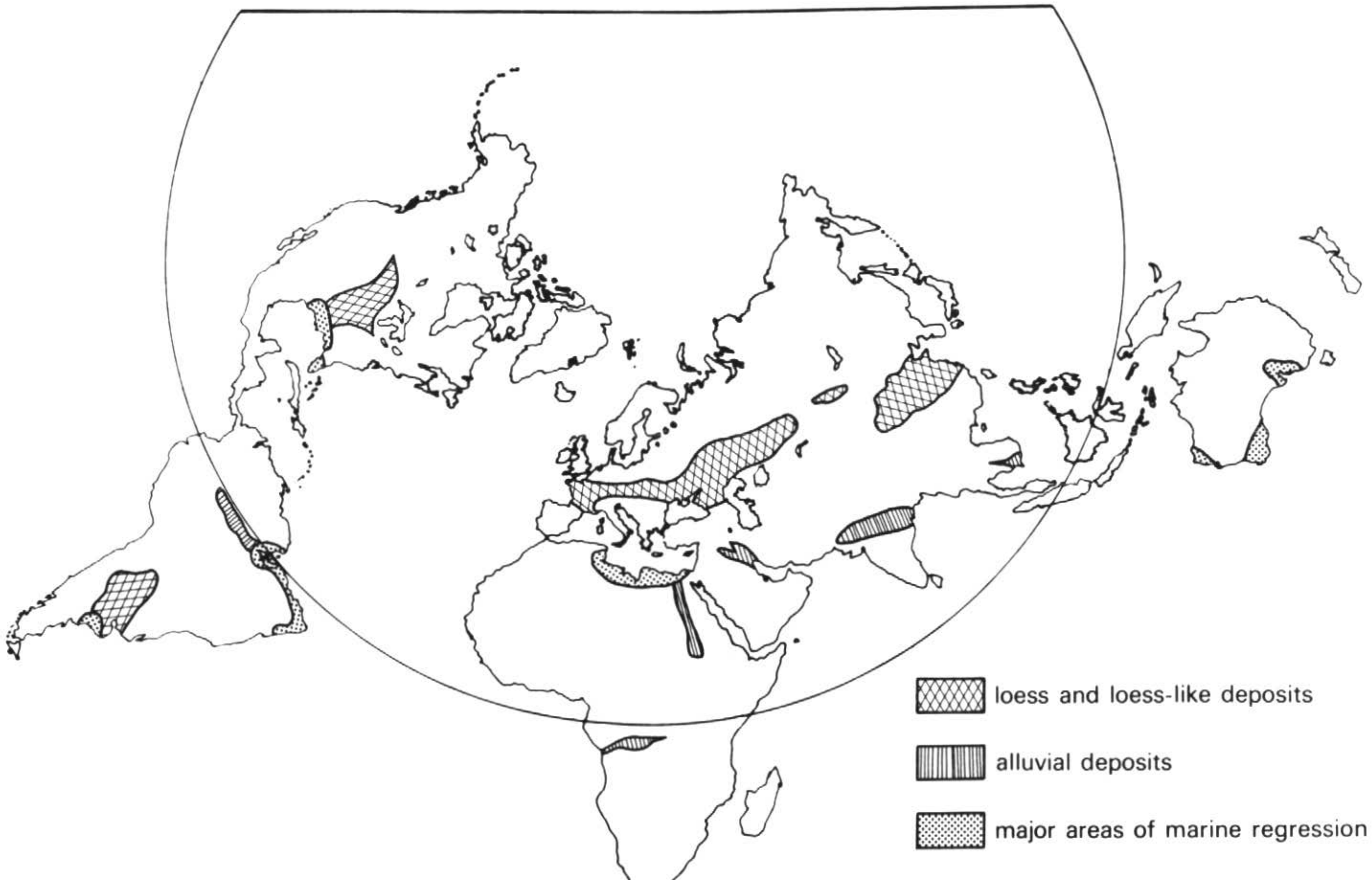


Figure 5 *Areas where sedimentary redistribution during the Cenozoic extended the effects of processes illustrated in Figure 4.*

significant contribution to the nutrient status of local soils seems hasty and ill-considered.

In zones of plate convergence, orogeny serves a similar purpose by tectonically uplifting plutonic and metamorphic rocks to high levels of the crust at continental margins, exposing them there to weathering and erosion. Sediments accumulating in dams in the western Cordillera, indicate that the general composition of new soil material provided in orogenic zones, is andesitic. The principal limitation of farming areas of this kind is topographic. However a topography of high relief is no more of a barrier to modern mechanised farming then it was to ancient peoples such as the Incas, or than it is to the present day societies of southeast Asia, where extensive and elaborate terracing allow a very efficient use of the land.

Glaciation revitalises the nutrient status of the landscape by scraping off products of an earlier weathering cycle, exposing fresh rock, and generating sediments that contain a high proportion of fresh rock. The presence of pre-Pleistocene duricrusts in Wisconsin (Dury and Haberman, 1978) and the occasional discovery of duricrust pebbles in North American tills, show that at least part of the land surface of this continent had reached an advanced state of low fertility by the time the ice-sheets were forming. By contrast the deposits left by the ice have provided the raw material for virtually all the soils of high productivity in the U.S.A. and Canada either directly or by later sedimentary redistribution. A comparison shows that whereas the highly leached soils of ancient landscapes in the tropics may have their major plant nutrients reduced to proportions of 0.01% or less, soils formed on Quaternary glacial deposits will have the same nutrients in concentrations at least two orders of magnitude greater (e.g., compare Kronberg *et al.*, 1979, with Kudrin, 1963). Unfortunately a major limitation to agriculture is that much glacial material is still in a cold and unfavourable climatic zone, and has not been exposed for a sufficiently long time to undergo appreciable weathering. Thus its fertility is potential rather than actual in many cases. In general, under Canadian conditions, some 10,000 years of exposure, seem to have been necessary to produce a good agricultural soil (Fig. 7). Again, in terms of mechanized agriculture, the irregular topography of most moraines and the stoniness of many tills are seen as barriers to crop-husbandry on deposits of this kind. To what degree these barriers are cultural and artificial, is seen by looking at those parts of the world already referred to where terracing is used to overcome topographic limitations, or to regions like Medoc in France, where an extremely stony soil has proved no barrier to the production of one of the world's great wines.[5] And in spite of limitations Catt (1979) concluded that the two thirds of England covered by Quaternary deposits had better agricultural soils, than the parts of the country where soils had developed on pre-Quaternary sediments.

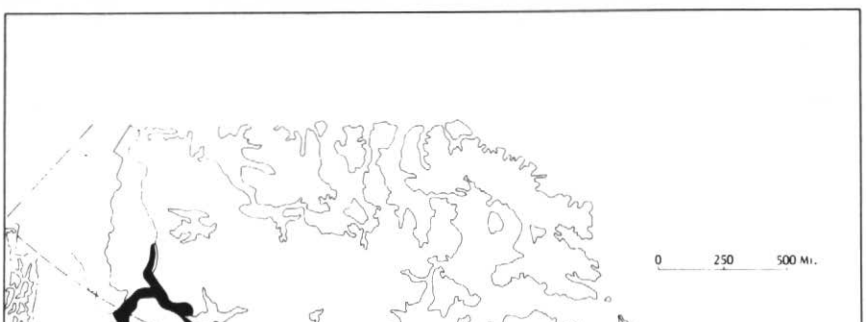


Figure 7 *Real and potential agricultural land in Canada (Nowland and McKeague, 1977). The outer limits are roughly coincident with the ice marginal positions of 10,000 years ago (see Prest, 1969).*

Sedimentary processes, specifically those of transport and deposition serve to spread the materials exposed by volcanism, orogeny and glaciation further afield. The ancient, so-called hydraulic, civilizations of Egypt, Mesopotamia and the Indus valley depended upon soils renewed by these processes. The Nile for example, brings down nutrient rich sediments from the volcanic highlands of East Africa, a reliable yearly source of fertiliser for the farmers of lower Egypt for 10,000 years.[6] Winds also play a similar role, eroding glacigene sediments and depositing the fertile loess of middle North America, of the Argentine pampas, of central Europe and at least part of northern China. Again rivers such as the Mississippi, la Plata, the Danube and the Huang Ho, have relayed the effects further. The loess-area of northern China is important as the oldest focus of Chinese agriculture. It has been the considerable achievement of farming in China that a 'permanent agriculture' has been maintained there for thousands of years without recourse to mineral fertilizers.

An inevitable consequence of weathering already noticed, is the loss by leaching of part of the nutrients released into solution. Erosion may remove more by transporting some in the form of elements stored on clay-sized particles. Although lost to the soil, nutrients carried away like this, are not lost to the biosphere. They are conducted into rivers, lakes and seas and help to support aquatic life. Ultimately they may be restored to the land-surface in the form of water-laid sediments, by a drop in water level. Nutrient-rich land has been exposed in this way along river-terraces along the Rhine and Moselle valleys, on the bottoms of former lakes Agassiz, Ojibway and Warren, and along former arms of the Champlain Sea. The best illustration of a region that depends upon this factor, however, is an artificial one. For more than 400 years the fertile sediments of lakes, and later of the sea, have been exposed and made available to farming by human ingenuity in Holland. Until quite recently the sandy and loamy sediments of the Nordoostpolder of the Zuider Zee were preferred to the more fertile clays of regions such as southern and eastern Flevoland (Anon., 1956). The heavier soils retained too much moisture and were difficult if not impossible to work with heavy machinery in wet seasons. The lighter soils were more suitable for this type of farming even though they needed more artificial fertilizer than the clays. Now, with the increased costs of energy and of fertilizers, priorities have been rearranged. The economic advantage of a high inherent fertility is felt to outweigh difficulties arising from machine cultivation. In any case, as a last resort, manual labour in the shape of the Dutch army succeeds where machines fail.

By way of summary, the efficiency of all these geological ways of renewing fertility, can be shown in a qualitative way by comparing the compositions of runoff from the various continents (Table II). North America, Europe and Asia appear much richer in nutrient cations than Africa, Australia and South America, a reflection of the more dramatic Cenozoic history of the former as compared with the latter group.

Conclusion

It is perhaps overstating the point to say that when farming became agribusiness, soil husbandry became soil exploitation; but there is a real element of rapaciousness about much of modern agriculture. When soil fertility is thought of as something to be bought in bags at the farmers' co-op (see Stewart, 1979, for his interesting comments on this attitude of mind), it is easy to treat the inherent fertility of soil as a negligible factor in feeding people. This makes no sense on a finite planet. All our best soils are found where the fertility of the land surface has been refreshed by geological processes operating in late Cenozoic times[7] (Fig. 8). The slowness with which this renewal goes on makes it imperative that we reconsider many of our current soil-management practices. The conservation of soil nutrients must be given a high priority in any future agricultural strategy (Fyfe and Kronberg, 1980).

Table II *Mean compositions of continental runoff, expressed as the sum of the nutrient ions* Ca^{+2}, Mg^{+2}, Na^{+1}, *and* K^{+1}, *in ppm.*[a]

	$\Sigma\,(Ca^{++} + Mg^{++} + Na^{+} + K^{+})$
Africa	12.6
Asia	29.1
Australia	10.9
Europe	33.6
North America	33.0
South America	12.0[b]

[a]Calculated from data in Meybeck (1979) and Livingstone (1963).
[b]Probably reflects a dominance of analyses from the Amazon and Drinoco systems.

The 'miracle' of industrialized agriculture has been won at considerable cost, not only in terms of a heavy dependence on mineral fertilisers, but also by a heavy reliance on monocultural techniques inimical to the maintenance of a good soil structure. Consider as an alternative, the astounding miracle of the Chinese in maintaining a homeostatic agriculture on loess and loess-like deposits for centuries. Without doubt Chinese farmers have their own difficulties to contend with[8]; but on the whole they have managed to evolve a careful husbandry that avoids such 'Grapes of Wrath' devastation as struck the similar deposits of the American midwest after only three or four generations of farming.

In the light of such experiences, our well intentioned attempts to export western-style agricultural techniques to third world countries, may not be the wisest kind of aid we can give.[9]

Acknowledgements

I am grateful for advice from many of my colleagues at the University of Guelph. In addition, I thank Dick Arnold of the U.S.D.A. for his comments on an early draft, and Ted Heeg for the photograph of Lanzarote.

Notes

1 "The largest single step in the ascent of man is the change from nomad to village agriculture" (Bronowski, 1973). In his film "The Harvest of the Seasons" Bronowski follows a nomadic tribe, the Bakhtiari of Persia, across six mountain ranges, through snow and flood, from winter to summer pastures. He shows clearly why "civilization can never grow up on the move," and why it needs the settled way of life that farming brings.

2 Jenny (1980, p. 364) discusses the difficulties of devising a generally accepted definition. He concludes: "It is embarassing not to be able to agree on what soil is. In this the pedologists are not alone. Biologists cannot agree on a definition of life and philosophers on philosophy".

3 "The struggle of two hundred generations of cultivators had its culmination in the high farming of the eighteenth and early nineteenth centuries. Now those thousands of years of wooing fertility under the sun and rain were to be half forgotten in a third way of living which resembles the first, that of the hunters, in its predatory dependence on the natural resources of the country" (Hawkes, 1953, p. 162).

4 The power of plants to extract materials from the soil is illustrated by Epstein (1977), who estimates that 6.1×10^9 tonnes of elements are annually taken out of the soil by plant roots.

5 There is a theory amongst viticulturalists that the best vintages are produced where the vine is subject to a certain amount of physical hardship. Aubert, one of the foremost French pedologists, used to tell his students "Il faut que la vigne souffre." In Medoc the vine suffers to good effect.

6 Things have changed with the building of the Aswan High Dam. The dam not only stores water, it allows silt to settle, so that "for the first time in 7000 years, the fertility of the delta is not being naturally replenished. Preliminary estimates suggest that, if all the new power generated by the dam were used to fix ammonia from nitrogen in the air, enough fertilizer could be produced to replace the silt to the delta" (Menard, 1974, p. 363)

7 Throughout this paper, I have stressed the relationship between Cenozoic geological happenings and soil fertility. It may be that there is a more occult relationship between regions where soils were nutritionally enriched in late Cenozoic times, and the well-being of the human race. The Soviet biologist N.I. Vavilov recognises a number of 'centres of genetic diversity' in the world, where the wild relatives of agricultural crops are to be found and where such plants first diversified and were domesticated. There is a marked coincidence between these centres and the areas identified on Figures 4 and 5. For details see Frankel (1980).

8 Needham (1974) identifies the specific drawbacks of Chinese agriculture as (a) periodic devastation by flood, (b) the need for a large labour force, (c) use of human manure-dangerous in an uncomposted stated, and (d) delay in the stimulus to improve crop plant varieties.

9 The intervention of western technology into third world agriculture, commonly known as 'the Green Revolution', is based on new high yield varieties of staple crops. These "can only work if they have plenty of water, if their diseases, pests and weeds are rigorously controlled by chemicals, if the standard of husbandry is high, and if liberal doses of artificial fertilizer are applied to them" (Naughton, 1981). In other words, they need a western-style infrastructure to work.

References

Agriculture Canada, 1976, Glossary of Terms in Soil Science: Canada Dept. Agric. Publication 1459, 44 p.

Anonymous, 1956, Excursiegids voor de Noordoostpolder en Oostelijk Flevoland: Directie van de Wieringermeer, Zwolle, 141 p.

Bronowski, J., 1973, The Ascent of Man: Toronto, Little, Brown and Co., 448 p.

Catt, J.A., 1979, Soils and Quaternary geology in Britain: Jour. Soil Sci., v. 30, p. 607-642.

Chesworth, W., 1973, The Parent Rock Effect in the Genesis of Soil: Geoderma, v.10, p. 215-225

Chesworth, W., 1975, Geochemical behaviour of elements during weathering: M.H. Miller, ed., Metals in the Biosphere; Univ. of Guelph, Ont., p. 4-14.

Chesworth, W., 1977, Weathering stages of the common igneous rocks, index minerals and mineral assemblages at the surface of the earth: Jour. Soil Sci., v.28, p. 490-497.

Clayton, J.L., 1979, Nutrient supply to soil by rock weathering: in A.L. Leaf, chairman, Proceedings Impact of Intensive Harvesting on Forest Nutrient Cycling: College Enviromental Science, State Univ., Syracuse, p. 75-96.

Cook, R.J., J.C. Barron, R.I. Papendick, and G.J. Williams, III, 1981, Impact on agriculture of the Mount St. Helens eruptions: Science v.211, p. 16-22.

Davies, B.E., 1980, Trace element pollution: in B.E. Davies, ed., Applied Soil Trace Elements: New York, Wiley and Sons, p. 287-351.

Dimbleby, G.W., 1962, The Development of British Heathlands and their Soils: Oxford, Clarendon Press, 120 p.

Dinkins, S., 1969, Lanzarote, the strangest Canary: National Geographic, v.135, p. 116-139.

Doyle, P.J., 1977, Regional geochemical reconnaissance and compositional variations in grain and forage crops on the southern Canadian interior plain: Ph.D. Thesis, University of British Columbia, 285 p.

Dury, G.H. and G.M. Habermann, 1978, Australian silcretes and northern hemisphere correlatives: in T. Langford-Smith, Ed; Silcrete in Australia: Australia, Univ. New England, p. 223-259.

Environment Canada, 1972, Land capability classification for forestry: C.L.I. Rept. 4, 72 p.

Environment Canada, 1976, Land capability for agriculture: Preliminary Report: C.L.I. Report 10, 27 p.

Epstein, E., 1977, The role of roots in the chemical economy of life on earth: Bioscience, v.27, p. 783-787.

F.A.O., 1979, Fighting World Hunger: Food and Agricultural Organization of the U.N., Rome, 76 p.

Fitzpatrick, E.A., 1971, Pedology, A Systematic Approach to Soil Science: Edinburgh, Oliver and Boyd, 306 p.

Fleming, G.A., 1968, Cobalt, selenium and molybdenum in Irish soils: Welsh Soils Discussion Group, Rept. 9, p. 41-56.

Frankel, O., 1980, Our evolutionary responsibility: UNESCO Courier, May 1980, p. 25-27.

Fyfe, W.S., 1977, Global resources: The evolution of the Earth's crust: The Bryan Priestman Lecture, Univ. of New Brunswick, 14 p.

Fyfe, W.S. and B.I. Kronberg, 1980, Nutrient conservation: the key to agricultural strategy: Mazingira, v.4, p. 64-69.

Hawkes, J., 1953, A Land: London, Readers Union, 205 p.

Jenny, H., 1980, The Soil Resource: New York, Springer-Verlag, 377 p.

Jones, D.B., 1972, Oxford Economic Atlas of the World: 4th Edition: Oxford Univ. Press, 239 p.

Karrow, P.F., 1963, Pleistocene geology of the Hamilton-Galt area: Ontario Dept. Mines, Geol. Rept. 16, 68 p.

Kronberg, B.I., W.S. Fyfe, O.H. Leonardas, Jr., and A.M. Santos, 1979, The Chemistry of some Brazilian soils: element mobility during intense weathering: Chem. Geol., v.24, p. 211-229.

Kudrin, S.A., 1963, Average chemical composition of the principal soil groups of the European U.S.S.R. by total analyses: Sov. Soil Sci., v.5, p. 425-428.

Livingstone, D.A., 1963, Chemical composition of rivers and lakes: chapter G: in M. Fleischer, ed., Data of Geochemistry, 6th Edition: United States Geol. Survey Prof. Paper 440-G, 64 p.

Menard, H.W., 1974, Geology, Resources and Society: San Francisco, Freeman and Co., 621 p.

Meybeck, M., 1979, Concentrations des eaux fluviales en eéleéments majeurs et apports en solution aux oceéans: Rev. Geéol. Dyn. et Geéog. Phys., v.21, p. 215-246.

Naughton, J., 1981, Why the Green Revolution failed: London Rev. of Books, v.2, p. 8-9.

Needham, J., 1974, Science and Civilization in China: Cambridge Univ. Press, v.5, pt. 1, p. 125.

Nowland, J.L. and J.A. McKeague, 1977, Canada's limited agricultural land resource: in R.R. Krueger and B. Mitchell, eds., Managing Canada's Renewable Resources: Toronto, Methuen, p. 109-117.

Papadakis, J., 1969, Soils of the World: New York, Elsevier, 208 p.

Prest, V.K., 1969, Retreat of Wisconsin and Recent ice in North America: Geol. Survey Canada Map 1257 a.

Smith, G.D., 1978, Soil: in D.N. Lapedes, ed., Encyclopaedia of the Geological Sciences: New York, McGraw-Hill, p. 765-769.

Soil Survey Staff, 1975, Soil Taxonomy: United States Dept. Agric. Handbook, v.436, 754 p.

Stewart, V.J., 1979, Fertilizers and soil fertility: Agriculture and Environment, v.4, p. 303-306.

MS received November 2, 1981

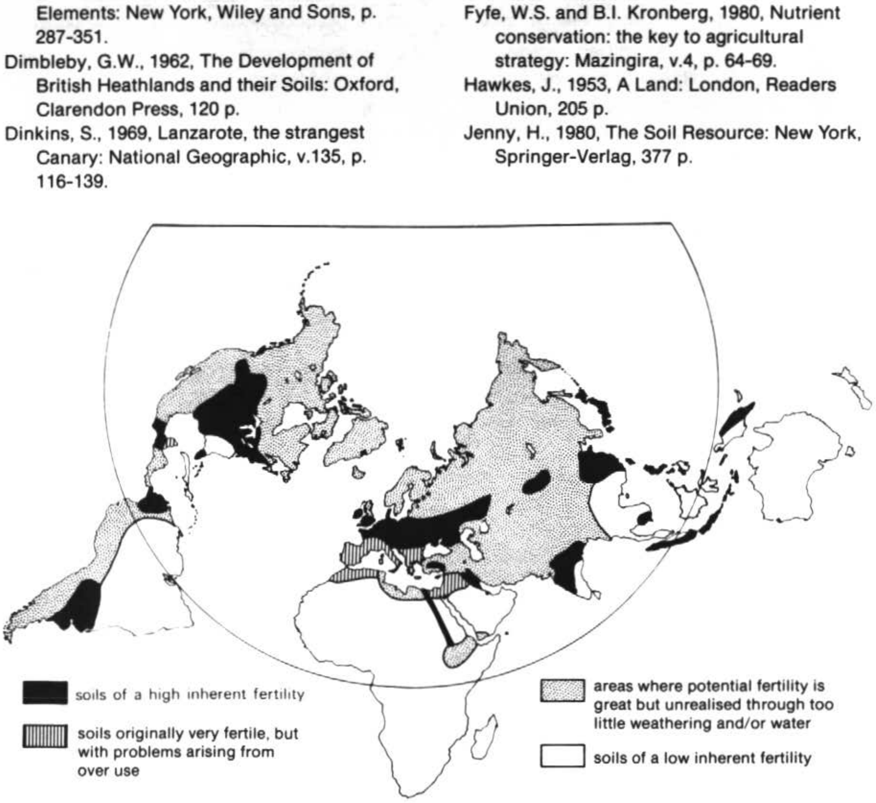


Figure 8 *Soils of the world from the standpoint of their fertility. As an antidote to the high degree of generalization on this map, compare the less generalized map on p. 25 of F.A.O. (1979).*