Soil in the Anthropocene

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Abstract. With scholars deliberating a new name for our geologic epoch, i.e., the Anthropocene, soil scientists whether biologists, chemists, or physicists are documenting significant changes accruing in a majority of Earth’s soils. Such global soil changes interact with the atmosphere, biosphere, hydrosphere, and lithosphere (i.e., Earth’s Critical Zone), and these developments are significantly impacting the Earth’s stratigraphic record as well. In effect, soil scientists study such global soil changes in a science of anthropedology, which leads directly to the need to transform pedostratigraphy into an anthro-pedostratigraphy, a science that explores how global soil change alters Earth’s litho-, bio-, and chemostratigraphy. These developments reinforce perspectives that the planet is indeed crossing into the Anthropocene.

1. Introduction

While the sciences of pedology and in fact of all Earth’s surface systems have historically focused on natural processes, human beings are transforming Earth’s surface systems from natural bodies to those that are human-natural bodies. Thus pedology and all Earth system sciences are in the midst of fundamental change.

Human-affected changes in pedology had been written about for decades [1-3], but it was the publication of a small book, Global Soil Change [4], that threw open the doors of pedology to human beings as soil-forming agents. No longer could human beings be treated only as agents of soil disturbance. This remarkable book outlined a science of anthropedology as it gave soil science a firm footing as a core environmental science [5].

Today, with over half of humanity living in urban centers, increasingly removed from traditional connections to land and soil, soil and all Earth scientists seem doubly challenged. Not only must the dynamics of global change be scientifically understood and quantified but the increasingly urban public needs continual reminding that the quality of human life and that of the environment is entirely dependent on the Earth’s soils and Critical Zone, i.e., the integrated system from the atmosphere and plant boundary layer down through soil into aquifers and the deepest penetration of biogeochemical alteration [6].

This paper’s objectives are to consider two interrelated and on-going changes in soil science:
• The transformation of pedology into anthropedology and of soil into a polygenetic and far deeper system than considered in the past. These changes grant to soil science important scientific, intellectual, and societal opportunities.
• The transformation of pedostratigraphy into a science of anthro-pedostratigraphy, which has important implications for the Anthropocene.

2. Pedology Past and Present: Achievements and Developments
The initial scientific conception of soil as a natural body came in the 19th century, that is, soil is a dynamic body that develops structures and processes over time in response to external environmental factors. Three scientists who are given most credit for describing soil’s natural forming factors include E.W. Hilgard [7] in Report on the Geology and Agriculture of the State of Mississippi, Charles Darwin [8] in The Formation of Vegetable Mould, through the Action of Worms, and Vasily V. Dokuchaev [9] in Russian Chernozem. Each described soil to be a dynamic system responsive to natural environmental forcings. Although Hilgard was employed as a state geologist to survey soils for potential economic development, he carefully addressed his essay entitled, “What is a soil?” by explicitly examining “virgin” rather than human-altered soil. Dokuchaev similarly was employed mapping soils for practical purposes of land taxation, and yet was most influential in his identification of five natural soil-forming factors. Darwin was motivated by his own curiosities but after a lifetime of earthworm observation and experimentation, developed an advanced view of the biogenic formation of soil organic matter, i.e., vegetable mould. All three were interested in soil as a natural system; human beings were agents of soil disturbance and were simply not part of pedological studies. Most pedologists have followed the direction set by Hilgard, Darwin, and Dokuchaev, for well over 100 years [5], although three important developments seem important to changes to come.

2.1 Integrating Human Beings into Pedology
Comfortably fitting human beings into the natural body model of soil formation has not been easy [4, 5, 10-14]. Dudal [15] pointedly asked, are we a soil-forming factor short?, out of concern that in a world where over half of Earth’s surface was actively managed, a pedogenetic model confined only to natural forming factors risks irrelevance. One of the earliest proposals to more formally integrate human beings into pedology came from Yaalon and Yaron [1]. Amundson and Jenny [10] examined the variety of ways that human beings interacted with soils, in ways that were culturally dependent, potentially self-aware, and modifiable based on human judgment.

One of the main claims of this paper is that the explicit integration of human beings into the natural body model of soil formation, i.e., into anthropedology, provides new opportunities for soil science to explore critical issues of societal relevance. Contemporary pedology can contribute to many environmental programs that continue to grow at many of the world’s universities, in governments, and in the private sector. The purview of contemporary pedology includes not only the patterns and processes of natural soil formation but also all the human-forced changes in soils from fertilizers, wastes, biocides, and chemical contaminants; harvests of biomass at various intensities; mixing by cultivation (anthroturbation); alterations from residential, industrial, and transportation uses; biogeochemistry due to drainage or intentional flooding; burning or not burning of organic detritus; alterations due to changing climate; and finally soil sealing and even soil extinction [13, 16]. A remarkable fact is that so much soil science is being practiced today, and not only by soil scientists, but by engineers, environmental chemists, ecologists, biologists, and geoscientists. Although pedologists have unique perspectives and expertise that can frame human-soil interactions within the broader context of soil formation, contemporary pedology
risks being incomplete and soon irrelevant if it does not vigorously expand its purview into the non-virgin landscape.

While pedology has always been interdisciplinary, this historic interdisciplinarity has largely been within the natural sciences of geology, biology, chemistry, physics, meteorology, climatology, hydrology, and geochemistry, a list that is impressively long. But as contemporary soils are a human-natural bodies, the list of sciences pertinent to pedology becomes much longer still and far wider ranging. Contemporary pedology involves not only social sciences but also the humanities; the science welcomes insights from economics, sociology, anthropology, and archaeology, and also environmental history, literature, theology, ethics, and even philosophy. Contemporary pedology is a natural and applied science.

2.2 Research Extends the Lower Boundary of Soil
Extending the lower boundary of soil represents a second important change in the traditional model of soil as soil has been greatly expanded in its material volume and process domain. While pedologists in the 19th and 20th centuries increased their depth of interest from O and A into B and C horizons [17, 18], soil studies even today continue to be mainly concentrated in surficial layers (i.e., the solum of the O, A, and B horizons, i.e., “true soil” in the words of Plaster [19]. Even today, many pedologists consider C horizons as “not formed by pedogenetic processes.”

Here, the practice of how deeply the scientific community samples soil is instructive. Figure 1 illustrates how in over 360 studies of how land-use change alters soil organic carbon, 90% of the 360 studies sampled soil to a maximum of 30-cm depth [20, 21]. While it is often difficult to sample soil, these relatively shallow depths have more to do with how scientists conceive of the soil itself than about sampling difficulty. Despite the fact that plant roots are well known to deeply explore soils to many meters in depth, both in concept and in practice, soil systems are too often treated as if the whole soil profile behaves like the surficial A horizons.

Figure 1. A histogram of the depth of sampling in the 360 studies reviewed by Post and Kwon [20] and West and Post [21] that investigated the effects of land-use change on soil organic carbon. The median depth of sampling was slightly over 15 cm, whereas 90% of the studies sampled soils to 30 cm or less.
In contrast, a concept of the deep soil profile has been advanced by geologists with the so-called weathering profile in which lower layers are described as regolith [22]. While some propose a hybridized pedological-geological profile to avoid conflict in concepts [23], Richter and Yalon [14] and Richter and Markewitz [18, 24] argue that contemporary understanding of soil requires that C horizons be recognized as fully integral parts of soil profiles. In point of fact, many of processes that form C horizons are fundamentally pedologic. The deep pedologic processes affecting C horizons include soil respiration coupled with carbonic acid weathering, rhizosphere interactions, and pedological alterations of O2 and redox potential [14, 18, 25-27].

The seasonality of soil respiration and the consequent wave of high CO₂ concentrations result from the annual pulsing of ecosystem metabolism (Figure 2). While most soil CO₂ effluxes back to the aboveground atmosphere, a small but critically important fraction diffuses downward, potentially well below roots and mycorrhizal hyphae, where at least some of it is consumed by weathering [28]. While the CO₂ dynamics of the upper soil layers are well studied [18, 29], the concentration gradient of CO₂ across the lower boundaries of the soil are rarely studied, even though concentration gradients must exist all the way down to the deep CO₂ sink at sites of carbonic acid weathering. In the example of Figure 2, carbonic acid weathering may well be most active at >15 meters in this soil (i.e., weathering profile) in which the full depth of soil plus unconsolidated saprolite (i.e., regolith) is about 30-m over unweathered granite [30].

**Figure 2.** CO₂ at Calhoun Experimental Forest in South Carolina USA. Topmost figure is modeled CO₂ [28] from 0 to 10 m illustrating the pronounced seasonal dynamics of CO₂ concentrations. The figure on the bottom is a Matlab image of CO₂ concentrations measured every two to three weeks over 4.5 years from multiple soil depths.

The lower boundary of soil is not only open, it may be highly heterogenous in chemical and physical structure, diffuse, and temporally variable as well. An organized sequence of depth-dependent biogeochemical fronts of weathering (carbonate and sulfide fronts) was recently described by Brantley et al. [31] in soils and weathering profiles derived from shale. Far more studies of the lower soil boundaries and weathering fronts are needed in a variety of soils and geologic materials. More use of quarries [32]
and deep drilling [5] will eventually reveal the variety of biogeochemical and structural patterns in the lower soil boundary (Figure 3).

Finally, the soil’s lower boundary conditions are not only under-explored, they are significant for understanding and managing water quality and the sustainability of ecosystems and the environment. With more attention paid to the lower boundary of soil, deep contamination problems can be much better quantified. A notable example is the currently controversial fracking issue and the effects of such mining techniques on the solid, liquid, and gas phases of the full soil system. Considering that the openness of soils and ecosystems is too rarely critically investigated with care and that many lower boundaries extend meters even to many meters, future research of soils’ lower boundary conditions and their relations to ecosystem resilience, represents an exciting and significant frontier for pedology and weathering science in general.

2.3 Soil as a Non-Equilibrium, Polygenetic System

A third development in pedology that has moved soil science far from the concepts of even mid-20th century, is a much fuller appreciation for soil-system dynamism, non-equilibrium, and how soils evolve and change over their residence times of 10s to 10⁶ s of years. A number of scientific disciplines contribute to the understanding that soil-forming factors vary through time, and specifically that soil inputs, removals, transformations, and translocations all vary over the life of most soils (to use the model of Simonson [33]). Such variations can be abrupt as in the periodic phenomena of Butler [34], others more gradual; some changes are externally forced, others derive from internal soil-dependent process. Such system behavior is known as polygenesis, i.e., that the high-order interactions of the factors of soil formation vary significantly over time. How remarkable that within a few decades, the science of pedology has grown from conceiving of soil bodies as largely monogenetic in their formation to understanding that most are polygenetic [35].

![Figure 3](image-url)

**Figure 3.** Quarries and deep coring are revealing new insights into the soil, saprolite, and the full weathering profile, i.e., into the belowground Critical Zone [32]. Illustrated is a quarry of Carolina slate, a meta-volcanic rock that in the Carolinas yields deep, highly weathered soils and saprolites.
There are also two ways that soils are polygenetic. One refers to the soil system in place, as profile and soilscape. Most soil profiles have long enough residence times to experience widely variable climates, atmospheric depositions, biotic rooting and organic matter inputs, erosion rates, geomorphic processes, chemical leaching, and human activities. The second meaning of polygenesis refers to the fact that many soil profiles and soilscape are composed of primary particles that have experienced pedogenesis and weathering when the particles were part of previous soil profiles in the distant past. This latter polygenesis can exhaust weatherable minerals from mineral substrates and contribute much to the understanding of why soils in some regions are largely of advanced weathering stage, i.e., Ultisols and Oxisols.

Accordingly, all soils and their structures and processes are fundamentally diagenetic, formed and changing over time. Pore networks, redoximorphic features, rooting channels, clay mineral suites, nutrient and element distributions, and structural aggregates, all respond to the ebbs and flows of changing environments and biota. Soils are therefore historical bodies, archives of accumulated and inherited features from past conditions of formation -- some features persistent, others disappearing, and others completely erased. Such polygenesis suggests the powerful metaphor of the soil is the palimpsest, a parchment made from animal hide used in the ancient world to record religious communiqués, learned texts, and political decrees, which was written upon, erased when the text was no longer needed, only to be over-written once again. Understanding soils as polygenetic palimpsests requires much more understanding about paleo-climates, biota, geomorphology, changes in geologic substrates, and soil residence times. While we can read the basics of many soils, we are far from understanding soil as an archive, and must realize that at some level the soil may always remain at least a bit shrouded in mystery.

3. Pedology’s Future: Anthropocene Soils and a New Science of Anthro-pedostratigraphy

The transformation of Earth’s soil from a natural to a human-natural system has many implications. Pedology must and will be framed by the human and natural forcings that are hybridizing contemporary soils. In other papers, we argue that human beings’ alteration and dependence on soils necessitates long-term soil-ecosystem experiments (LTSEs) that reach their potential if they are passed from one generation of scientists to the next [36, 37, 38]. Here, in addition to the need for LTSEs, we consider a second implication of soil’s transition from a natural to human-natural body – that pedostratigraphy be transitioned into a science of anthro-pedostratigraphy. We describe the beginnings of this transition and make the case that anthro-pedostratigraphy will be a useful and special contribution to geologists’ deliberations about how the planet has crossed a boundary into the Anthropocene [39, 40].

3.1 Pedostratigraphy

In the past, the science of pedostratigraphy uses paleosols (i.e., technically, soils of the past that are buried, fossilized, and found in the stratigraphic record) to interpret past climates and environments. Geologists have recognized paleosols to be a part of the geologic-climatic record for over a century [41]. In 1961 the American Commission on Stratigraphic Nomenclature instituted formal recognition of paleosols as soil-stratigraphic units. These were not often used but in 1983 the stratigraphic code was revised [42] in part to expand the concept and application of soil-stratigraphic units. Such pedostratigraphic units were named geosols [42, 43] and described to be buried, traceable, three-dimensional bodies of rock that consist of one or more differentiated pedologic horizons with uppermost and lowermost boundaries being the definite physical boundaries of a buried soil profile.

Pedostratigraphy, geosols, and pedo-stratigraphic criteria are summarized well in the latest revision of the North American Stratigraphic Code [44]. Revisions to the code are intended to be slow in coming but they must keep pace with scientific advances. In the 1983 Code, for example, pedostratigraphic strata and geosols were confined to the archaic solum concept, i.e., the A, E, and B horizons, excluding the C horizon.
as “non-soil”. In the 2005 revision, however, the C horizon is included in the concept of geosol. According to the 2005 Code, the problem is locating the lower boundary of the C horizon. To the pedologist, however, this is not at all surprising as the lower boundaries of the B and C horizons are frequently the most difficult boundaries to locate in an actively forming soil, much less in a geosol. We hypothesize that ancient, weathered “paleosol C horizons” are common throughout the world but simply have not been widely recognized to date.

While the 2005 Code was modified to expand with the lower boundary of paleosols, understanding and description of new soil orders, notably Andisols, Gelisols, and Oxisols, need consideration in future revisions of the stratigraphic code. Geosols must apparently be overlain by a formally defined lithostratigraphic unit, and thus geosols are rarely if ever found in Holocene materials. Perhaps more clarity is needed on distinguishing pedostratigraphic from other stratigraphic units, and may in this regard be similar to what has been called the archaeosphere [40]. The fundamental core distinction of pedostratigraphic layers is that they are time transgressive, non-synchronous, i.e., they only form over time. Paleosols and pedostratigraphic units are often layered in horizons but these cannot be separated from the whole profile, for soil horizons are separated in space but not in time [45]. We suggest that the North American Code and International Stratigraphic Guide [46] be revised on a decadal rather than multidecadal cycle.

3.2 Onward to an anthro-pedostratigraphy

Global soil change indicates how the Earth as a natural planet is transitioning to a human-natural system. A polygenetic wave of human-affected soil change is being recorded in Earth’s litho-, bio-, and chemostratigraphies and these anthropic signals have yet to be described in the North American Stratigraphic Code and International Stratigraphic Guide. These records form the basis for identifying anthropic strata and boundaries, and they signal how the planet is transitioning from a natural to human-natural system, and crossing into the Anthropocene [39, 40]. Here we sketch some litho-, bio-, and chemostratigraphic signals that record the human alteration of Earth’s soil.

3.2.1. Lithostratigraphic signals. Human alteration of soils and paleosols includes soil profiles eroded, mixed with, and buried under new layers of natural and human-made deposits. These “event beds” are the lithostratigraphic signals of the Anthropocene. Most stream and river sediments derive from the world’s $1.5 \times 10^9$ ha of cultivated soils, although major amounts come from residential construction areas, mine lands, roads, and abandoned, historically cultivated lands. Hooke [47] estimated that humans are Earth’s chief geomorphic agent as gauged by the volume and mass of soil and rock moved by human beings; Wilkinson et al. [48] reinforced this view by estimating that human accelerated rates of sedimentation are an order of magnitude greater than those over geologic time; and Haff [49] expanded on these estimates to include a number of natural and human forced advective and diffusive processes. At the same time, many rivers are dammed and are trapping enormous volumes of eroded soil [50]. Coastlines, always highly dynamic environments, are also actively being modified, supplemented, and restructured in human attempts at stabilization and reclamation [51]. Off-shore, rivers are delivering human-accelerated sediments to the coastal shelf in plumes and large fans of what some might call “subaqueous soil-sediments.”

Human beings also create built environments in cities, towns, and villages. The structural materials of such environments are designed to resist degradation, physical and chemical weakening, corrosion, fire, and decomposition. Such structures and their waste products derive from wood, stone, cements, sand, clays, gravels, limestones, mine waste rock, plastics, glass, metals and their alloys. The lower boundary of urban soils are important to consider as the built environment is highly altered belowground. Foundations,
pipelines, pilings, and drill boreholes proliferate through the urban subsurface. In the past, with pedology confined as a basic, natural science, the science of urban soils lay practically undeveloped. Today, the pedology of the urban and human-altered environment is a scientific frontier and a burgeoning science [52-54].

3.2.2. Biostratigraphic signals. Because land-use change significantly impacts soil microbes, invertebrates, and vertebrates [55-57], the fact that more than half of Earth’s soil are today actively managed means that the Anthropocene is marked by significant impacts on the Earth’s biota. While most of the planet’s biodiversity resides in the soil, soil’s keystone species include engineers such as earthworms, beavers, ants, and mangroves and all are particularly responsive to human activities. Managed and domesticated plants such as corn, rice, and wheat, and perennial crops of trees and vines have root structures and functions that alter soil hydrology, the development of soil horizons, and the physical, biological, and chemical properties of soil. Soil management also alters seed banks, pollen deposits, and the biologically mediated mixing of soil, known as bioturbation.

Human beings have long been responsible for biotic extinctions [58] but also intercontinental mixing of biotic species, which results in some becoming actively invasive. Human-associated extinction of large animals (the mega-fauna) and their replacement by large domesticated cattle, pigs, sheep, and chickens have caused major shifts in the bone records of Pleistocene, Holocene, and Anthropocene soils. Overall, the biostratigraphic signals of human influence are highly significant to the anthropo-stratigraphic record.

3.2.3. Chemostratigraphic signals. The biogeochemical cycles of carbon, nitrogen, phosphorus, acidity, metals, radionuclides, and organic compounds have been significantly altered by human beings, and such chemostratigraphic signals in soils and paleosols are global in scale [59, 60]. Nearly all soil profiles and sediments are chemically altered in some way by human imprints from fertilizers, wastes, irrigation solutes, and various airborne pollutants and radionuclides.

Chemical markers define many geologic boundaries, one of the most famous being the iridium anomaly of the Cretaceous-Paleogene boundary when the extraterrestrial bolide collided with the Earth approximately 65 million years ago. Isotope excursions of several elements are also used to mark geological boundaries and may be particularly useful to signaling the Anthropocene given the human emissions to the atmosphere of a family of long-lived isotopes. Lead isotopes demonstrate pollution histories over several millennia of mining and smelting [61], and sulfur isotopes trace sources of acid rain from the industrial age. Stable isotopes of carbon and nitrogen track effects of fossil fuel combustion and the rapid rise of nitrogen fertilization in the late 20th century. Radioisotopes from aboveground nuclear bomb testing, including $^{99}$Tc, $^{129}$I, and $^{239}$Pu, are detectable across the planet due to their liberation and long-distance transport from the 1950s through the mid-1960s [62].

4. Conclusions: An Anthro-pedostratigraphy for the Anthropocene

Over much of the Holocene, human beings have fundamentally transformed soil, biologically, chemically, and physically. Paleosol formation has been greatly accelerated as both fluvial and aeolian erosion and deposition have been greatly increased relative to long-term natural rates. As soils are transformed into human-natural systems, soil fluxes of energy, gases, water, solutes, and solids and energy with the atmosphere, hydrosphere, lithosphere, and biosphere are altered in ways difficult to predict. The human imprint on Earth’s soil has created the need for a new science, that of anthro-pedostratigraphy, to track the effects of human altered soils and paleosols on litho-, chemo-, and bio-stratigraphies. The transformations of both pedology to anthropedology and pedostratigraphy into anthro-pedostratigraphy signal clearly that
a boundary has been crossed: the Earth itself is transitioning to a human-natural system, i.e., in the Anthropocene.

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