

# “The Changing Model of Soil” Revisited

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In 1961, the late Marlin G. Cline wrote a remarkable essay entitled, “The Changing Model of Soil” for the 25th Anniversary Issue of the *Soil Science Society of America Proceedings*. Cline was most impressed with how geomorphology was enriching pedology, and with the increasingly sophisticated views of soil time and of the *processes* of soil formation. We revisit Cline’s general objectives by re-evaluating the changing model of soil from the perspective of the early 21st century, and by taking stock of the application of soil models to contemporary needs and challenges. Today, three ongoing changes in the genetic model of soil have far-reaching consequences for the future of soil science: (i) that soil is being transformed globally from natural to human-natural body, (ii) that the lower boundary of soil is much deeper than the *solum* historically confined to O to B horizons, and (iii) that most soils are a kind of pedogenic paleosol, archival products of soil-forming processes that have ranged widely over the life of most soils. Together and each in their own way, these three changes in the model of soil impact directly human–soil relations and give structure and guidance to the science of anthropopedology. In other words, *human forcings represent a global wave of soil polygenesis altering fluxes of matter and energy and transforming the thermodynamics of soils as potentially very deep systems*. Anthropogenesis needs much better quantification to evaluate the future of soil and the wider environment.

**Abbreviations:** LTSEs, long-term soil-ecosystem experiments.

Throughout history, humanity has worked with and conceived of soil for food production, water collection and distribution, and foundational support for roadways and buildings. Even still, a fundamental development in the model of soil (i.e., the soil profile) came in the 19th century when soil was first described as a natural body, worthy of its own science and genetic model.

From the perspective of 1961, Marlin Cline, a long-standing professor of soil science at Cornell University (Grossman, 2011), was moved to write about how the model of soil as a natural body was changing, the natural body first articulated by Hilgard (1860), Darwin (1882), and Dokuchaev (1883), and so well formulated by Jenny (1941). By “changing model”, Cline (1961) meant the changing “mental picture” of the soil profile, organized and constructed by quantitative relationships. Cline’s scientific model was analogous to Thomas Kuhn’s scientific paradigm, an idea that exploded through the sciences and popular culture starting in the mid-1960s (Kuhn, 1962; Bird, 2011).

Cline was most impressed with how geomorphology was enriching pedology, and with the increasingly sophisticated view of soil time and of the dynamic processes of soil formation. These latter changes foreshadow the alliterative phrase we will use later in this paper that “most soils are a kind of polygenetic paleosol,” by

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which, we mean that as long-lived archival systems, soils accrue features over their lifetimes due to temporally variable soil-forming processes, natural and human-forced.

Viewed from today's perspective, there is special opportunity in revisiting Cline's general objectives, re-evaluating the changing genetic model of soil, and taking stock of contemporary soil science and its application to 21st-century needs and challenges. In so doing, we are motivated by our colleagues who refer to our geologic epoch as the Anthropocene in recognition for how extensively humanity is altering Earth systems (Crutzen, 2002; Zalasiewicz et al., 2008; Certini and Scalenghe, 2011), by colleagues who in 1990 wrote the classic pedological text, "Global Soil Change" (Arnold et al., 1990), and by those who have recently developed the highly integrative concept of the Earth's Critical Zone (NRC, 2001, 2010; Brantley et al., 2006; Wilding and Lin, 2006). More than anything, these ideas underline obligations and opportunities for soil science in this important period of Earth and human history (Yaalon, 2007; Lin, 2011; Baveye et al., 2011; Grunwald et al., 2011; Janzen et al., 2011).

In this paper, we describe and evaluate how the genetic model of soil is being altered by the soil and Earth science communities in three major ways.

- The first transforms soil from a natural to a human-natural body.
- The second expands soil from relatively shallow *solum* to a much deeper and more voluminous system whose lower boundary is typically diffuse but is determined by the full depth of matter affected by pedogenic processes.
- The third involves the recognition and quantification that most soils are polygenetic, that is, archival products of pedogenic processes that range widely over time.

These three changes are interrelated. In other words, the ongoing acceleration of human forcings of soils represents a new global wave of soil polygenesis greatly altering fluxes of matter and energy and transforming the thermodynamics of soils as potentially very deep systems. Together the three changes in the model of soil emphasize the fundamental importance of anthropedology as an applied and basic science. Human impacts on soil are well studied in archeology, geoarchaeology, anthropology, and environmental science (Eidt, 1977; Butzer, 1982; Davidson, 1982; Short et al., 1986; Johnson and Lindberg, 1992; Alexandrovskaya and Alexandrovskii, 2000; Hiller, 2000; Holliday, 2004; Howard and Olszewska, 2011). A major challenge for contemporary soil scientists is to grow an anthropedology that extends pedology's inherent interdisciplinarity (Cline, 1961; Dobrovolskii, 2006) and that precisely and accurately quantifies human interactions with soils and the ecosystems they support.

Cline (1961) anticipated much about these ongoing changes. Well aware of the rising human influence on soils, Cline stated that intensifying land management "... magnifies man and his activities as factors of soil formation and demands recognition of his work." About the soil as *solum*, Cline suggested that

research with the lower boundary of soil, may force us "to extend the lower limit of our model of soil to greater depth...", clearly anticipating the deepening of the genetic model of soil and even the concept of Earth's Critical Zone (NRC, 2001; Brantley et al., 2006; Wilding and Lin, 2006).

Human-soil relations, soil's lower boundary, and soil polygenesis have wide application for humanity and are critical to the development of soil science in the 21st century, a time that is placing unprecedented demands on the Earth's soil economically and environmentally. We are moved to write this paper to encourage more explicit attention to these issues across all disciplines of soil science, to further the science of anthropedology, and to help recruit the best young scientists to our venerable profession. We might even suggest that in another half century, a student of a newly recruited scientist might venture yet another Cline-like essay on the changing model of soil.

## SOIL AS A HUMAN-NATURAL BODY

The most fundamental historical development in the model of soil (technically, the soil profile) came in the 19th century when soil was first described as a natural body, worthy of its own science and genetic model; a natural and dynamic system complete in itself. In the 21st century, however, natural soil bodies are disappearing rapidly due to humanity's unprecedented and expansive growth (Amundson et al., 2003; Ellis and Ramankutty, 2008; Galbraith, 2006), with humanity today being Earth's primary geomorphic agent (Hooke, 2000; Wilkinson, 2005). As a result, the concept of soil as a human-natural body can be argued to be as important to pedology today as was the 19th century articulation of the natural-body concept by Hilgard, Darwin, and Dokuchaev (Yaalon and Yaron, 1966; Richter, 2007). Recognizing humanity to be "a fully fledged factor of soil formation" (Dudal et al., 2002) not only enriches the orientation of our science, but reinforces the special role to be played by soil science in resource and environmental problem solving of the 21st century (Grunwald et al., 2011).

Transforming soil from a natural body to a human-natural body does more to our science than simply add a sixth factor to a state-factor equation (Bidwell and Hole, 1965; Yaalon and Yaron, 1966). While the details of this transformation are hardly resolved (Amundson and Jenny, 1991; Richter et al., 2011a), the human-natural system fundamentally alters the soil as our subject of study in two distinctive ways: (i) Human forcings take us well outside our scientific experience with soil as a natural body; and (ii) Human forcings deepen and broaden the dialog of our science, necessitating new interactions not only with the social sciences and the humanities but with the public at large.

1. *Human forcings take us well outside our experience with soil as a natural body*, as humanity substantially transforms soil's physical, chemical, and biological properties and processes. These changes affect soil's functioning in local management units such as farmers' fields, foresters' stands of trees, city parks, and local residential neighborhoods and villages. The changes also impact the wider environment, especially the Earth's atmosphere and

water systems. The accelerating pace of change is illustrated by Fig. 1, in which changes in soil organic carbon due to cultivation, manuring, and reforestation contrast greatly with rates of change in soils as natural bodies. One of the most impressive points about Fig. 1 is the wide variation in soil responses to land uses. Quantifying rates of change and associated fluxes of materials and energy is key to predicting humanity's forcings of soil from local to global scales (Smith et al., 1997; Nave et al., 2010).

As human-natural systems, soils have long memories that accumulate over time (Targulian and Goryachkin, 2008). Many historic human impacts continue to influence features and processes of contemporary soils (Richter and Markewitz, 2001; Schaetzl and Anderson, 2005), and distinguishing contemporary changes from those of the past is important not only to understanding soil as a human-natural body (Bridges, 1978; Showers, 2006) but to improving soil and land management (van Wesemael et al., 2010). Figure 2 illustrates a framework of anthropedogenesis organized by three overlapping time scales: multi-millennial pedogenesis of traditional natural-body pedology, the historic legacies of human forcings, and contemporary human influence. Such a framework, complete with feedbacks and interactions with the wider environment, illustrates why Earth's soil is a most remarkable natural, historical, cultural, and environmental system (Amundson and Jenny 1991) with potentially wide human interest and application.

2. *Human forcings deepen and broaden the dialog of our science*, as humanity must aspire to become much more than a force that disrupts the natural soil body. While the narrative is deeply rooted that humanity only disturbs, destroys, or even conquers nature (Marsh, 1874; Osborn, 1948; Carson, 1962), *soil scientists are tasked to help humanity become a more sustaining soil-forming agent*. Whether soil science can succeed in this endeavor is not known, but success will be much more likely with joint efforts with natural and social scientists, engineers, humanities' scholars, and policy analysis as well. Promoting humanity as a fully fledged soil-forming agent has become our science's ultimate challenge, and depends on nothing less than encouraging humanity to use the ax, the shovel, and the plow "for the good of the land" (Leopold, 1949).

## SOIL AS EARTH'S VOLUMINOUS CRITICAL ZONE

Since the first conceptualization of soil as a natural body, the scientific model of soil has expanded into increasingly deep layers of the Earth's crust (Tandarich et al., 2002). Chizhikov (1968) traced this pattern, starting in 19th century

Russia when surficial accumulations of soil organic matter (O and A horizons) were initially considered the main part of soil. The B horizons were subsequently recognized to be illuvial environments (Simonson, 1968; Bridges, 1997), and to contrast with A horizons in texture, structure, color, and in accumulations of aluminosilicate clays, Fe and Al oxyhydroxides, salts, and carbonates. Taken together, the O, A, E, and B horizons are defined as the *solum*, which for much of the 20th century has been the modal concept of the soil. In the words of Plaster (1992), the *solum* is the "true soil."

Underlying B horizons, however, are C horizons that join the *solum* with unweathered materials below (Brady and Weil, 2002). The C horizons range from shallow to very deep, sometimes extending many meters in depth (Buol, 1994; Richter and Markewitz, 1995; Bacon et al., 2012). Historically, relatively little pedologic research has evaluated C horizon formation, and C horizons are often considered more the domain of inorganic geochemistry than to be an integral part of the soil. Even today, C horizons are formally defined as being "little affected by pedogenic processes" by the most recent *Keys to Soil Taxonomy* which technically confines soil to the upper 2 m of the ground surface (Soil Survey Staff, 2010).

A few scientists however have harbored ideas that the soil profile can be massively deep and voluminous. Hunt (1986) labeled the *solum* as "agriculturists' soil," in an effort to broaden perspectives about the processes that form Earth's soil. Ramann (1928) conceived of soil as "the entire upper weathering layer of the earth's crust." Glinka (1931) suggested that soils could be 10s of meters deep. In recent decades, the lower boundaries of soil are receiving increased attention (Schoeneberger and Wysocki, 2005). Questions about C horizons environments have been explored from the perspective of pedology

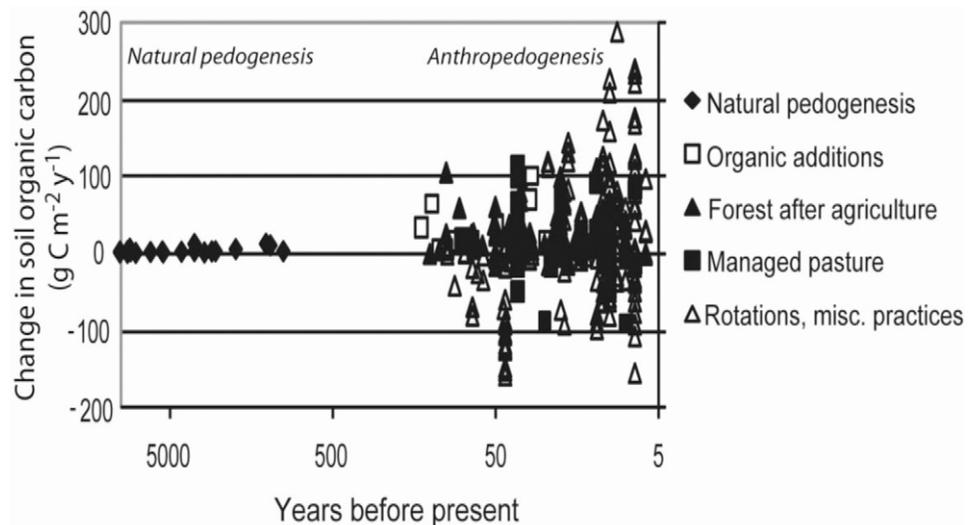


Fig. 1. Rates of change in soil organic carbon in response to cultivation, manure amendments, reforestation, and other practices contrast with rates of change in soils that are products of natural soil formation. Plotted are average rates of change over the indicated age of soil or soil-management regime. Natural soil formation accruals of organic carbon are estimated from 22 chronosequence studies of a variety of Holocene soils, on dunes, alluvium, volcanic debris, and glacial deposits from the tropics to the tundra (Schlesinger, 1990). Anthropedogenic rates of carbon gain and loss are from paired plot comparisons, chronosequences, and long-term soil studies (Post and Kwon, 2000; West and Post, 2002).

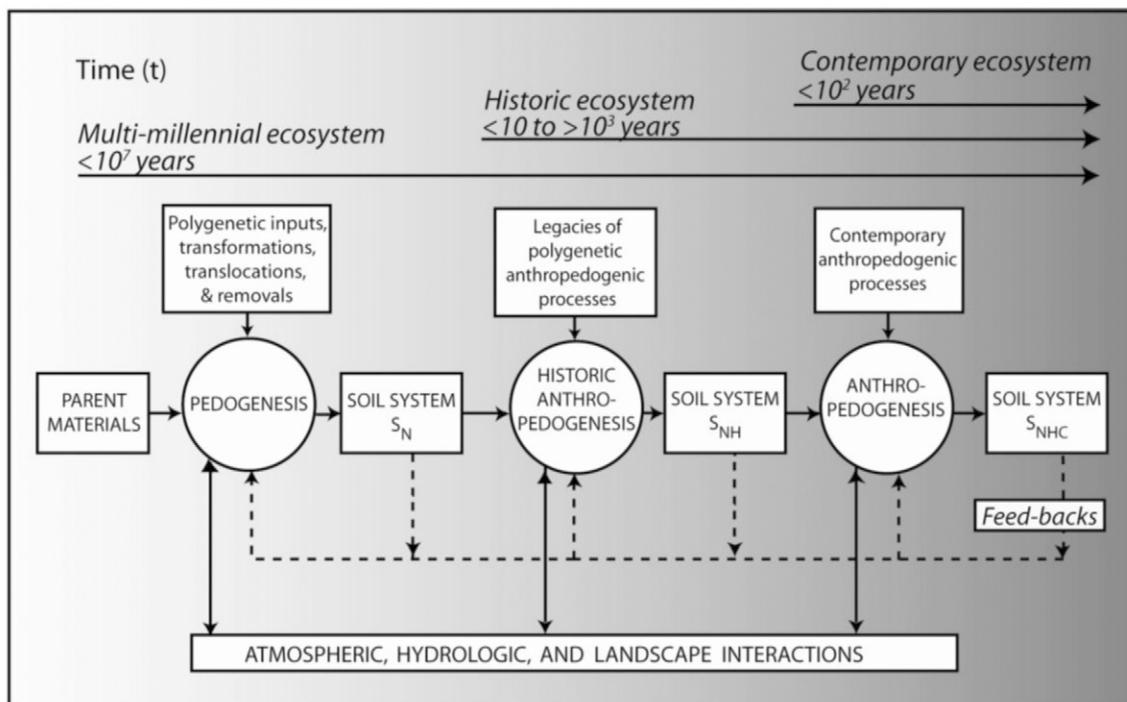


Fig. 2. Framework for understanding soil change organized by three time scales: the multi-millennial natural soil system ( $S_N$ ), potentially stretching back for several millions of years; the historic soil system ( $S_{NH}$ ), affected by both natural processes and legacies of human impact usually lasting up to several thousands of years (with notable exceptions of historic human impacts lasting much longer); and the contemporary human-affected system ( $S_{NHC}$ ), affected by natural and historic processes and ongoing management typically for less than 100 yr (modified from Richter [2007] and Yaalon and Yaron [1966]). Feedbacks are illustrated to indicate effects of internal soil profile development, as are atmospheric, hydrologic, and landscape interactions.

(Calvert et al., 1980; Buol and Weed, 1991; Stolt et al., 1992; Graham et al., 1994; Richter and Markewitz, 1995; Buol et al., 2003; Bacon et al., 2012), geomorphology (Birkeland, 1999), groundwater hydrology and chemistry (Montgomery, 2007), microbiology (Chapelle, 2001), and plant-soil science and deep rooting (Stone and Kalisz, 1991; Nepstad et al., 1994; Jackson et al., 1996; Jobbagy and Jackson, 2001; Harrison et al., 2011). A taxonomy for C horizons was developed by Buol (1994) with the help of soil scientists, engineers, and geologists.

Omission of the soil environment below 2-m depth from any contemporary model of soil would be a serious shortcoming. Not only are many C horizons voluminous and massive, but these environments are significantly influenced by gases, solutes, roots, and microorganisms that are all an integral and active part of the soil system (Graham et al., 1994; Richter and Markewitz, 1995). Soils that include pedogenically formed “C horizons” range from 10 to 100 m in depth in biogeomorphically stable landforms of, for example, Malaysia, Hong Kong, and the Southern Piedmont of North America (Carroll, 1970; Ruxton and Berry, 1957; Eswaran and Bin, 1978; Richter and Markewitz, 1995; Bacon et al., 2012).

Figure 3a illustrates how soil  $CO_2$  concentrations reach peak concentrations in lower B and in C horizons, demonstrating how soil respiration and gas diffusion drive carbonic acid weathering deeply into subsoils (Richter and Markewitz, 1995; Markewitz et al., 1998; Oh and Richter, 2004; Bernhardt et al., 2006; Richter et al., 2007b). Figure 3b illustrates extreme biogeochemical effects of pedogenic

weathering that extend many meters below the *solum* in nine soil profiles derived from granite (Rasmussen et al., 2011). Tau is a weathering index that when negative, expresses the loss of chemical elements due to pedogenic weathering relative to unweathered parent materials in these cases granitic bedrocks (Fig. 3b). The highly negative Taus for Na ( $<-0.8$  or 80% loss) down through 6 m of depth in nine soils indisputably illustrate effects of pedogenic weathering well below the *solum* because nearly all of the Na in Na-plagioclase has been lost during soil formation.

As predicted by Cline (1961), research is forcing us “to extend the lower limit of our model of soil to greater depth.”

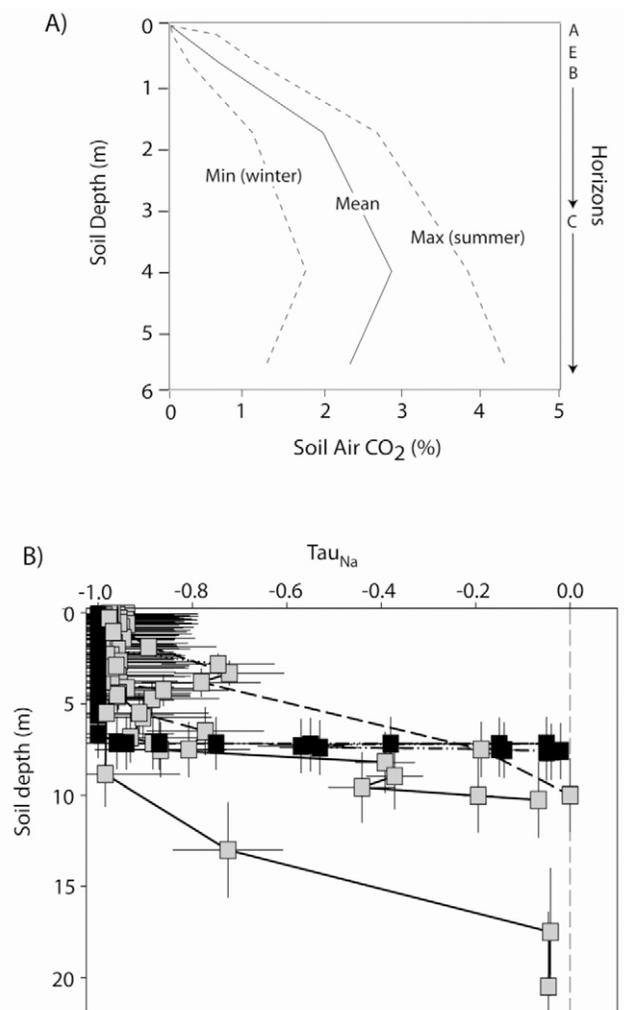
## SOIL AS POLYGENETIC PALEOSOL

A third change in the model of soil involves the growing recognition and quantification that most soils are formed by polygenesis (Buol et al., 2003), and that as long-lived systems, soils are formed by processes that have ranged widely over pedogenic time. Soil-forming processes that vary over the life of a soil include atmospheric deposition (of water, dust, and solutes), mineral weathering, organic decomposition, pedoturbation, plant rooting, redox reactions, fire effects, chemical leaching, and erosion, which *together* combine to produce soil organic matter, organo-mineral complexes, secondary minerals, aggregates, clay skins, complex surface areas, soil pans, and pore networks themselves. As a consequence, soils by their nature are products of multiple environments and many contain within them records of the past. Many soils are a kind of polygenetic paleosol.

Consider Fig. 4, a simulated trajectory of soil development in a landscape in which pedogenic processes are dynamic through time (Johnson 1985). Here, soil thickness is modeled over 39,000 yr, and determined by soil deepening (e.g., soil production from below), upbuilding (e.g., deposition from above), and removal (e.g., surficial erosion). The special value of this model is its focus on the polygenetic nature of soil deepening, upbuilding, and erosion, that is, soil-forming processes that range widely through time. According to Schaetzl and Anderson (2005), “thickness is a dynamic property that ebbs and flows through time; so it is with soil development.” The exceptional soil is therefore the monogenetic soil, a soil created under the influence of a single bundle of major pedogenic processes throughout its lifetime. Such a soil is called a Vetusol by Busacca and Cremaschi (1998).

Many scientists continue to treat soil-forming factors and processes as if they are relatively constant and directly observable from the contemporary environment. Perhaps the best critique of this perspective of soil formation is that of Vreken (1975) who observed that there are two perspectives to soil time with only one widely appreciated, that being the perspective that time is the duration of soil formation, that is, a soil’s chronological age. Soil profiles, however, form during *particular* geologic periods (Pavich and Chadwick, 2004; Monger et al., 2009), over decades, hundreds, many thousands, and even millions of years, time scales with widely varying climatic, biotic, and geomorphologic forcings. By definition, as soils age they experience multiple forcings and overlays. There is great need for more concrete understanding of the variability in climate, biota, and geomorphology over pedogenic time and the legacies of their soil effects (Targulian and Goryachkin, 2008). A number of recent papers are giving detail to soil polygenesis. Two excellent examples are a soil micromorphology study of Sedov et al. (2011) in which sequences of Pleistocene volcanic soils in Mexico and Armenia are shown to combine features of both arid and humid pedogenesis. During relatively long intervals between soil burials from volcanic eruptions, polygenetic soil profiles contain both carbonates and illuvial weathered clays, as products of shifting climates of dry and more humid periods, respectively. Second are human-induced records of polygenesis. In a national study of soil carbon sequestration, recent soil-carbon gains in upland grasslands of Belgium were traced to cropland abandonments a half-century ago, indicating a long-term drawdown in soil carbon under the plow followed by more than 50 yr of carbon accrual under grass (van Wesemael et al., 2010). Similarly, in rural South Carolina, four decades of secondary forest growth accumulated soil organic carbon in long-cultivated A horizons that had been depleted by historic cultivation for cotton (*Gossypium hirsutum* L.) before 1955 (Richter et al., 1999). Soil profiles are increasingly subject to multiple waves of anthropedogenesis.

In Iowa, where soils have formed over the last tens of thousands of years, Ruhe and Scholtes (1956) documented in a classic and complex study, effects of shifting climate and vegetation on soil formation. Their paper opens with a blunt understatement that is unfortunately applicable even today:



**Fig. 3. Pedogenic processes greatly affect C horizons. (A)** Soil CO<sub>2</sub> concentrations are likely most elevated below the solum in many soils with deep plant rooting (Richter and Markewitz, 1995; Bernhardt et al., 2006). The data illustrated are from 2-yr mean CO<sub>2</sub> concentrations under 40-yr loblolly pine forests at the Calhoun Experimental Forest in South Carolina (Richter and Markewitz, 1995). Soil respiration’s CO<sub>2</sub> drives carbonic acid weathering, a major pedogenic acidification process in the full soil profile (Richter and Markewitz, 2001; Oh and Richter, 2004; Richter et al., 2007b). **(B)** Depth profiles of the sodium mass transfer coefficients (tau-Na) for nine biogeomorphically stable soils derived from granites in a range of temperate and tropical climates. All soils had lost more than 80% of Na originally present in the bedrock throughout 6 m of soil profiles, demonstrating plagioclase weathering to great depths and extreme intensity of pedogenic weathering well below the solum (Rasmussen et al., 2011). Error bars are relative standard deviations and are explained in the supplemental materials of Rasmussen et al. (2011).

“Assumptions (are) made that vegetation and climate have been stable as influencing factors in soil formation. The possibility that vegetation and climatic patterns may have changed during periods of soil development has not been considered.” Since soil development can be influenced by shifting environments even in such youthful Holocene and late Pleistocene soils (Ruhe and Scholtes, 1956; Chadwick and Davis, 1990; Muhs and Bettis, 2003; Monger et al., 2009), older soils are most certainly polygenetic. *Polygenesis is the rule, monogenesis the exception.*

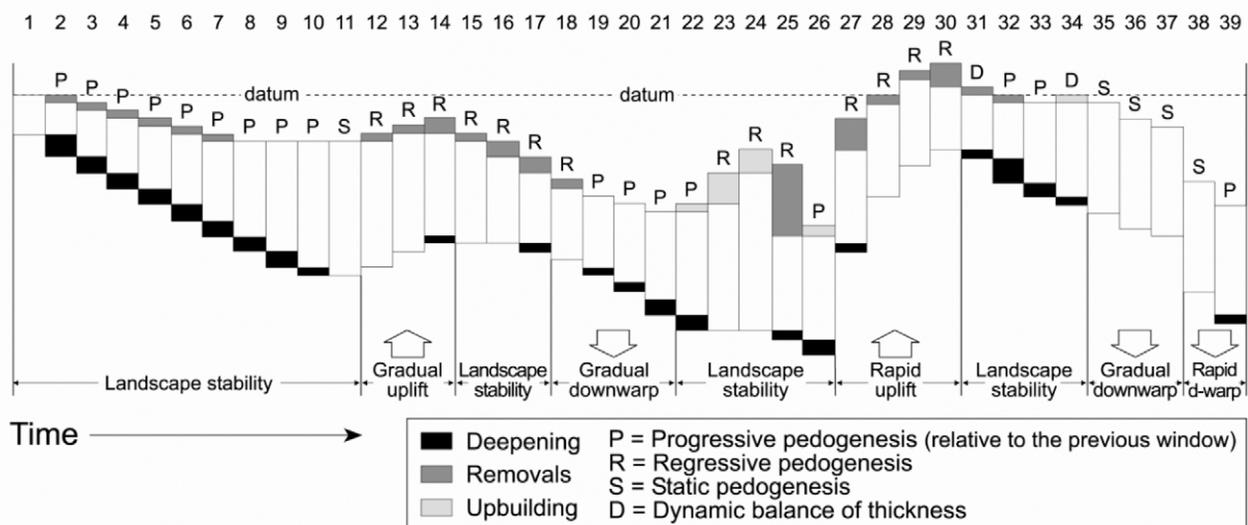


Fig. 4. Relationships of soil thickness processes in a hypothetical dynamic landscape over 39,000 yr (Johnson, 1985). Each time step represents 1000 yr of change relative to a constant datum, and illustrates net results of: (D) deepening at the base of the soil profile into relatively unweathered materials, (U) upbuilding of the surface of the soil profile from surface-accreted materials, and (R) removal by soil erosion and mass wasting. Crustal uplifts and downwarping also influence this polygenesis. Johnson (1985) called thickening of the profile “progressive” pedogenesis and loss of profile depth “regressive” pedogenesis. According to Schaetzl and Anderson (2005), “thickness is a dynamic property that ebbs and flow through time; thus it is with soil development.”

Closely associated with soil polygenesis are concepts known as “soil evolution” (Nikiforoff, 1949; Simonson, 1959; Johnson and Watson-Stegner, 1987). Soil evolution represents a major advance from concepts of zonal soils that were seen to be pedogenetically determined by regional vegetation and climate (Marbut, 1935; Whittaker, 1970). Zonal soils were mapped over large geographic areas and were conceived as a maturation toward an equilibrium endpoint, often under a generally stable suite of soil-forming factors. In notably parallel developments, the science of plant ecology in the early and mid-20th century was keenly interested in vegetative successions of plant species that over time developed into relatively stable climax plant communities (Oosting, 1948; Curtis, 1959; Whittaker, 1970; Binkley, 2006). Today, whether in pedology or ecology, these latter ideas seem stiffly linear and deterministic. More contemporary ideas are that soil and ecosystem change has an underlying nonlinear and sometimes even an unpredictable character (Phillips et al., 1996). These developments are attributable to additional decades of field observation, and to a greater appreciation for thresholds (Chadwick and Chorover, 2001) and the complexities of systems controlled by high-order interactions.

As a result of soil polygenesis, paleosolic features accumulate over the life of a soil, and while some features are erased, others persist. Given traditional definitions of paleosol that emphasize buried or fossilized soils of the distant past (Ruhe, 1975; Retallack, 2001), some readers may be surprised by the use of paleosol in this context. However, we consider the statement that “most soils are a kind of polygenetic paleosol” to be justified and to describe well the changing model of soil.

In the late 19th century, Dokuchaev stated as “a slogan” according to Targulian and Goryachkin (2004), that “soil is the mirror of the landscape.” As polygenesis and paleosolic features have become more fully appreciated, the analogy of mirror

has been carefully but emphatically replaced by “memory.” In other words, “soil is the memory of the landscape” according to Targulian and Sokolov (1978) and Targulian and Goryachkin (2004). This transformation from *soil as mirror* to *soil as memory* is significant for several reasons, not the least of which is the recognition that the soil’s solid phase provides a record of its polygenetic evolution. In fact, Yaalon (1983) asserted that recognition that soil profiles could be used to reconstruct their evolutionary history was the greatest advance in pedology since Dokuchaev. In other words, understanding soil formation means understanding and reconstructing soil environments of the past. The task for pedologists is to learn to read and interpret soil profiles as archival records, especially challenging because soil systems are so exceedingly complex (Young and Crawford, 2004).

As features in soils owe much to both past and present process interactions, the metaphor of palimpsest, the ancient Greek word meaning overprint, describes soil well (Targulian and Goryachkin, 2004). The word is actively used in architecture, archeology, and the humanities, and can be directly applied to soil formation. Targulian and Goryachkin (2008) recently organized a massive collection of papers around the mirror-to-memory transition, and differentiate soil as palimpsest from that of a system with a more chronological character. Soils rarely move continuously through time, and speaking metaphorically, most soils are like ancient palimpsests made from animal skins that were written on, erased, and overwritten; skins used and re-used by different peoples writing different and evolving languages across history (Netz and Noel, 2007). Returning to Fig. 1, while contemporary human forcings explain much of the illustrated changes in soil carbon, some unknown portion of these human-forced variations is attributable to legacies of historic land uses (Fig. 2).

## WHY SOIL MODELS MATTER

Cline (1961) credited much to Dokuchaev including “the most fundamental change in the concept of soil in history” which resulted from Dokuchaev’s revolutionary model of natural soil formation which grew directly from his mapping work with Russia’s Department of Agriculture, the large-scale mapping of the Russian steppes for purposes of farmland taxation. In a similar way, practical soil problems stimulated the independent creation of the natural-body concept of soil in North America (Jenny, 1961). Here E.W. Hilgard (1860) wrote his natural-body essay entitled “What is soil?” while mapping the soils of the state of Mississippi for purposes of agricultural development. Both Dokuchaev and Hilgard mapped soils as natural bodies to match soils and landscapes with the needs and opportunities of agriculture. The two understood implicitly why and how soil models matter to soil and land management. Similarly, all three changes in the model of soil discussed in this paper are critically linked with practical aspects of contemporary soil and land management.

First, the model of soil as a human-natural system is critical to human health and well being and environmental management. In the coming few decades, the Earth’s soil as a human-natural system will be managed to greatly increase food production to support demands for the billions of additional persons living on Earth. Whether soils are capable of sustaining a near-doubling of food production, all while managing adverse effects on the atmosphere, water, and biodiversity, is one of society’s most important unanswered questions (Rice et al., 2009; Richter et al., 2007a).

Beyond food production, the model of soil as a human-natural system is important to producing bioenergy, fiber, and an array of chemical compounds, peat and clay, building materials, and many minerals. The human-natural model also includes soil’s regulation services that provide a more stable, healthy, and resilient environment. Human-altered soils regulate floods, filter nutrients and contaminants, provide habitat for a fantastic diversity of biota, control and harbor pests and diseases, recycle organic and inorganic wastes, and both

consume and emit greenhouse gases. In the Anthropocene epoch, the new geologic period in which humanity is altering Earth’s systems on a global scale, the science of soil as a human-natural body informs us about the sustainability of managed ecosystems.

Finally, soils in cities, towns, and villages are an important part of the lives of more than 80% of humanity (Table 1) on a land area of nearly 1.0 billion hectares or about 7% of Earth’s soils (Ellis and Ramankutty, 2008). In the immediate vicinity of most human beings, soils are altered by residential, transportation, and industrial activities; deeply compacted and drained; sealed with impervious surfaces; mined for a variety of products; and chemically contaminated, liquefied, scalped, and physically mixed. An unvarnished fact is that the model of soil as a natural body has stimulated little attention to soil’s hydrologic, physical, and ecological services in urban and residential landscapes (De Kimpe and Morel, 2000). On a more optimistic note, the human-natural model excites the world’s urban-soil specialists who are carefully surveying many urban soils, urban areas previously without mapping units or simply appearing on maps as “urban complex.” Urban soil specialists are variously engaged in mapping profiles and urbic horizons to identify soil-contaminant risks or to develop deeper understanding of community history and culture (Meijboom et al., 2004).

Second, the model of soil with an extended depth to lower boundary also matters greatly to humanity and the environment. As open systems, inputs from “above” (sunlight, plant and animal detritus, fertilizers, and atmospheric deposits such as dusts and other aerosols and gases) have been studied in detail, however, soil is also open from below and influenced by deep rooting that cycles materials into surficial volumes of the soil. Deep soil horizons are important for plant water supply during dry seasons, and as a source of nutrients via deep root uptake. Chemical pollutants are also penetrating deeply into soil profiles (Yaron et al., 2012). For example, pollutant attenuation in runoff waters will be long affected by the behavior of contaminants in

**Table 1. Major landcover or soil environments of the world at the turn of the 21st century, including their human populations and net primary productivity, modified slightly from Ellis and Ramankutty (2008).**

Environment	Description	Human population	Land area	Net primary productivity
		10 <sup>9</sup> persons	10 <sup>9</sup> ha	Pg C yr <sup>-1</sup>
Urban	Built environments, very high populations (11)	1.87	0.06	0.2
Dense settlements	Mixed urban, rural populations, with suburbs and villages (12)	0.70	0.09	0.5
Irrigated villages	Villages dominated by paddy rice and irrigated crops (21, 22)	1.09	0.18	0.8
Cropped, pastoral villages	Villages dominated by crops and pastures (23–25)	0.97	0.38	1.5
Mosaic villages	Villages with rainfed trees and crops (26)	0.50	0.22	1.6
Residential irrigated cropland	Irrigated cropland with substantial human populations (31, 33)	0.28	0.31	1.6
Residential mosaic cropland	Rainfed cropland with trees and substantial human populations (32)	0.61	1.67	10.8
Nonresidential cropland	Rainfed cropland with minor human populations (34, 35)	0.04	0.74	3.6
Residential rangeland	Rangeland with substantial human populations (41)	0.23	0.73	2.2
Nonresidential rangeland	Rangeland with minor human populations (42, 43)	0.04	3.24	5.6
Populated forests	Forests with human inhabitants (51)	0.04	1.12	8.1
Nonpopulated forests	Forests with few to no human populations (52, 61)	0	2.23	12.4
Sparse vegetation	Low density trees in cold and arid lands with few to no human population (62)	0	0.97	1.2
Barren land	Deserts, cold, and frozen lands (63)	0	1.15	0.1
Global total		6.38	13.1	50.1

deep C horizons. In sum, full soil profiles (O to C horizons) are critical to the sustainability of ecosystems, they often control the quality and quantity of ground and surface waters, and they interact actively with the larger weathering geochemistry of the Earth's crust.

Third, the model of soil as a polygenetic system most certainly matters to humanity and the environment. The natural-body model of soil has been seriously strained to accommodate human beings, especially if soil as a natural body is taken to mature toward an equilibrium endpoint only to be disturbed by humans. As a human-natural body, human forcings represent new waves of polygenesis. Given that humanity and soils evolve jointly and interactively, an objective for the human-natural model is to improve land management and sustainability. A critical question is whether human-altered soils and their anthropedogenic processes can remain connected with those of the past (Fig. 2). Global soil change (Arnold et al., 1990) thus tests the veracity of soil being *both mirror and memory of the landscape*.

## TESTING THE MIRROR AND MEMORY OF SOIL CHANGE

There is much to learn about how soils are responding to humanity, about how soils change internally as central components of land-management systems and externally in relation to the wider environment (Hillel, 1991; Yaalon, 2007; Richter et al., 2011a). The quantification of soil responses to humanity's mounting economic and environmental demands is critical to improving land management. The three changes in the model of soil discussed here lead to a similar outcome: *that new ways to quantify human-forced changes in the soil are imperative*.

Well over a century of soil science has taught us much about many details of the Earth's soil. Most of soil science has been built from studies of individual soil components and processes, from investigations of soil samples in the laboratory, under microscopes, or from field tests of soil over a few years at most. We have advanced soil science largely with reductionist studies.

While reductionist approaches have brought much to soil science, we wholeheartedly agree with Walter Kubiěna (1970) in that we know far too little about the soil as a whole system, about how soil's components work together, about functional relations between parts, about the interconnected complexity of processes, and most especially about how soil systems respond to human and natural forcings over decades and centuries. The subject of our science after all, is a long-lived system far greater than the sum of its many parts, a persistent system that is also dynamically responsive to high-order and difficult-to-predict interactions that occur instantly and also that play out over years, decades, centuries, and much longer. In addition to Kubiěna (1970), the three changes in the model of soil lead us to conclude that a carefully orchestrated network of anthropedological field experiments is imperative if we are to begin to manage soil and ecosystem change in the years and decades ahead (Richter et al., 2007a; Schmidt et al., 2011; van Wesemael et al., 2011).

Ironically, one of the earliest scientific approaches to understanding soils is the long-running field experiment, first advanced more than 150 yr ago. By mid-19th century, John Lawes, Henry Gilbert, Jean Baptiste Boussingault, and others had initiated field experiments to observe and test changes in plants and soils, that is, whole ecosystems both above *and* belowground, as they responded to agricultural management over years and decades (Rasmussen et al., 1998). These field experiments led to major discoveries in the 19th century about nitrogen fixation, organic and inorganic fertilization, nitrate leaching, fertilizer-use efficiency, nutrient cycling, and the sustainability of plant production (Richter and Markewitz, 2001).

Jenkinson (1991) used examples from the Rothamsted studies in a summary of the unique understanding that can be gained from long-term field experiments. Here, to emphasize the new imperative for long-running field experiments, we highlight several dozen 40-yr old field experiments in Asia designed to test the sustainability of intensively managed rice (*Oryza sativa* L.). The Asian studies support the sustainability of intensive rice production and aim to detect and minimize rice-yield declines. On-going results have direct implications for several billion people entirely dependent on rice-based nutrition (Dawe et al., 2000; Bhandari et al., 2002; Tirol-Padre and Ladha, 2006) and on environmental externalities of >150 million hectares of intensive rice production (FAOSTAT, 2005). These long-running Asian rice experiments are among the world's most important anthropedological field experiments in existence today.

Looking more closely, one of these long-running Asian-rice experiments is of special interest. Since the early 1960s, the maximum biological potential of rice productivity has been tested in a Philippine study at the International Rice Research Institute, and the history of this study illustrates well how invaluable and surprising results from long-term soil experiments can be (Cassman et al., 1995; Dobermann et al., 2000). In the first 6 yr in the 1960s, dry-season rice yields averaged about 9000 kg ha<sup>-1</sup>, high yields supported by fertile soil and intensive cropping, irrigation, fertilization, and pesticides. Over the next 25 yr, however, the experiment that was designed to test the maximum biological potential of rice, only declined steadily in yields down to about 6000 kg ha<sup>-1</sup> by the 1990s. The declines spurred concern and scientific study especially on how intensive practices may have been impacting soils and soil processes. While many studies proved inconclusive, management interventions in the 1990s, which included brief drainage and aeration of the soil, led directly to rapid recoveries of high rice yields. The surprising and substantial yield declines were eventually attributed to the development of a progressive N limitation (despite high N fertilization), affected by prolonged low redox potentials of continuous triple-rice cropping (Dobermann et al., 2000). Precautions about the maximum biological potential of rice and the detailed soil-N studies by Olk et al. (1996) could only have been possible in such a well operated long-term field experiment.

Adapting Voltaire's famous quotation, "in the best of all possible Anthropocenes", we would systematically initiate on global scale an efficient network of long-term soil-ecosystem

experiments (LTSEs) to test soil responses to a variety of land uses across contrasting soils, climates, landforms, and human cultures (Richter and Mobley, 2009; Banwart, 2011). Soil and off-site interactions would be periodically examined, samples archived, and accumulating data of soil solids, biota, water, and gases used to test hypotheses about specific forcings, processes, and changes in the human-natural body of soil. The LTSE research would be aimed at critical questions of soil sustainability and results would broaden impacts of this science on land management and society at large.

But this is hardly the best of all possible Anthropocenes, and we must make the most of what ongoing LTSEs have to offer. The world's existing LTSEs have been inventoried over the last 5 yr (Richter et al., 2007a; Richter et al., 2011b), and we conclude this paper by briefly taking stock of the world's ongoing LTSEs as anthropedological studies.

Overall, the global inventory of LTSEs include a total of about 250 studies, 60% are in Europe and North America (Fig. 5). With the exception of the Asian rice experiments, the developing world is underrepresented, with especially few LTSEs in Africa and South America, a most notable deficiency given the critical soil-management challenges faced on these continents. About 55% of all LTSEs test responses of soils in 3 of *Soil Taxonomy's* 12 soil orders (Soil Survey Staff, 2010), three soil orders that are most important to world agriculture, Alfisols, Mollisols, and Vertisols (Fig. 5). As for land uses, more than 80% of LTSEs test agro-ecosystems with experimental treatments that test agronomic crops, fertilization, organic matter amendments, tillage, crop rotations, and liming (Fig. 5).

Forest soils account for only about 10% of inventoried LTSEs, and few ongoing LTSEs test hay, pastures, horticultural crops, mine reclamation, wetland restoration, or urban and suburban developments. Notably few LTSEs experiment with

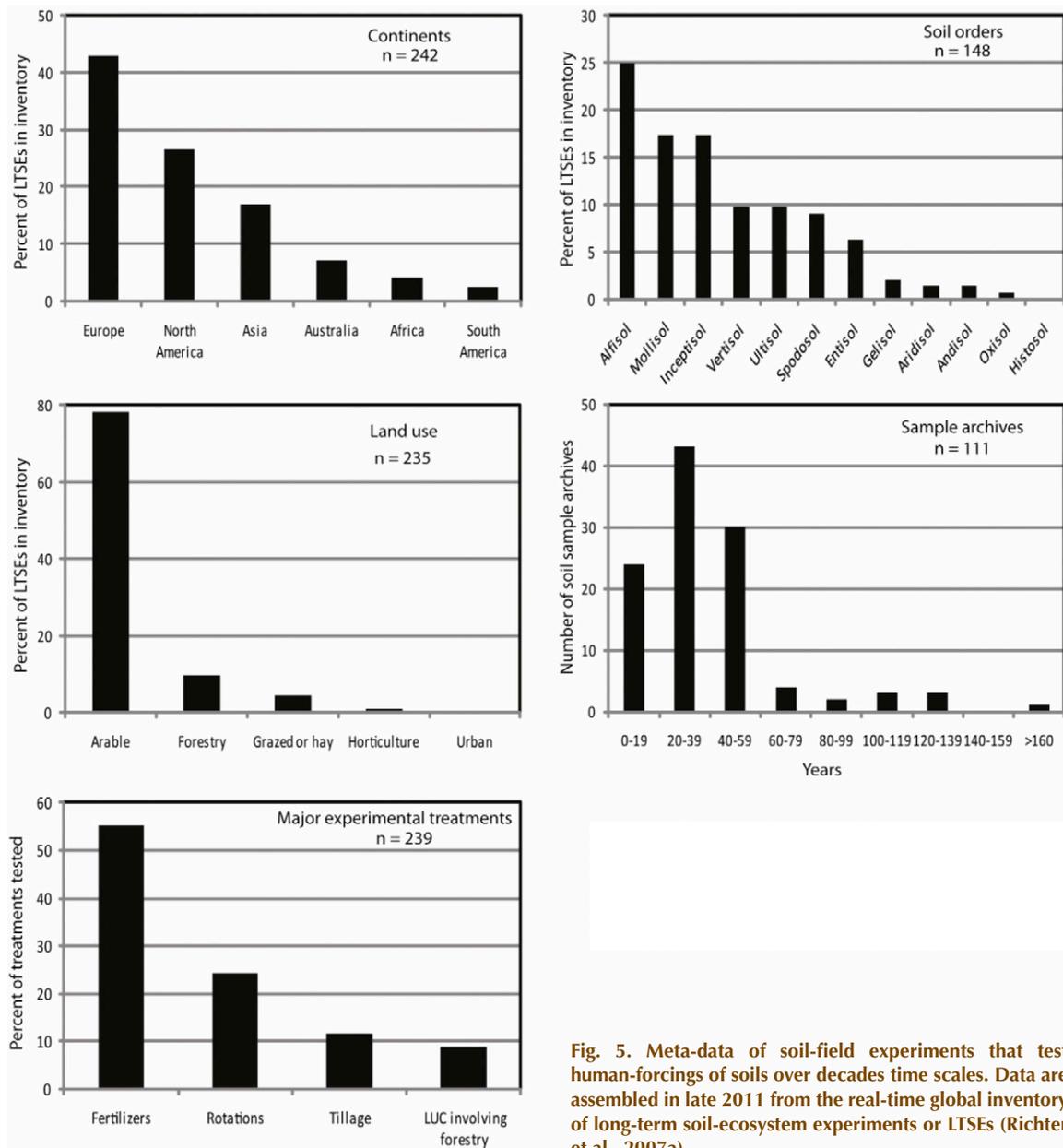


Fig. 5. Meta-data of soil-field experiments that test human-forcings of soils over decades time scales. Data are assembled in late 2011 from the real-time global inventory of long-term soil-ecosystem experiments or LTSEs (Richter et al., 2007a).

Oxisols, Histosols, or Gelisols, soils undergoing large-scale land-use conversions in the tropics, soils often drained but increasingly reflooded, and soils that are warming with loss of permafrost, respectively (Fig. 5). Also underrepresented are Aridisols and Entisols, desert soils and youthful soils, respectively, soils that cover especially large areas of the planet. The lack of LTSEs in arid and semiarid systems is a critical deficiency as not only do arid lands cover a third of the Earth's land surface but they have many soils that are highly sensitive to climate and land-use change given the water-limitations of many processes in these soils (Rodriguez-Iturbe and Porporato, 2004; Reynolds et al., 2007). There are therefore many important opportunities for new LTSEs. New LTSEs in the coming years should be designed to quantitatively support improvements in urban-soil management, mine reclamation, grazing and grassland management, conservation and industrial forestry, wetland management and restoration, landscape architecture, and many other land uses.

*But while new LTSEs are being contemplated for the future, there is immediate need and opportunity to get much more from new coordinated research based at ongoing LTSEs.* By leveraging existing LTSEs, a cross-site sampling of soil could in relatively short order make a new contemporary examination of the cumulative soil effects of long-practiced intensive agricultural practices. Such cross-site analyses could span climates and management systems and greatly increase understanding of the sustainability of intensive fertilization, organic amendments, and tillage and on soil's interactions with the atmosphere, water, and climate (Smith et al., 1997; Ladha et al., 2011; Richter et al., 2011a). Obviously, this could be critical anthropedological information for management and research in the coming few decades.

## CONCLUSIONS

Soil science is seriously challenged by new economic and environmental demands placed on soils and also by a changing model of soil that brings with it needs for new data. Humanity is accelerating soil change across the diversity of Earth's soils and the model of the soil profile has expanded to include much greater depths as well. Most soils can be understood to be polygenetic systems, with human forcings representing a new global-scale wave soil polygenesis.

To provide the large human population projected for 2050 with a more stable, healthy, and resilient environment, the changing model of soil appears well positioned to help soil science address some of the most important scientific needs of humanity: for example, how will productivities and ecosystem services of human-altered soils change and be managed over the coming few decades (Wall, 2004)? While scientists will use many scientific approaches in coming decades to investigate anthropedogenic problems (Rice et al., 2009; Grunwald et al., 2011), there are major opportunities for one of the most traditional of approaches in soil science, that of the long-running soil-ecosystem field experiment. An efficiently operating network of LTSEs aimed squarely to improve soil and land management

can accelerate development of anthropedology, and help assure the future of soil science itself.

In this age of human-forced global soil change (Arnold et al., 1990), the converse is most certainly true as well. Changes in soil directly influence the evolution of human societies and cultures. This is a mutual co-genesis, with soil and humanity developing jointly and interactively. If in the coming decades, expanding demands for food and related products overwhelm soil's capabilities, the future co-genesis of soils and humanity will involve painful societal adjustments and environmental degradation. If however in these decades, we are able to feed the world and improve soil's management, the future co-genesis will benefit not only human well being, soils, and the wider environment, but perhaps even the character of humanity as well.

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