 DOI: 10.1002/jpln.201900320

Game Changer in Soil Science
The Anthropocene in soil science and pedology

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Take Home Message

The venerable science of pedology, initiated in the 19th century as the study of the natural factors of soil formation, is adapting to the demands of the Anthropocene, the geologic time during which planet Earth and its soils are transitioning from natural to human-natural systems. With vast areas of soils intensively managed, the future of pedology lies with a renewed science that can be called anthropedology that builds on the pedology of the past but proceeds from "human as outsider" to "human as insider." In other words, the human in pedology must shift from being a soil-disturbing to soil-forming agent. Pedology is well prepared to respond to the challenges of the Anthropocene, given the decades of research on human-soil relations throughout human history and throughout the period of the Great Acceleration (*Steffen* et al., 2015). However, quantitative understanding of soil responses to the diversity of human forcings remains elementary and needs remedy.

Key words: Anthropocene Epoch / Anthropedology / Dan Yaalon / Vasily Dokuschaev

Accepted July 24, 2019

1 An Introduction to the Anthropocene

The Anthropocene was first described by 1995 Chemistry Nobel Prize winner Paul Crutzen and University of Michigan ecologist Eugene Stoermer (*Crutzen* and *Stoermer*, 2000; *Crutzen*, 2002) to refer to the geologic time during which the Earth is transitioning from a natural to a human-natural planet. The Anthropocene concept is circulating vigorously through the academic disciplines and popular media and today has several definitions—here, we use two. Given the geologic implications of the Anthropocene, the Subcommission on Quaternary Stratigraphy (SQS), a part of the International Commission on Stratigraphy (ICS), has tasked the Anthropocene Working Group (AWG) to craft a proposal to distinguish the Anthropocene as a formal geological time unit distinct from and following Holocene (*Waters* et al., 2016; *Zalasiewicz* et al., 2019). The AWG recently voted to support the mid-20th century as the most practical time to stratigraphically mark the beginning of the Anthropocene Epoch. The proposed Anthropocene Epoch is expected to be formally voted upon by the ICS in the 2020s. This first definition of Anthropocene is specifically crafted for and by stratigraphers, who resolve the main episodes of Earth history and represent these as named units in the Geologic Time Scale.

A second definition of Anthropocene, while directly related to the first, is much wider in scope, and more interdisciplinary and embracing of the long history (*i.e.*, the diachronicity) of human-Earth interactions. This is the Anthropocene of late-Pleistocene extinctions, domestication of plants and animals, development of agricultural economies and landscapes, and the onset of the Industrial Revolution. This is also the Anthropocene of the humanities and arts, but also of many non-geologic sciences as well, ranging across anthropology (*Latour*, 2017), archeology (*Edgeworth* et al., 2015), biology (*Kidwell*, 2015), ecology (*Corlett*, 2015), engineering (*Allenby* et al., 2009), finance (*Shrivastava* et al., 2019), environmental economics (*Smith*, 2017), history (*Chakrabarty*, 2009; *Thomas*, 2014), literature (*Menely* and *Taylor*, 2017), and of course the environmental scholarships (*Castree*, 2014).

The contemporary phenomena associated with the two Anthropocenes include the well-publicized human-forcings of the Earth's cycles of carbon, nitrogen, phosphorus, and other chemical elements, together with new and novel chemical compounds; the complex interactions with the climate associated with rapid increases in atmospheric greenhouse gases and rises in oceanic sea levels and acidity; the changes in the biosphere, pedosphere, hydrosphere, and lithosphere that result from land conversions, cultivation, urbanization, mining, exploitive hunting, animal domestication, and the mixing of biotic species including pathogens among regions and continents; the proliferations and global dispersions of many new technofossils that are 'minerals' and 'rocks' including concrete, fly ash, and plastics; and the massive acceleration in soil erosion and sedimentation associated with agriculture and with the geomorphologic reshaping of the Earth's surface from mining, transportation, residential, urban, and industrial development.

From many perspectives, what is most of interest is that human forcings are altering Earth's many systems (*Steffen* et al., 2018) and that many of these alterations will persist throughout the coming millennia as they become written into

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Earth's critical zone (*Brantley* et al., 2007; *Richter* and *Billings*, 2015), *i.e.*, sediments, weathering zones, soils, ecosystems, including human societies, some of which will become fossilized as future geological strata. Our planet is a palimpsest with human actions today accelerating erasures and rewrites that intellectually challenge the sciences, the humanities, and the arts. This Game Changer essay examines how the science of pedology, *i.e.*, the science of how soils form in nature, is repositioning itself as it transitions to an anthropedology. This essay may be read to be about changes in soil science, but also perhaps as a reflection on how the Anthropocene interacts with sciences and academic disciplines at large.

We first review the origins of pedology as a natural and basic science whose subject was soils devoid of human influence. As the 20th century proceeded, scientists increasingly studied human interactions with soil, until in the 1960s, a call was issued for a new pedology due to the extent and intensity of human influence (*Yaalon* and *Yaron*, 1966). We follow the literature through the 21st century and argue that the new science of anthropedology is as significant to the development of soil science as was the natural-body concept of soil first described in the 19th century by Dokuchaev and Hilgard (*Richter Jr.*, 2007). While acknowledging how humans transform soils biologically, chemically, and physically, we use the simple and elegant insight into soil of *Gilbert* (1877) to drive home the idea that whether defined by stratigraphers or the broader scholarly community, the Anthropocene is a game changer for soil science and pedology.

2 Transitioning from Pedology to Anthropedology

Most histories of pedology lead us back to the 19th century scientists Vasily *Dokuchaev* in Russia (1883; *Tandarich* and *Sprecher*, 1994; *Warkentin*, 2006) and E. W. *Hilgard* in the United States (1860; *Jenny*, 1961), scientists who first described soils as natural bodies, as fundamental parts of nature and worthy of their own study (*Brevik* and *Hartemink*, 2010). Thereafter, the science of pedology developed mainly as a basic and natural science that focused almost exclusively on the natural factors and processes of soil formation. For example, in a high profile 1938 review on "Formation of Soil," *Byers* et al. (1938) hardly mentioned human influence, even with regard to agricultural practices. From 1937 through 1990, eight editions of one of the world's most widely circulated soils textbooks, *Nature and Properties of Soils*, coauthored by Lyon, Buckman, Brady, and Weil, explicitly promoted pedology as a basic science and a "soil science in most restricted form." Even on the first page of these texts (*Lyon* and *Buckman*, 1946), pedology was defined as a science that aimed to "consider the soil purely as a natural body with little regard for practical utilization."

A notable exception was the great pedologist Hans *Jenny* (1941), who was fascinated by human alteration of soil and who placed human influence within the biological factor of the Dokuchaev–Jenny state factor equation:

$$S = f(cl, o, r, p, t, \ldots). \quad (1)$$

In other words, soils are a function of the large-scale factors of climate, organisms (biota), relief, parent material, and time, with local factors specified in the trailing string of dots. *Jenny* (1941) flatly declared that "Cultivation and fertilization of soils and the removal of crops are widely practiced activities that stamp man as an outstanding biological soil-forming factor" (Fig. 1). Jenny extended these ideas in his 1990s exploration of human-soil interactions (*Amundson* and *Jenny*, 1991). However, over the first half of the 20th century, *Jenny* (1941) seems the exception and most pedologists like *Byers* et al. (1938) were not much interested in human–soil relations and considered human activities to simply disturb the natural formation of soils. This was fully in keeping with *Hilgard* (1860) who cast his essay entitled "What is a soil?" to be about what he considered to be "virgin soils." If pedologists considered human influence at all, they considered humans to be within the biological factor.

By the 1950s, however, soil scientists were increasingly quantifying the many ways humans alter soils, but few considered their work to contribute to pedology. Three examples include: *Simonson* (1951) whose comparison of soil properties under natural and cultural environments was published in a soil conservation journal; *Albrecht* (1956) who contributed a paper on land use effects on soil biology, chemistry, and physics to the Wenner–Gren Foundation's major anthropological symposium "Man's Role in Changing the Face of the Earth"; and *Steinbrenner* and *Gessel* (1955) who quantified effects of forest-tractor logging on soil physical properties such as permeability, porosity, and bulk density. The primary audiences for these papers were agronomists, soil conservationists, and foresters, respectively, decidedly not 1950s pedologists.

In the 1960s, however, soil scientists increasingly brought the human factor within the scope of pedology. *Cline* (1961) in his review of the future of pedology explicitly challenged his soil science colleagues about how intensifying land use

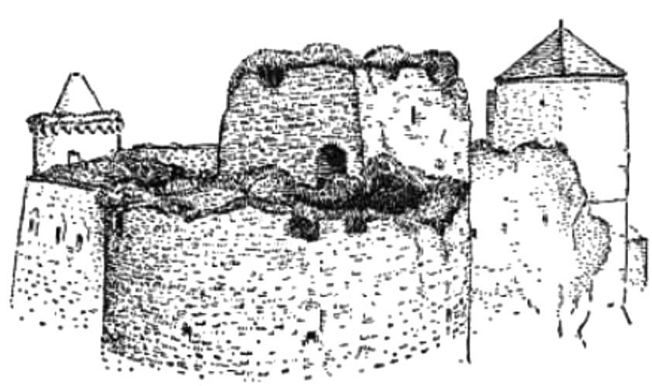

Figure 1: *Jenny*'s (1941) illustration emphasizes the interest he had in human-soil relations and bears the caption, "View from Kamenetz fortress from the west (after photograph)." *Jenny* (1941) was particularly impressed with the rapid rate that rendzina soils formed on the slabs of calcareous rock of the fortress' walls, which he understood to have been built in 1362 and abandoned in 1699 (previously studied by *Akimtzev*, 1932).

"… magnifies man and his activities as factors of soil formation and demands (pedological) recognition of his work." *Jackman* (1960) wrote about "effects of man on soils" in a paper on New Zealand pasture and soil improvement, and *Jacks* (1962) conceived of the human soil-forming factor in terms of soil fertility in a paper entitled, "Man: the fertility maker." *Bidwell* and *Hole* (1965) systematically explored how human activities affected all five state factors in the *clorpt* equation. Thus, human action altered *climate* by altering temperature and moisture; *organisms* by altering depths of rooting and pedoturbation, and reorganizing and even extinguishing plants and animals; *relief* and *parent materials* by physical mixing, resorting, and rearranging enormous volumes of mineral and organic materials and their landforms in cultivated fields, riparian zones, cities and suburbs, roadways, industrial areas, mine lands, and war zones; and *time* by accelerating the pace of soil change and evolution. *Bidwell* and *Hole* (1965) seemed concerned that consolidating human influence within one of the five factors, *i.e.*, within the biotic factor, diminished the complexity of human–soil relations. In their words, "A single agricultural program, such as irrigation farming, has affected all five factors of soil formation simultaneously."

In 1966 came a powerful outline for an entirely new pedology. *Yaalon* and *Yaron* (1966) proposed that human influence had created a new reference system for soil formation, "a new t_0 (time zero) from which a new wave of polygenesis has begun." The authors starkly and analytically portrayed natural soil bodies to be the parent materials upon which human-affected changes operate. *Yaalon* and *Yaron* (1966) not only wed humanity and soil formation, they called the new pedology to be a study of metapedogenesis, what has since been called anthropedogenesis (*Richter* and *Yaalon*, 2012). Anthropedogenesis can be defined as the human-natural formation of new soils that are critical to human and environmental health and wellbeing and to land management.

In the 1970s and 1980s, the rise of the environmental sciences began to infiltrate pedology, *i.e.*, anthropedology began to grow. The pedogenesis of mineland soils became an important field of pedologic study, for example, led by *Sencindiver* (1977), *Schafer* (1979), *Indorante* and *Jansen* (1984), and *Ciolkosz* et al. (1985). The theme of humans as pedogenic fertility makers was explored by many, perhaps no one better than *Conry* (1972) in Ireland. An early systematic study of urban soils was accomplished on the Washington mall (*Short* et al., 1986a, 1986b), a study that according to *Howard* (2017) was initiated to work through early difficulties in applying the then new concepts of *Soil Taxonomy* to anthropogenic environments (*Soil Survey Staff*, 1975).

In 1990, a small book, *Global Soil Change*, coauthored by 13 of the world's leading pedologists, including Yaalon, systematically described and evaluated how natural soils were being transformed by human activities (*Arnold* et al., 1990). It concluded with 12 recommendations, the 12^{th} being the need to more systematically monitor human-forced soil changes at individual sites and at national and international levels. The importance of soil monitoring has been hailed by many soil scientists, including 30 in *Richter* et al. (2011), but even still, monitoring of human-forced soil change has yet to be well organized beyond an inventory of about 200 long-term studies (*Richter* and *Yaalon*, 2012).

Since 1990, anthropedology research has proliferated (*Howard*, 2017). A fundamental difference is now widely recognized between human-altered (HA) and human-transported (HT) soils, a difference significant for both soil processes and classification (*Galbraith* et al., 2007; *Capra* et al., 2013). Urban pedogenesis and mapping, while still too small a field, is gaining credibility. How ironic that the soils of our front- and backyards are a soil-science frontier! How amazing that so many soil maps that include landscapes with towns and cities map soils within cities as "urban soil complex" (with such soils typically unsampled)! Urban soil science is internationally expanding with new textbooks, new concepts about urban pedogenesis, and new soil classifications (*Blume*, 1989; *Bullock* and *Gregory*, 1991; *Craul*, 1992; *Effland* and *Pouyat*, 1997; *Stroganova* et al., 1997; *Gerasimova* et al., 2003; *Zhang* et al., 2005; *Pouyat* et al., 2007; *Capra* et al., 2015; *Schad*, 2018).

During this recent period, the world's soil classification systems and soil taxonomies have been modified to better address human–soil interactions. In 1988, the International Committee on Anthropogenic Soils (ICOMANTH) was organized to formulate a system of anthrogenic soil classification within Soil Taxonomy. This was no easy matter because Soil Taxonomy historically and intentionally attempted to minimize human-influence on soil taxa (*Richter* and *Yaalon*, 2012). After much discussion and persistence, the final recommendations of ICOMANTH were accepted in 2014, complete with photographs of landfill and rice paddy soils on the cover of the 2014 *Keys to Soil Taxonomy* (Fig. 2).

In 1992, the World Reference Base for Soil Resources (WRB) was organized as an international classification system and is successor of the FAO–UNESCO Soil Maps of the World from the 1970s and 1980s. Today the WRB has 32 reference soil groups two of which, the Anthrosols and Technisols, include soils with strong human influence. The Anthrosols include many agricultural soils affected by long-term manuring, irrigation, flooding, and deep cultivation. The Technosols include urban and industrial affected soils with accumulations of artifacts, landfills, cinders, mine spoils, and contaminants; soils covered by pavements and that contain geomembranes; and soils that have been intentionally constructed. These developments demonstrate the clear direction that pedology is moving, *i.e.*, toward an anthropedology that Dan Yaalon would certainly approve.

It is important to recall that these developments were not easily won. After all, changes in human–soil relations were on-going and coincident with the development of the science of pedology itself. According to *Dudal* et al. (2002), traditional pedology required a fundamental shift from "human as outsider" to "human as insider." *Schaetzl* and *Thompson* (2015) described the traditional state-forming equation, *i.e.*, $S = f(cl, o, r, p, t, \ldots)$, having a string of dots to represent local forming factors such as "eolian dust, sulfate deposition in acid rain, or the effects of humans." In the late 19^{th} century, *Hilgard* (1860)

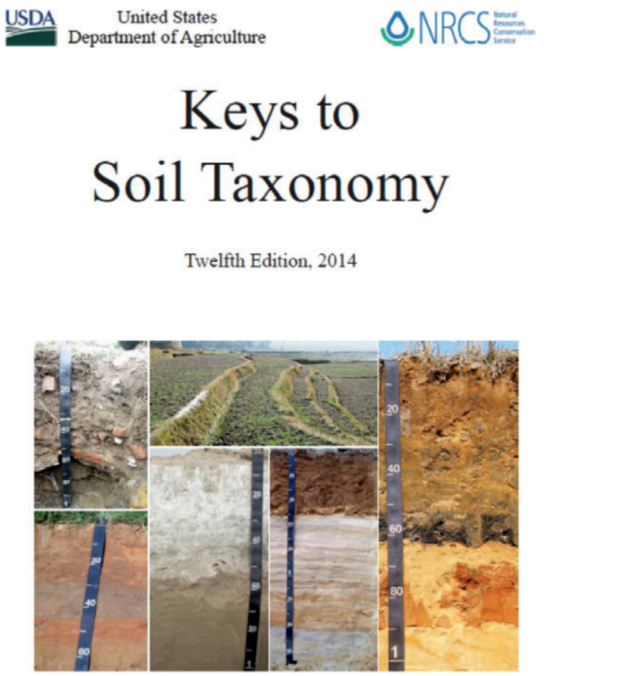

Figure 2: Cover photographs on the 12th edition of *Keys to Soil Taxonomy* (*Soil Survey Staff*, 2014) that welcomed human-altered soils into pedology. The 2014 *Keys* incorporated many of the recommendations of the International Committee on Anthropogenic Soils (ICOMANTH) that had worked since the 1990s. Clockwise from upper upper left, the photographs are of human-altered and human-transported soils in city parks, rice and vegetable paddies, dredgings, coastal salt flats, and machine-compacted soilscapes.

sampled what he considered to be "virgin soils" across the state of Mississippi, clearly an impossible proposition today as nearly all soils surveyed by Hilgard have been converted to a variety of intensive land uses.

Significantly, the transition from pedology to anthropedology is forged not only by the mid–20th century's Great Acceleration of *Steffen* et al. (2015), but also by the many pedological studies that have explored the diachronous beginnings of human influences on soil, specifically during the time when human influence has been traditionally considered to be local and part of the trailing dots of the state factor equation (*Sandor*, 2006; *Warkentin*, 2006; *Edgeworth* et al., 2015; *Schaetzl* and *Thompson*, 2015). From local to regional scales, soil scientists have documented the long history of human-soil relations in Africa, Asia, Europe, and the Americas (*McNeill* and *Winiwarter*, 2004). *Amundson* and *Jenny* (1991) evaluated the variety of ways that soils have been altered by Pacific island colonizers, Great Plains Indians in North America, Midwestern USA farmers, and 19th and 20th century city-park managers. *Richter* and *Markewitz* (2001) documented human-altered soil biogeochemistry from 19th century cotton farming to subsequent 20th century reforestation of old cotton fields, changes often depth-dependent. *Sandor* (2006) studied soils as they were altered by prehistoric agricultural terraces, and led efforts to archive historic records of soil uses (*Sandor*, 2006). Some of the most surprising studies of ancient soil alteration by humans are of Amazonian landscapes, where persistent human-generated Dark Earths range in area from 0.5 to 100 ha (*Sombroek* et al., 2002; *Lehmann* et al., 2003). Also remarkable is the acceleration of soil formation documented under 2000 years of rice-paddy management in China, in which soil change proceeds in depth-dependent trajectories (*Kölbl* et al., 2014). *McNeill* and *Winiwarter* (2004) argue that since the rise of cities over about five millennia, the routing of soil resources from rural fields to cities has inevitably created problems with soil-fertility depletion in rural fields.

During the same decades that pedologists such as *Bidwell* and *Hole* (1965) and *Yaalon* and *Yaron* (1966) were awakening to the significance of the intensive and extensive transformations of soil in the late 20th century (during the proposed Anthropocene Epoch), scientists have also been detailing that humans have been a significant soil-forming factor throughout the recent millennia. Given these latter developments, pedologists are well justified in elevating human influence to "a fully fledged factor of soil formation, a sixth one in addition to the five" (*Dudal* et al. (2002). As pedologists and soil scientists we might even ask ourselves whether traditional soil science has been a soil-forming factor short since the very beginnings of pedology.

3 The Significance of Accelerated Erosion in the Anthropocene

In 1877, *Gilbert* stated with wonder: "Over nearly the whole of the earth's surface, there is a soil, and wherever this exists we know that conditions are more favorable to weathering than to transportation." In his geological survey of the Henry Mountains in Utah, *Gilbert* (1877) described this fundamental state of the natural planet—that the extensive coverage of soil from the tundra to the tropics meant that across nearly all of the Earth's diverse landscapes, weathering's production of soil particles and solutes (W) outpaced transport-related losses of particles and solutes *via* erosion and subsurface runoff (T). Even on landscapes that are naturally erosive, W keeps pace with T. Given liquid water, freeze–thaw, and biogeochemical weathering agents, W liberates mineral particles and inorganic solutes, T removes a fraction of those products, and landscapes accumulate the remainder. *Buol* et al. (2011) recently estimated that soils cover about 98.6% of the Earth's terrestrial surface and bare rock but 1.4%. Remarkably, *Gilbert*'s (1877) insights have only circulated among geomorphologists and pedologists since late in the 20th century (*Humphreys* and *Wilkinson*, 2007).

Human activities, however, from agriculture and land-use development, have vastly increased Gilbert's T relative to W as the Earth transitions from a natural to a human-natural planet. *Haff* (2012) considered how, as a physical system, this accelerated movement of solid particles represents a revolution of sorts in the functionality of the Earth system. *Hooke* (2000) estimated that humanity is today the Earth's primary geomorphic agent accounting for > 100 Gt y^{-1} of soil mixing, rock excavation, and erosion. *Wilkinson* and *McElroy* (2007) estimated that erosion from agriculture to total ≈ 75 Gt y^{-1} globally, compared with natural geologic erosion at ≈ 20 Gt y^{-1}. Also significant for the Anthropocene, the spatial pattern of human-accelerated erosion across the globe is entirely different compared with the patterns of natural geologic erosion (*Wilkinson* and *McElroy*, 2007). Erosion has been accelerated almost entirely at < 1000 m elevation, where most people live, grow crops, and interact with the terrestrial environment. Natural geologic erosion, however, is mainly from high mountain slopes between 4,000 to 6,000 m (Fig. 3).

Such massive shifts in *Gilbert*'s (1877) T relative to W signal the acceleration of fundamental soil changes ongoing today. In Europe, *Panagos* et al. (2015) estimated that 21st century soil losses to erosion averaged 2.5 Mg ha^{-1} y^{-1}, while *Verheijen* et al. (2009) estimated soil formation to average 1.4 Mg ha^{-1} y^{-1}. With Gilbert's T increasing overall relative to W, the accelerated particle movement and particle deposition have had massive consequences for Earth's terrestrial and aquatic ecosystems. Figure 3 thus describes accelerated erosion at < 1000 m elevation to be a process as much about soil loss as it is about massive deposition of colluvial and alluvial legacy sedimentation (*James*, 2013). Remarkably, *James* (2013) credits *Gilbert* (1917) with being the first to comprehensively study what are now called legacy sediments, and specifically the dynamics of sediment waves that move downstream as erosion accelerates from the land (*James*, 2010). For these reasons, *Merritts* et al. (2011) argued that Anthropocene landscapes are characterized by their historic deposits of legacy sediment. In parallel, Wade et al. (submitted) argue that soils forming in legacy sediments also characterize Anthropocene floodplains in most regions occupied by people.

4 Some Conclusions

In the Anthropocene, the basic science of pedology, the study of natural soil formation, is transitioning to the science of anthropedogenesis. Pedology is well prepared for this transition based on many decades of study of contemporary and historic human-alterations of soil (*Holliday*, 2004; *McNeill* and *Winiwarter*, 2004; *Sandor*, 2006). The Soil Survey Manual has been amended with descriptions of human altered and human transported materials (HAHT soils), the 2014 *Soil Taxonomy Keys* is updated with over two decades of work accomplished by ICOMANTH, and WRB recognizes soils altered by agriculture, urban, and industrial development.

Even still, there is very much to do. Recent research that points to future work includes that by *Dotterweich* (2013) who coupled historic written records with geomorphic field evidence to describe landscapes long used and abused by agriculture, and *Brecheisen* et al. (2019) and *Bonetti* et al. (2019) who identified and modelled erosional impacts on landform surface roughness and hillslope morphology based on high-resolution LiDAR. But perhaps of most pressing importance is how to address the fact that quantitative understanding about how human forcings are changing soils that can only be described to be elementary (*Tugel* et al., 2005; *Richter* and *Yaalon*, 2012). Human forcings alter a wide range of soil properties and processes, and pedology's frontier lies as much in corn and rice fields, urban developments, mine reclamation sites, abandoned lands, city parks, and back yards, as it does in remote landscapes with soils that have experienced minimal human influence. With up to 10 billion persons dependent on the Earth's soil by 2050, it is time to support an international soils-research base of long-term studies to better monitor soil changes in the Anthropocene.

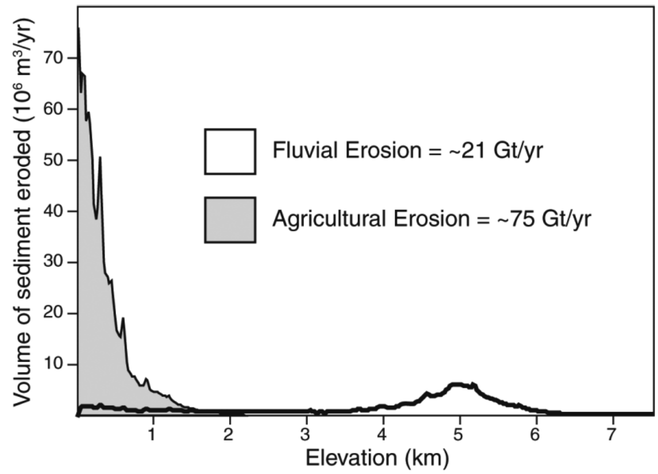

Figure 3: Soil erosion on Earth as a function of elevation and from natural fluvial and agricultural sources (*Wilkinson* and *McElroy*, 2007). Most agriculture is practiced at < 1000 m elevation on relatively low-slope landforms and contrasts greatly with natural geologic erosion that is concentrated at high-elevation in high-slope environments. The distributions emphasize the global-scale signatures of accelerated agricultural erosion and massive deposition of legacy sediment, both at relatively low elevation.

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