



# Reviews and syntheses: Agropedogenesis – humankind as the sixth soil-forming factor and attractors of agricultural soil degradation

Yakov Kuzyakov<sup>1,2</sup> and Kazem Zamanian<sup>1</sup>

<sup>1</sup>Department of Soil Science of Temperate Ecosystems, Georg-August-Universität Göttingen, Büsgenweg 2, 37077 Göttingen, Germany

<sup>2</sup>Department of Agricultural Soil Science, Georg-August-Universität Göttingen, Büsgenweg 2, 37077 Göttingen, Germany

**Correspondence:** Yakov Kuzyakov (kuzyakov@gwdg.de) and Kazem Zamanian (zamanians@yahoo.com)

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**Abstract.** Agricultural land covers  $5.1 \times 10^9$  ha (ca. 50 % of potentially suitable land area), and agriculture has immense effects on soil formation and degradation. Although we have an advanced mechanistic understanding of individual degradation processes of soils under agricultural use, general concepts of agropedogenesis are absent. A unifying theory of soil development under agricultural practices, of agropedogenesis, is urgently needed. We introduce a theory of anthropedogenesis – soil development under the main factor “humankind” – the sixth factor of soil formation, and deepen it to encompass agropedogenesis as the most important direction of anthropedogenesis. The developed theory of agropedogenesis consists of (1) broadening the classical concept of factors  $\rightarrow$  processes  $\rightarrow$  properties  $\rightarrow$  functions along with their feedbacks to the processes, (2) a new concept of attractors of soil degradation, (3) selection and analysis of master soil properties, (4) analysis of phase diagrams of master soil properties to identify thresholds and stages of soil degradation, and, finally, (5) a definition of the multidimensional attractor space of agropedogenesis. The main feature of anthropedogenesis is the narrowing of soil development to only one function (e.g. crop production for agropedogenesis), and this function is becoming the main soil-forming factor. The focus on only one function and the disregard of other functions inevitably lead to soil degradation. We show that the factor humankind dominates over the effects of the five natural soil-forming factors and that agropedogenesis is therefore much faster than natural soil formation. The direction of agropedogenesis is largely opposite to that of natural soil development and is thus usually associated with soil degradation. In contrast to natural pedogenesis leading to *divergence*

of soil properties, agropedogenesis leads to their *convergence* because of the efforts to optimize conditions for crop production. Agricultural practices lead soil development toward a quasi-steady state with a predefined range of measured properties – attractors (an attractor is a minimal or maximal value of a soil property toward which the property will develop via long-term intensive agricultural use from any natural state). Based on phase diagrams and expert knowledge, we define a set of “master properties” (bulk density and macroaggregates, soil organic matter content, C : N ratio, pH and electrical conductivity – EC, microbial biomass and basal respiration) as well as soil depth (A and B horizons). These master properties are especially sensitive to land use and determine the other properties during agropedogenesis. Phase diagrams of master soil properties help identify thresholds and stages of soil degradation, each of which is characterized by one dominating process. Combining individual attractors in a multidimensional attractor space enables predicting the trajectory and the final state of agrogenic soil development and developing measures to combat soil degradation. In conclusion, the suggested new theory of anthro- and agropedogenesis is a prerequisite for merging various degradation processes into a general view and for understanding the functions of humankind not only as the sixth soil-forming factor but also as an ecosystem engineer optimizing its environment to fulfil a few desired functions.

## 1 Introduction

### 1.1 Soil degradation by agricultural land use

Soils ( $S$ ) as natural bodies are formed via interactions of soil-forming factors, i.e. climate ( $cl$ ), organisms ( $o$ ), relief ( $r$ ) and parent material ( $p$ ) over time ( $t$ ) (Dokuchaev, 1883; Glinka, 1927; Jenny, 1941; Zakharov, 1927):  $S = f(cl, o, r, p, t, \dots)$  (see the copy–paste history of the equation in the Supplement).

The processes of additions, losses, transfers and translocation, and transformations of matter and energy over centuries and millennia produce a medium – soil (Simonson, 1959), which supports plant roots and fulfils many other ecosystem functions (Lal, 2008; Nannipieri et al., 2003; Paul, 2014). These functions commonly decrease due to human activities, in particular through agricultural practices because of accelerated soil erosion, nutrient loss (despite intensive fertilization), aggregate destruction, compaction, acidification, alkalization and salinization (Homburg and Sandor, 2011; Sandor and Homburg, 2017). Accordingly, the factor humankind has nearly always been considered to be a soil-degrading entity that, by converting natural forests and grasslands to arable lands, changes the natural cycles of energy and matter. Except in very rare cases that lead to the formation of fertile soils such as Terra Preta in the Amazon Basin (Glaser et al., 2001), Plaggen in northern Europe (Pape, 1970) and Hortisols (Burghardt et al., 2018), soil degradation is the most common outcome of agricultural practices (DeLong et al., 2015; Homburg and Sandor, 2011). Soil degradation begins immediately after conversion of natural soil and involves the degradation in all physical, chemical and biological properties (Table 1). The result is a decline in ecosystem functions.

Soil degradation gains importance with the rapid increase in the human population (Carozza et al., 2007) and technological progress. Increasing food demand requires either larger areas for croplands and/or intensification of crop production per area of already-cultivated land. Because the land resources suitable for agriculture are limited, most increases in food production depend on the second option: intensification (Lal, 2005). While prohibiting or reducing degradation is essential in achieving sustainable food production (Lal, 2009), many studies have addressed individual mechanisms and specific drivers of soil degradation (Table 1). Nonetheless, there is still no standard and comprehensive measure to determine soil degradation intensity and to differentiate between degradation stages.

Agricultural soils (croplands plus grasslands) cover  $5.1 \times 10^9$  ha, corresponding to about 34 % of the global land area. Huge areas are located in very cold regions that are continuously covered by ice ( $1.5 \times 10^9$  ha); in hot deserts, mountainous areas or barren regions ( $2.8 \times 10^9$  ha); and sealed in urban and industrial regions and roads (ca.  $0.2 \times 10^9$  ha). Accordingly, agricultural lands cover about 50 % of the area potentially suitable for agriculture (<https://ourworldindata.org/>

yields-and-land-use-in-agriculture, last access: May 2019). Even though huge areas of land are occupied by agriculture, and humans have modified natural soils over the last 10–12 thousand years, a theory of soil formation as affected by humankind – anthropogenesis and its subcategory agropedogenesis – is absent. This paper therefore presents for the first time a unifying theory of anthropogenesis – soil development under the main factor humankind – the sixth factor of soil formation. Moreover, we expand it to encompass agropedogenesis as a key aspect of general anthropogenesis.

### 1.2 Humans as the main soil-forming factor

Humans began to modify natural soils at the onset of agriculture ca. 10–12 thousand years ago (Diamond, 2002; Richter, 2007), resulting in soil degradation. Examples of soil degradation leading to civilization collapses are well known, starting at least with Mesopotamia (18th to 6th centuries BCE; Diamond, 2002; Weiss et al., 1993). Notwithstanding all the negative impacts humans have on soils, the intention was always to increase fertility to boost crop production (Richter et al., 2011; Sandor and Homburg, 2017), reduce negative environmental consequences and achieve more stable agroecosystems. To attain these aims, humans have (i) modified soil physical and hydrological properties (for example, by removing stones and loosening soil by tillage, run-off irrigation, draining and terracing); (ii) altered soil chemical conditions through fertilization, liming and desalinization; and (iii) controlled biodiversity by sowing domesticated plant species and applying biocides (Richter et al., 2015; Richter, 2007). Although these manipulations commonly lead to soil degradation (Homburg and Sandor, 2011; Paz-González et al., 2000; Sandor et al., 2008), they are aimed at decreasing the most limiting factors (nutrient contents, soil acidity, water scarcity, etc.) for crop production regardless of the original environmental conditions in which the soil was formed (Guillaume et al., 2016b; Liu et al., 2009). Thus, agricultural land use always focused on removing limiting factors and providing optimal growth conditions for a few selected crops: 15 species make up 90 % of the world's food, and three of them – corn, wheat and rice – supply two-thirds of this amount (FAO, 2018). These crops (except rice) have similar water and nutrient requirements in contrast to the plants growing under natural conditions. Consequently, agricultural land use has always striven to narrow soil properties to uniform environmental conditions.

Humans can even change soil types as defined by classification systems (Fig. S1 in the Supplement) by inducing erosion, changing the thickness of horizons and their mixture, decreasing soil organic matter (SOM) content, destroying aggregates, and accumulating salts (Dazzi and Monteleone, 2007; Ellis and Newsome, 1991; Shpedt et al., 2017). A Mollicsol (similar to Chernozems or Phaeozems), for example, turns into an Inceptisol (similar to Cambisols) by decreas-

**Table 1.** Processes and mechanisms of soil degradation by agricultural land use.

	Degradation directions and consequences	Processes and mechanisms	References
Physical properties	Structure:		Homburg and Sandor (2011)
	↓ granular structure	– ↓ SOM content and litter input	Ayoubi et al. (2012), Celik (2005), Khormali et al. (2009)
	↑ hard clod formation	– aggregate destruction	
	↑ micro-aggregates and large blocks	– ↓ rhizodeposition and mucilage	
	Density:		Carducci et al. (2017), Holthusen et al. (2018), Horn and Fleige (2009), Severiano et al. (2013)
	↑ bulk density	– compaction by heavy machinery	
	↑ subsoil compaction	– ploughing at a constant depth	
	↑ formation of massive layers	– destruction of aggregates	
	Porosity:		Celik (2005), Lipiec et al. (2012)
	↓ total porosity	– ↓ root density	Flynn et al. (2009), Ponge et al. (2013)
	↓ water-holding capacity	– ↓ burrowing animals	
	↓ soil aeration	– ↓ large and medium aggregates	
	↓ soil depth	– ↑ water and wind erosion	Ayoubi et al. (2012), Govers et al. (1994), Lal (2001)
		– ↑ tillage erosion	
		– ↑ soil density	
	↓ SOM content	– ↑ SOM mineralization by increasing aeration	Lisetskii et al. (2015), Liu et al. (2009), Sandor and Homburg (2017)
	↓ easily available and low-molecular-weight organic substances	– removal of plant biomass via harvesting	
		– residual burning	
		– destruction of macroaggregates	
Chemical properties	↓ element or nutrient content	– removal of plant biomass via harvesting	Hartemink (2006), Lisetskii et al. (2015), Sandor and Homburg (2017)
	loss of nutrients	– nutrient leaching	
	narrowing of C : N : P ratio	– SOM mineralization and N-P fertilization	
	Acidification:		Homburg and Sandor (2011), Obour et al. (2017), Zamanian and Kuzyakov (2019)
	↓ pH	– N fertilization	
	↑ exchangeable aluminium	– cation removal by harvest	
	↓ CEC (cation exchange capacity)	– ↓ buffering capacity due to cation leaching and decalcification	
		– acidification and H <sup>+</sup> domination on exchange sites	
		– loss of SOM	
	↑ salts and/or exchangeable Na <sup>+</sup>	– irrigation (with low-quality water and/or groundwater level rise by irrigation)	Dehaan and Taylor (2002), Emdad et al. (2004), Jalali and Ranjbar (2009), Lal (2015)

Table 1. Continued.

	Degradation directions and consequences	Processes and mechanisms	References
Biological properties	<ul style="list-style-type: none"> <li>↓ biodiversity</li> <li>↓ microorganism and organism density and abundance</li> </ul>	<ul style="list-style-type: none"> <li>– weeding</li> <li>– pesticide application</li> <li>– monocultures or narrow crop rotations</li> <li>– mineral fertilization</li> <li>– ↓ SOM content and litter input</li> <li>– ↓ root amounts and rhizosphere volume</li> <li>– ploughing and grubbing</li> <li>– ↓ total SOM</li> <li>– pesticide application</li> </ul>	Lal (2009), Zhang et al. (2017) Breland and Eltun (1999), Fageria (2012)
	<ul style="list-style-type: none"> <li>↓ microbial activities               <ul style="list-style-type: none"> <li>– respiration</li> <li>– enzyme activities</li> </ul> </li> </ul>	<ul style="list-style-type: none"> <li>– recalcitrance of remaining SOM</li> <li>– ↓ microbial abundance</li> <li>– ↓ litter and rhizodeposition input</li> <li>– mineral fertilization</li> <li>– ↓ organism activity, diversity and abundance</li> <li>– shift in microbial community structure</li> <li>– ↓ soil animal abundance and activity</li> </ul>	Breland and Eltun (1999), Bosch-Serra et al. (2014), Diedhiou et al. (2009), Ponge et al. (2013)

↑ and ↓ mean increase or decrease, respectively.

ing total SOM (Lo Papa et al., 2013; Tugel et al., 2005) and/or thinning of the mollic epipedon by tillage and erosion and destroying granular and sub-polyhedral structure (Ayoubi et al., 2012; Lo Papa et al., 2013). Accordingly, humankind can no longer be treated solely as a soil-degrading but also as a soil-forming factor (Amundson and Jenny, 1991; Dudal, 2004; Gerasimov and Fridland, 1984; Richter et al., 2015; Sandor et al., 2005). The result is the formation of anthropogenic soils (soils formed under the main factor humankind). This is well known for rice paddies, i.e. Hydragric Anthrosols (Chen et al., 2011; Cheng et al., 2009; Kölbl et al., 2014; Sedov et al., 2007), Horticultural Anthrosols (long-term fertilized soils with household wastes and manure) and Irrigated Anthrosols (long-term irrigated soils in dry regions; WRB, 2014). These effects have stimulated the ongoing development of soil classifications to reflect new directions of soil evolution (Bryant and Galbraith, 2003; Richter, 2007): anthropedogenesis, i.e. soil genesis under the main factor humankind, and in particular agropedogenesis, i.e. soil genesis under agricultural practices as a subcategory of anthropedogenesis.

Human impacts on soil formation have immensely accelerated in the last 50–100 years (Dudal, 2004; Gerasimov and Fridland, 1984; Richter, 2007) with the (1) introduction of

heavy machinery, (2) application of high rates of mineral fertilizers, especially after discovery of N fixation by the Haber–Bosch technology, (3) application of chemical plant protection, and (4) introduction of crops with higher yield and reduced root systems. We expect that, despite various ecological measures (no-till practices, restrictions on chemical fertilizer applications and heavy machinery, etc.), the effects of humans on soil formation will increase in the Anthropocene and will be even stronger than for most other components of global change. This urgently calls for a concept and theory of soil formation under humans as the main factor.

## 2 Concept of agropedogenesis

Anthropedogenesis is the soil formation under the main factor “human” (Amundson and Jenny, 1991; Bidwell and Hole, 1965; Howard, 2017; Meuser, 2010; Richter, 2007; Yaalon and Yaron, 1966). Agropedogenesis is the dominant form of anthropedogenesis and includes soil formation under agricultural use – mainly cropland (Sandor et al., 2005). The other forms of anthropedogenesis are construction of completely new soils (Technosols, e.g. urban soils or mine soils). These other forms of anthropedogenesis are not treated here because they are not connected with agriculture.



**Table 2.** Soil formation processes under agricultural practices.

Additions	Losses	Translocation	Transformation
Irrigation	Mineralization ↑	Irrigation	Fertilization
– water	– organic matter	– dissolved organic matter ↓	– acceleration of nutrient (C, N, P, etc.) cycles
– salts ↑ <sup>a</sup>	– plant residues	– soluble salts ↑	– formation of potassium-rich clay minerals
– sediments	– organic fertilizers		
	– N (to N <sub>2</sub> O and N <sub>2</sub> ) ↑		
Fertilization	Erosion	Evaporation	Mineralization ↑
– mineral	– fine earth erosion ↑	– soluble salt transportation to the topsoil ↑	– humification of organic residues ↓
– organic (manure and crop residues)	– whole soil material		– organo-mineral interactions ↓
Pest control	Leaching	Ploughing or deep ploughing	Heavy machinery
– pesticides	– nutrients leaching ↑	– soil horizon mixing	– compaction of top- and subsoil
– herbicides	– cations ↑	– homogenization	– aggregate destruction ↑
	– CaCO <sub>3</sub>	– bioturbation ↓	
Amendments	Harvesting		Pest control
– liming	– nutrients		– fungal community ↓
– gypsum	– ballast (Si, Al, Na, etc.) elements		
– sand <sup>b</sup>			
– biochar			

<sup>a</sup> ↑ and ↓ imply the increase or decrease, respectively, in rates of processes that may also occur under natural conditions.

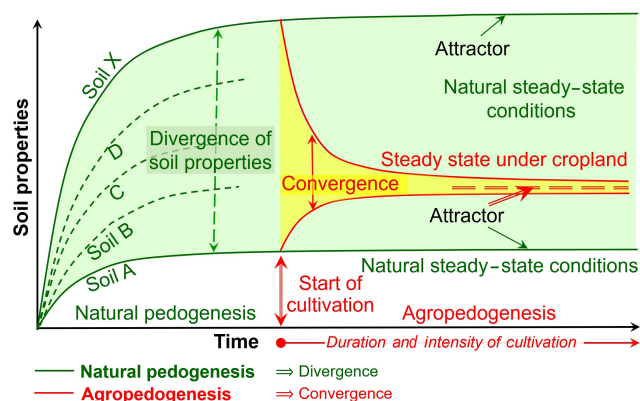
<sup>b</sup> Sand improves soil texture and permeability.

Agropedogenesis should be clearly separated from the natural pedogenesis because of (1) strong dominance of the factor “human” over the other five factors of soil formation, (2) new processes and mechanisms that are absent under natural soil development (Table 2), (3) new directions of soil developments compared to natural processes (Table 2), (4) frequent development of processes in the reverse direction compared to natural pedogenesis, and (5) much higher intensity of many specific processes compared to natural developments and consequently faster rates of all changes.

Agropedogenesis and natural pedogenesis are partially opposite. Natural soil formation involves the development of soils from parent materials under the effects of climate, organisms, relief and time (Dokuchaev, 1883; Jenny, 1941; Zakharov, 1927; Supplement). Here, soil formation will reach the quasi-steady state typical for the combination of the five soil-forming factors (Targulian and Goryachkin, 2004) (Fig. 1). Agropedogenesis, in most cases, is a process involving the loss of soil fertility, i.e. degradation because of intensive agriculture and narrowing of soil properties. Agropedo-

genesis is partially the reverse of soil formation, but the final stage is not the parent material (except in a few cases of extreme erosion). Agropedogenesis also leads to a quasi-steady state of soils (Fig. 1; Eleftheriadis et al., 2018; Wei et al., 2014). The time needed to reach this quasi-steady state, however, is much shorter (in the range of a few centuries, decades or an even shorter time period) than for natural pedogenesis, which involves millennia (Tugel et al., 2005). The range of soil properties at this quasi-steady state will show the end limit of agricultural effects on soil development.

Our theory of agropedogenesis is based on five components: the (1) concept of “factors → processes → properties → functions”, (2) concept of “attractors of soil degradation”, (3) selection and analysis of master soil properties, (4) analysis of phase diagrams between the master soil properties and identification of thresholds and stages of soil degradation, and (5) “multi-dimensional attractor space” and trajectory of pedogenesis.

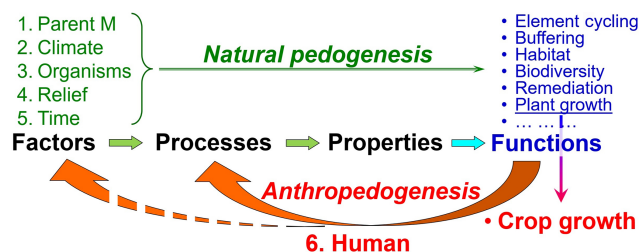


**Figure 1.** Conceptual scheme of soil development, i.e. pedogenesis, under natural conditions (green lines) and agropedogenesis due to long-term agricultural practices (red lines). Green area: the increasing variability in natural soils during pedogenesis. Yellow area: decrease in the variability in soil properties by agricultural use. Double-line vertical arrow: the start of cultivation.  $x$  axis: time for natural soil development and duration and intensity of cultivation under agricultural use. Natural pedogenesis leads (from the initial parent material) to a wide range of steady-state values (green dashed arrow) for a given soil property over hundreds or thousands of years due to various combinations of the five soil-forming factors. Natural pedogenesis leads to divergence of soil properties. In contrast, agricultural practices and the dominance of humans as the main soil-forming factor cause each property to tend toward a very narrow field of values, i.e. attractors of that property defined by human actions, namely land management for optimizing the production of few crops. Therefore, agropedogenesis leads to convergence of soil properties.

## 2.1 Concept: factors → processes → properties → functions

The original concept of “soil factors → soil properties” was initially suggested by Dokuchaev (1883) and Zakharov (1927) and was modified by “processes”, which are dependent on the factors of soil formation and develop the properties (Gerasimov, 1984; McBratney et al., 2003). This triad, factors → processes → properties, enables understanding soil development from the initial parent materials by the effects of climate, organisms and relief, over time. This describes the visible morphological soil properties in the field and measurable parameters in the lab very well, leading to the development of various semi-genetic or genetic soil classifications (KA-5, 2005; KDPR, 2004; WRB, 2014).

Considering the recent development of functional approaches and ecosystem perspectives, this triad is insufficient. We therefore introduce the concept factors → processes → properties → functions (Fig. 2). Rather than describing here the very broad range of functions of natural soils as related to clean air and water, biodiversity, decontamination of pollutants, biofuel and waste management,

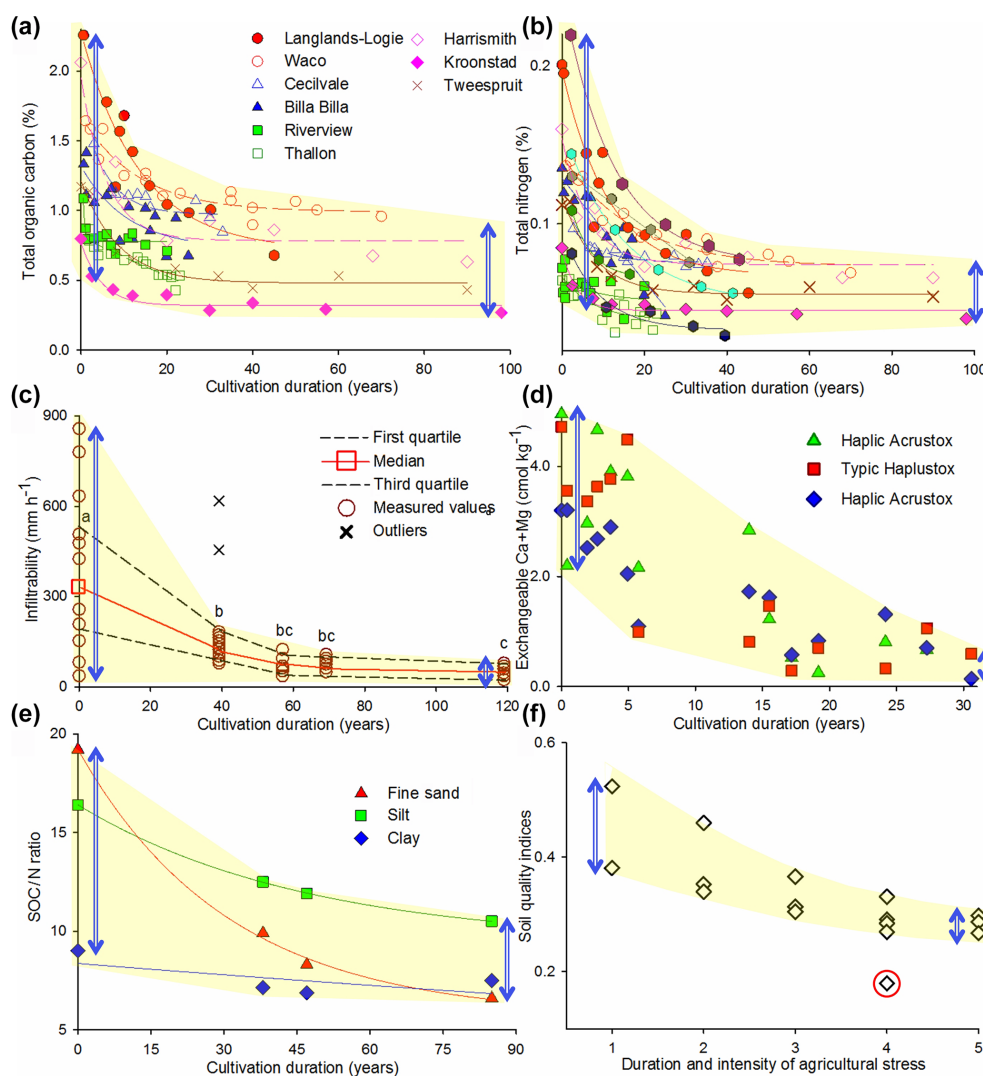


**Figure 2.** Soil genesis based on the five natural factors of soil formation and the sixth factor: human. Natural processes are presented in green, and human processes are presented in red. The concept factors → properties was suggested by Dokuchaev (1883) and Zakharov (1927; see Supplement) and later by Jenny (1941). The theory we introduced, factors → processes → properties → functions, considers not only the functions of natural soils but also human modification of soils toward only one function of interest (here crop growth). Anthropogenic optimization of only one function involves strongly modifying processes and factors, leading to formation of a new process group: anthropedogenesis. The arrows pointing downward reflect the main specifics of anthropogenesis: one of the functions becomes a factor of pedogenesis and modifies the processes.

etc., we refer to excellent reviews focused on soil functions (Lal, 2008; Nannipieri et al., 2003).

One function – plant growth – is crucial for agropedogenesis (Fig. 2) because humans change this natural function to an anthropogenic function – crop growth – thus adapting and modifying natural soils to maximize productivity and crop yields. As it is not possible to simultaneously maximize all functions, the functions other than “crop growth” decrease or even disappear. Accordingly, agropedogenesis is driven by processes pursuing the maximization of only one function – crop growth. The consequence is that all other soil functions are reduced. We define *soil degradation* as a *reduction of functions*. Initially, all functions will be reduced at the cost of increased crop production. As degradation advances, however, the production function decreases as well. Nearly all previous definitions of soil degradation were based on declining crop productivity. The principal difference between our concept of soil degradation and the most common other concepts is that the degradation starts with the reduction of one or more functions – before crop productivity decreases. This concept, based on multifunctionality, is much broader and considers the ecosystem functions and services of soil and the growing human demand for a healthy environment.

Agropedogenesis clearly shows that the natural sequence factors → processes → properties → functions is changed by humans: functions are no longer the final step in this sequence because *one function becomes a factor* (Fig. 2). This is because humans tailor the processes of soil development for the main function of agricultural soils – crop production. Based on the example of agropedogenesis, we conclude that all types of anthropedogenesis are directed at the functions



**Figure 3.** Examples for attractors of soil properties by anthropogenic degradation: **(a)** soil organic carbon content, **(b)** total nitrogen content, **(c)** infiltration rates, **(d)** exchangeable  $\text{Ca}^{2+}$  and  $\text{Mg}^{2+}$  contents, **(e)** C : N ratio, and **(f)** overall decrease in soil quality, i.e. degradation over the cultivation period. Yellow shading area: covering all experimental points, showing a decrease in the area with cultivation duration. Blue double arrows: range of data points in natural soils (left of each panel) and strong decrease in data range due to cultivation (right of each panel). **(a)** Narrowing range (blue arrows) of soil organic C over cultivation periods in southern Queensland, Australia (six sites; Dalal and Mayer, 1986a), and savanna soils in South Africa (three sites; Lobe et al., 2001). The natural soils in different climatic regions have various ranges of properties, e.g. organic C from 0.8 % to 2.3 %. During cultivation, however, the organic C content strongly narrows to between 0.3 % and 1.0 %. **(b)** Narrowing range (blue arrows) of total soil N over cultivation periods. Sampling sites similar to **(a)** plus five sites (hexagons) from the Great Plains, USA (Haas et al., 1957). Before agriculture start, the Great Plains soils had a wide range of texture classes (silt loam, loam, clay loam and very fine sandy loam), an initial organic C content of 1.13 %–2.47 % and a total N content of 0.05 %–0.22 %. Nonetheless, the total N range narrowed to 0.03 %–0.07 % over 45 years of intensive agriculture. As Haas et al. (1957) anticipated, all soils may finally reach a similar value for total N (i.e. the attractor for N) by continuing the ongoing management (in line with Australian and South African soils). **(c)** Infiltration rates as a function of years since land-use change from forest to agriculture (Nyberg et al., 2012). Note the narrowing trend (blue arrows) from forest ( $t = 0$ ) toward long-term cultivation ( $t = 39, 57, 69$  and 119 years since conversion). The value at ca. 120 years is defined as the attractor of the infiltration rate, and 120 years is the time needed to reach that attractor. **(d)** Narrowing content (blue arrows) of exchangeable  $\text{Ca}^{2+}$  and  $\text{Mg}^{2+}$  in the first 15 cm of Oxisols during 31 years (1978–2009) of sugar cane cultivation (Morrison and Gawander, 2016). The three soils developed under various natural vegetation prior to cultivation and received different management thereafter. **(e)** Narrow ranges of C : N ratios in all texture classes (sand, silt and clay) over 85 years of cultivation (Eleftheriadis et al., 2018). Note that the different rates of C : N decrease in the three fractions. That ratio in the sand fraction is more susceptible to cultivation duration but is rather resistant in the clay fraction. **(f)** Dependence of the soil quality index on duration and intensity of soil cultivation (on the x axis: 1 – virgin land, 2 – idle land in the modern era, 3 – modern-day ploughed land, 4 – post-antique idle land – and 5 – continually ploughed land) over 220 to 800 years cultivation (Lisetskii et al., 2015). Note that soil quality became similar (blue arrows) with increasing cultivation duration and/or cultivation intensity (from 1 to 5; value in red circle is an outlier).

that humans desire from the soil; hence, the one function becomes the factor of soil development (Fig. 2).

## 2.2 Attractors of soil degradation: definitions and concept

Despite a very broad range of individual properties of natural soils, long-term intensive agricultural land use strongly narrows their range (Homburg and Sandor, 2011; Kozlovskii, 1999; Sandor et al., 2008) and ultimately brings individual properties to the so-called attractors of degradation (Kozlovskii, 1999):

- An attractor of a soil property is a numerical value toward which the property develops from a wide variety of initial or intermediate states of pedogenesis.
- An attractor of agricultural soil degradation is a minimal or maximal value, toward which the property tends to develop by long-term intensive agricultural use from a wide variety of initial conditions common for natural soils.

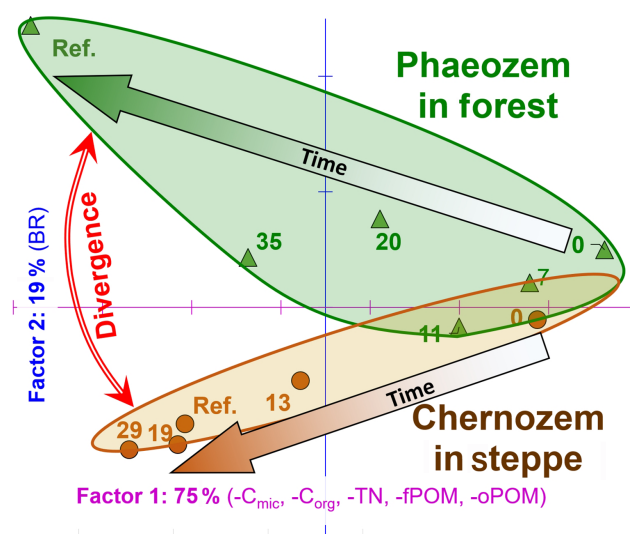
Attractors of soil properties are common for natural pedogenesis and anthropedogenesis (Fig. 1). The well-known examples of natural pedogenic attractors are the maximal SOM accumulation ( $C \approx 5\%–6\%$  for mineral soils), the highest increase in clay content in the Bt horizon by a  $\sim 2$ -fold illuviation compared to the upper horizon (without lithological discontinuity), the upper depth of the Bt horizon for sheet erosion, a minimal bulk density of mineral soils of  $\sim 0.8 \text{ g cm}^{-3}$ , and the maximal weathering in wet tropics by removal of all minerals until only Fe and Al oxides remain (Chadwick and Chorover, 2001).

Natural pedogenesis leads to a divergence of pedogenic properties and consequently to the broadening of the multidimensional attractor space (see below) because various soils develop to steady state from the same parent materials depending on climate, organisms and relief (Fig. 1). The time necessary for natural processes to reach these attractors is at least 1–2 orders of magnitude longer than the periods to reach the attractors of agropedogenesis (see below).

In contrast to natural pedogenesis, agropedogenesis narrows the soil properties by optimizing environmental conditions for agricultural crops with similar requirements (Lo Papa et al., 2011, 2013). Consequently, each soil property follows a trajectory from a specific natural level toward the unified agrogenic attractor (Fig. 1). Therefore, in contrast to natural pedogenesis resulting in divergence of soil properties, *agropedogenesis leads to convergence of soil properties*.

## 2.3 Examples of attractors of soil degradation

The convergence in soil properties (and thus reaching an attractor) after starting in various initial states is evident by comparing soils under long-term (e.g. decades and centuries) cultivation (Sandor and Homburg, 2017). The challenges that

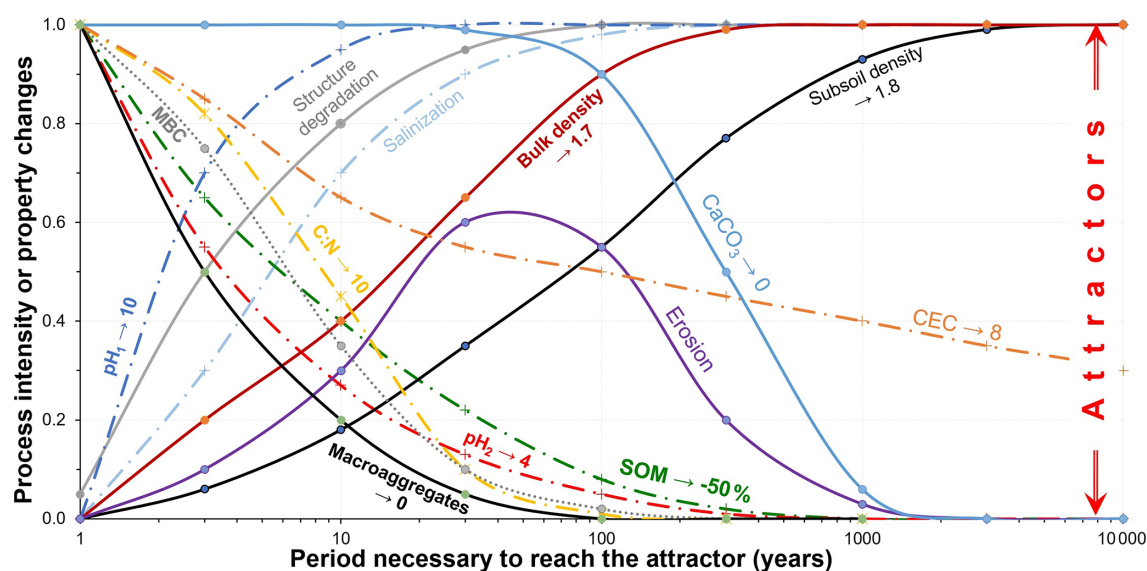


**Figure 4.** Example of the divergence of soil properties of abandoned agriculturally used Chernozem (under steppe) and Phaeozem (under forest) after termination of cultivation (Ovsepyan et al., 2019, modified). The soil properties were analysed by principal component analysis (PCA). The soils had very similar properties due to long-term ( $> 100$  years) cropping (time point “0”). After abandonment, they started to develop to their natural analogues (Ref.: natural reference soils), leading to strong divergences of their properties. This figure reflects the divergence by natural pedogenesis, i.e. the opposite situation to agropedogenesis. Numbers close to points: duration of abandonment, 0, is agricultural soil, and Ref. is natural analogues (never cultivated under natural vegetation). The soil parameters primarily driving the divergence are on the x axis: microbial biomass C ( $C_{mic}$ ), soil organic C ( $C_{org}$ ), total N (TN), free particulate organic matter (fPOM) and occluded organic matter (oPOM). On the y axis is basal respiration (BR). For details, see Ovsepyan et al., 2019.

ancient farmers faced were fundamentally the same as today, although recent decades are characterized by a major intensification of chemical impacts (fertilization and pesticides) and heavy machinery (Dudal, 2004; Sandor and Homburg, 2017). The main difference between soil degradation in the past and in the modern era is the rates and extent but not the processes or mechanisms themselves. The dynamics of soil properties in long-term cultivations have revealed a narrowing in the measured values of a given property over time, i.e. a tendency toward the attractor of that property (Alletto and Coquet, 2009; Dalal and Mayer, 1986a, c; Haas et al., 1957; Nyberg et al., 2012; Figs. 3, 4, 5, and S2).

In reaching the attractor values, however, the process rates and dynamics differ among various soil properties (Figs. 5 and 6), in various geo-climatological regions (Chen et al., 2011, p. 29 011; Guillaume et al., 2016b; Hartemink, 2006) and according to land-use intensity. For example, microbial biomass carbon (C) (Henrot and Robertson, 1994) and aggregate stability (Wei et al., 2014) respond faster than SOM and total N to cultivation. Cultivation affects total N and P





**Figure 5.** Overview on rates of key processes of agropedogenesis and their trajectory in reaching their attractors. Curves start from 0 or 1 (relative values) at the onset of cultivation and go to 1 or 0 for the specific attractors. Each curve is labelled with the specific property. Small arrows after each parameter title show the estimated level of attractor in absolute values. After approaching its attractor, each process slows down and finally stops. The timescale is logarithmic. Curve shape, time to reach attractor and attractor levels are only estimates and require future adjustment based on experimental data. pH<sub>1</sub> is for alkaline, and pH<sub>2</sub> is for acidic soils. Note that not all attractors are defined yet. Properties in bold are master soil properties for agropedogenesis (see Table 3). MBC is microbial biomass carbon, SOM is soil organic matter and CEC is cation exchange capacity. Continuous lines present physical properties or processes. Dotted–dashed lines correspond to chemical properties, and dotted lines correspond to biological properties.

content less than organic C because of N and P fertilization (Guillaume et al., 2016a), whereby a strong decrease in C input is inferred by the decreasing C : N ratio with cultivation duration (Wei et al., 2014). Whereas cultivation on deforested lands in the tropics can degrade soils within a few years, converting temperate prairies and steppes to agricultural fields supports crop production without fertilization for decades (Tiessen et al., 1994). Generally, the degradation rates (e.g. C losses) in the moist tropics are faster (e.g. about 4-fold faster) than in the dry tropics (Hall et al., 2013). Despite the differences in rates, however, the long-term cultivated soils ultimately reach similar degradation levels (Lisetskii et al., 2015; Fig. 3f).

## 2.4 Master soil properties

Soils and their functions are characterized by and are dependent on the full range of physical, chemical and biological properties. A few of them – the master soil properties – however, are responsible for a very broad range of functions and define other properties (Lincoln et al., 2014; Lisetskii et al., 2013; Seybold et al., 1997). We define a soil property as being a master property if it has a strong effect on a broad range of other properties and functions and if it cannot be easily assessed based on the other properties. For natural pedogenesis, such master properties – inherited partially from the parent material – are clay mineralogy and CaCO<sub>3</sub> content,

texture, nutrient content, and bulk density. The master properties that are cumulated or formed during pedogenesis are soil aggregation and structure, depth of A and B horizons, SOM stock and C : N ratio, pH, electrical conductivity (EC), etc. (Table 3). These properties largely define the other properties and soil functions under natural conditions and generally under agricultural use as well.

The master properties of agropedogenesis may differ from those of natural soil development. The crucial difference is that the *master properties of agropedogenesis must sensitively respond to agricultural use over the cultivation period*. Accordingly, properties such as texture, clay content and mineralogy – crucial master properties of natural pedogenesis, are not relevant in agropedogenesis. Note that although these properties may change under certain circumstances (Karathanasis and Wells, 1989; Velde and Peck, 2002), they fail to qualify as master properties in agropedogenesis because they are relatively insensitive to agricultural land use and soil degradation.

Master soil properties have an additional important function: they are responsible or co-responsible for the changes in other properties. Changes in a master property over time may therefore intensify or dampen changes in other (secondary) properties. The stability of macroaggregates, for example, increases with the content and quality of SOM (Boix-Fayos et al., 2001; Celik, 2005). The infiltration rate and water-holding capacity decrease with increasing bulk density (Rasa

**Table 3.** Soil properties suggested in the literature and in agropedogenesis theory as being master properties

Suggested minimum set of master properties	References
Clay content, CEC, bulk density	Minasny and Hartemink (2011)
CEC, CaCO <sub>3</sub> content, exchangeable sodium percentage (ESP), sodium absorption ratio, pH	Nabiollahi et al. (2017)
Bulk density, Mg content, total N, C : N ratio, aggregate size distribution, penetration, microbial respiration	Askari and Holden (2015)
Labile phosphorus, base saturation, extractable Ca	Lincoln et al. (2014)
C : N ratio, labile phosphorus, C <sub>humic</sub> : C <sub>fulvic</sub> , Gibbs energy, SiO <sub>2</sub> : (10R <sub>2</sub> O <sub>3</sub> )	Lisetskii et al. (2013)
pH, sodium absorption ratio, potentially mineralizable N, labile phosphorus	Andrews et al. (2003)
Labile (active) carbon	Bünemann et al. (2018)
Microbial biomass, microbial respiration	Guillaume et al. (2016a)
pH, arylsulfatase activity	Raiesi (2017)
Geometric means of microbial and enzyme activity	Raiesi and Kabiri (2016)
Coarse fragments, pH, SOC, total N, ESP, exchangeable cations (Ca, Mg and K), available phosphorus	Rezapour and Samadi (2012)
Physical:	
bulk density (1.7 g cm <sup>-1</sup> ), macroaggregates (0 %), soil depth (A and B horizons are 20 cm)	
Chemical:	
SOM content (50 % natural), C : N (8–10), pH (4 or 10), EC (16 dS m <sup>-1</sup> ) <sup>a</sup>	This study <sup>b</sup>
Biological:	
microbial biomass C, basal respiration	

<sup>a</sup> CEC has been omitted from chemical master properties because it depends on (i) clay content and clay mineralogy, whose properties are resistant to agricultural practices, and (ii) SOM, which is considered a master property.

<sup>b</sup> The values in brackets are very preliminary attractors of each property by anthropogenic soil degradation. The two pH attractors are presented for acidic (humid climate) and alkaline (semiarid climate) soils. Note that not all attractors can be suggested in this study. The criteria for selecting master soil properties are described in the text.

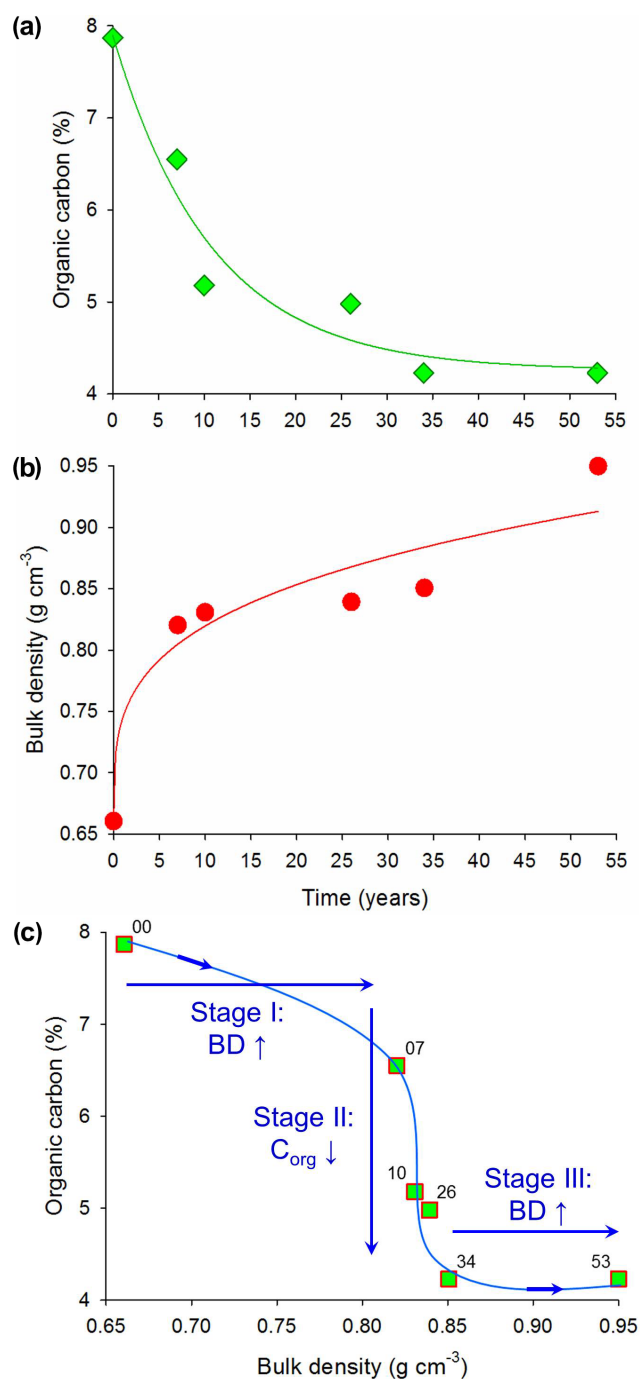
and Horn, 2013; Raty et al., 2010), promoting erosion. These relations between soil properties, however, seem to be significant only within certain ranges, i.e. until thresholds are reached. Beyond such thresholds, new relations or new master properties may govern. For example, an increasing effect of SOM content on aggregate stability in extremely arid regions of the Mediterranean was recorded at above the 5 % SOM content threshold (Boix-Fayos et al., 2001). Increasing organic matter contents up to this 5 % threshold had no effect on aggregate stability: instead, the carbonate content was the main regulator (Boix-Fayos et al., 2001). Microbial biomass and respiration in well-drained Acrisols in Indonesia are resistant to decreasing SOM down to 2.7 % of SOM but strongly dropped beyond that value (Guillaume et al., 2016a). While the amounts of SOM and total N in sand and silt fractions may continuously decrease with cultivation duration, those values in the clay fraction remain stable (Eleftheriadis et al., 2018; Fig. 3e). Bulk density increases non-linearly with SOM decrease, and the rates depend on SOM content (Fig. 6). Phase diagrams are very useful in identifying such thresholds (see below).

Summarizing, we define master properties as a group of soil-fertility-related parameters that (1) are directly affected by management, i.e. are sensitive to agricultural use and soil degradation, (2) determine the state of many other (non-master) parameters and soil fertility indicators during agropedogenesis, and (3) should be orthogonal to each other, i.e. independent (or minimally dependent) of one other (Ko-

zlovskii, 1999). Note that, in reality, all soil properties are at least partially dependent on each other. Nonetheless, the last prerequisite – orthogonality – ensures the best separation of soils in multidimensional space (see below) and reduces the redundancy of the properties.

Considering the three prerequisites and based on expert knowledge, as well as on phase diagrams (see below), we suggest soil depth (A and B horizons) and eight properties as being master properties (Table 3): density, macroaggregates, SOM, the C : N ratio, pH, EC, microbial biomass C and basal respiration. We consider these nine to be sufficient to describe the degradation state of most other parameters during agropedogenesis: water permeability, penetration resistance, erodibility, base saturation, exchangeable sodium percentage, sodium absorption ratio, N mineralization, availability of other nutrients, etc.

The combination of master properties provides a minimum dataset to determine soil development stages with cultivation duration (Andrews et al., 2002). Organic C content is the most important and universally accepted master property that directly and indirectly determines the state of many physical (soil structure, density, porosity, water-holding capacity, percolation rate and erodibility; Andrews et al., 2003; Nabiollahi et al., 2017; Seybold et al., 1997; Shpedt et al., 2017), chemical (nutrient availability, sorption capacity and pH; Lal, 2006; Minasny and Hartemink, 2011) and biological (biodiversity, microbial biomass and basal respiration; Raiesi, 2017) properties. The values of the mentioned secondary properties can



**Figure 6.** Effects of duration of forest conversion to cropland on decreasing soil organic carbon (SOC) (a) and increasing bulk density (b) over 53 years (southern Ethiopian Highlands; Lemenih et al., 2005). (c) Phase diagram: relation between SOC and bulk density at corresponding time. Note the stepwise changes in bulk density following decreasing SOC content below the thresholds of 7.8 %, 6.5 % and 4.2 %. Numbers beside symbols refer to years after conversion.

be estimated with an acceptable uncertainty based on robust data on SOM content (Gharahi Ghehi et al., 2012). Finding additional soil properties beyond SOM to form the set of master properties is, however, not straightforward (Homburg et al., 2005) because it depends on the desired soil functions (Andrews et al., 2003) such as nutrient availability, water permeability and holding capacity, crop yield quantity and quality, etc. (Andrews et al., 2002). Therefore, various types of master properties, depending on geo-climatological conditions (Cannell and Hawes, 1994), have already been suggested (Table 3). Nonetheless, the dynamics, sensitivity and resistance of such properties to degradation and with cultivation duration remain unknown (Guillaume et al., 2016a).

## 2.5 Analysis of phase diagrams and identification of thresholds and stages of soil degradation

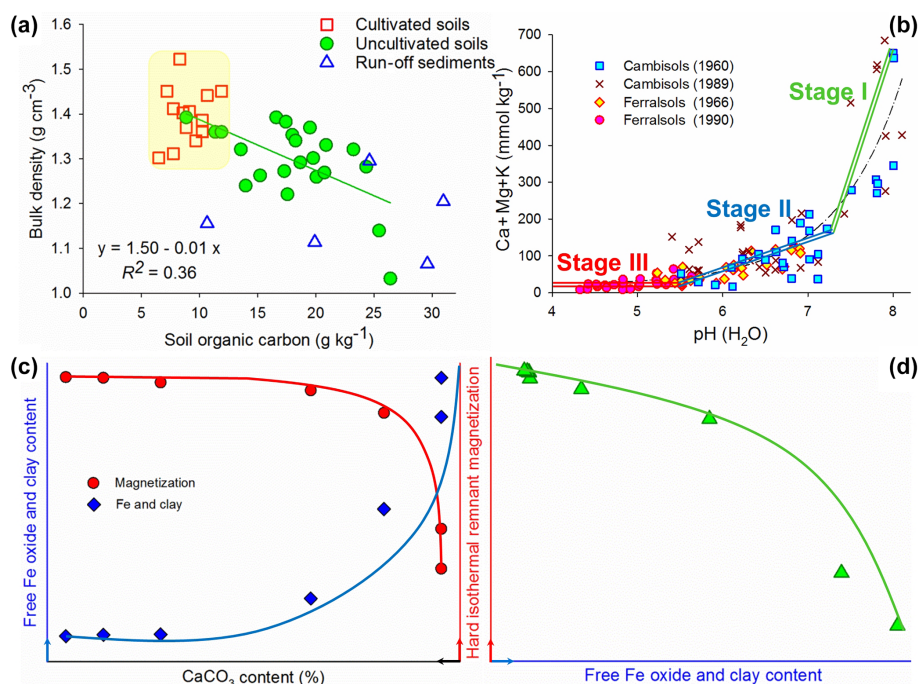
All the properties described above move toward their attractors over the course of soil degradation with time (Figs. 3 and 6). The duration, however, is difficult to compare between soils because the process rates depend on climatic conditions and land-use intensity. One option for understanding and analysing soil degradation independent of time is to use phase diagrams. Generally, a phase diagram is a type of chart for showing the state and simultaneous development of two or more parameters of a matter<sup>1</sup>. Phase diagrams present (and then analyse) properties against each other without the time factor (Figs. 6c and 7). Thus, various properties measured in a chronosequence of soil degradation are related to each other on 2-D or even 3-D graphs (Fig. 8), and time is excluded.

Phase diagrams have two advantages: (1) they help evaluate the dependence of properties on each other – independent of time, climate or management intensity. They represent generalized connection between the properties. This greatly simplifies comparing the trajectory of soil degradation under various climatic conditions, management intensity levels and even various land uses. (2) Such diagrams enable identifying the thresholds and stages of soil development and degradation.

We define these terms as follows.

- Thresholds of soil development and degradation are relatively abrupt changes in process rates or process directions leading to a switch in the dominating mechanism of soil degradation.
- Stages of soil degradation are periods confined by two thresholds and characterized by one dominating degradation mechanism (Fig. 6c).

<sup>1</sup>Note that in chemistry, mineralogy and materials sciences, a phase diagram is a type of chart used to show conditions (pressure, temperature, volume, etc.) at which thermodynamically distinct phases (e.g. solid, liquid or gaseous states) are at equilibrium.



**Figure 7.** Phase diagrams of various properties of agricultural soils. Small arrows at the start or end of the axes show the increase in the corresponding soil property. **(a)** Narrow range (yellow shaded area) of organic carbon and bulk density in ancient agricultural soils cultivated for 1500 years at Mimbres (New Mexico, USA) compared to uncultivated soils and run-off sediments (Sandor et al., 2008). Note that the decreasing trend of bulk density with increasing soil organic carbon content (green line with regression equation for uncultivated soils) is absent in cultivated soils (Sandor et al., 2008). **(b)** Changes in exchangeable base cations depending on soil pH in Cambisols and Ferralsols in coastal plains of Tanzania (Hartemink and Bridges, 1995). Ferralsols clearly decline in exchangeable cations (i.e. two separated groups in stage II and III) with decreasing pH over ca. 24 years of cultivation. The exchangeable cations in Cambisols remain in stage I. Double lines: stages of exchangeable cation decrease with decreasing soil pH. Content of exchangeable cations levels off at  $\sim 25 \text{ mmol kg}^{-1}$  (stage III). This value – which corresponds to the amount of exchangeable  $\text{Ca}^{2+}$  and  $\text{Mg}^{2+}$  shown in Fig. 3d (31 years of sugar cane cultivation on Fijian Ferralsols) – is an attractor. **(c)** The content of free iron oxides, clay content and hard isothermal remnant magnetization (IRMh) as a function of  $\text{CaCO}_3$  content in soil (adopted from Chen et al., 2011). **(d)** The relation between IRMh vs. free iron oxides and clay content.

Importantly, soil degradation does not always follow a linear or exponential trajectory (Kozlovskii, 1999; Kozlovskii and Goryachkin, 1996). This means that changes (absolute for linear or relative for exponential) are not proportional to time or management intensity (Kozlovskii and Goryachkin, 1996; Matus and Egli, 2019). Soil degradation proceeds in stages of various levels of duration and intensity. The key consideration, however, is that each stage is characterized by the dominance of one (group) of degradation processes, whose prerequisites are formed in the previous phase.

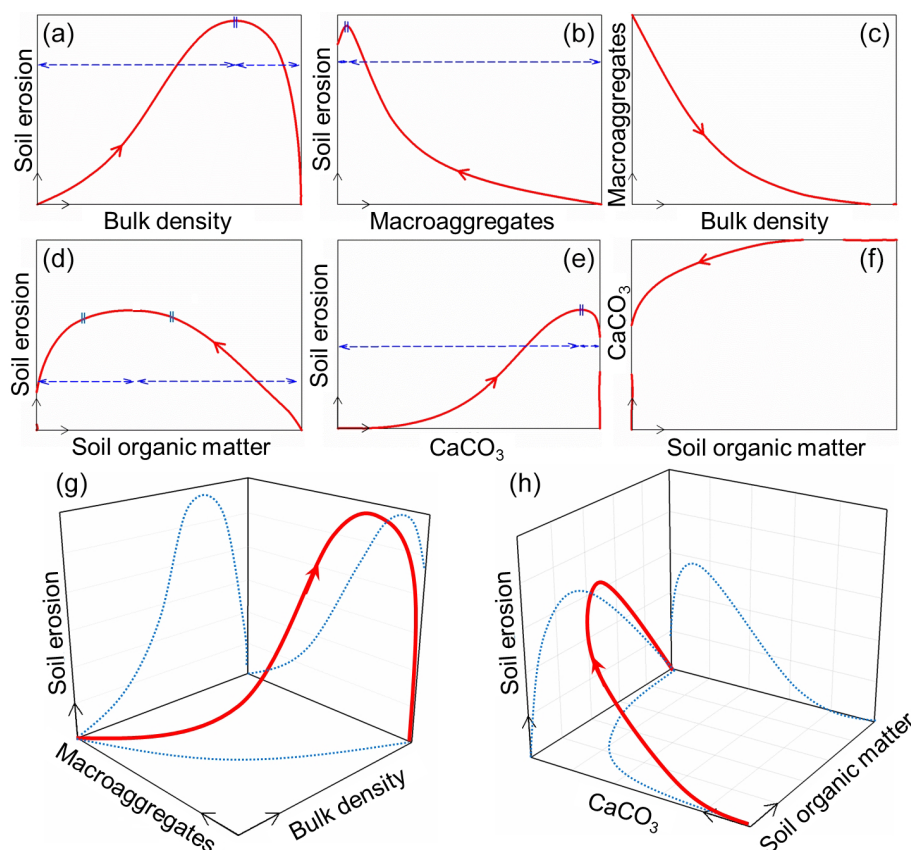
We conclude that phase diagrams (1) enable tracing the trajectory of various soil properties as they reach their attractors, independent of time, land-use or management intensity, and (2) are useful for analysing not only the dependence (or at least correlation) between individual properties but also for identifying the thresholds of soil degradation. The thresholds clearly show that soil degradation proceeds in stages (Figs. 6c, 7 and 8), each of which is characterized by the dominance of one specific degradation process with

its specific rates (and affecting the degradation of related soil properties).

## 2.6 Multi-dimensional attractor space

The phase diagrams described above were presented in 2-D or 3-D space (Figs. 7 and 8) and help in evaluating the connections between the properties and the stages of soil degradation. The suggested nine master soil properties are orthogonal, and the phase diagrams can therefore be built in multidimensional attractor space – the space defining the soil degradation trajectory based on the master soil properties (Fig. 8g and h). Therefore, development of master soil properties during long-term agricultural land use and degradation forms a multidimensional space of properties (multi-dimensional space) toward which the soil will develop (trajectory) during agropedogenesis and will then remain unchanged within this equilibrium field. Accordingly, the multidimensional space of attractors defines the final stage of agropedogenesis.

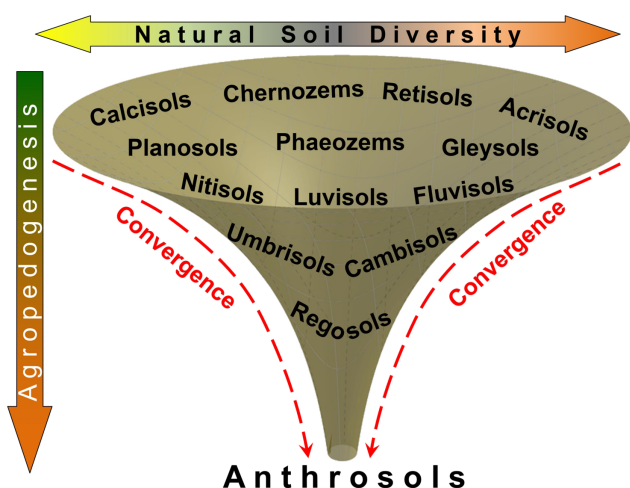




**Figure 8.** Examples of conceptual 2-D and 3-D phase diagrams linking soil erosion intensity with (a, b, g) bulk density and macroaggregate content and (d, e, h) SOM and  $\text{CaCO}_3$  contents during agropedogenesis. The original curves were taken from Fig. 6. Small red arrows on curved lines show the direction of soil degradation and correspond to the increasing duration or intensity of agricultural use. Vertical blue double lines show the arbitrary thresholds of soil degradation, and horizontal blue dashed arrows show the degradation stages. The stages are time-lapse to reach a threshold for a given soil property. After a threshold the trend may slow down or reverse. Projections of 3-D lines (light blue) in (g, h) correspond to the individual lines on the 2-D phase diagrams in (a)–(c) and (d)–(f). Similar phase diagrams can be built in multidimensional space corresponding to the number of master soil properties (Table 3).

The degraded soil will remain within this multidimensional space even if subsequently slightly disturbed (or reclaimed). This explains why long-term agricultural fields that have been abandoned for centuries or even millennia still show evidence of soil degradation (Hall et al., 2013; Jangid et al., 2011; Kalinina et al., 2013; Lisetskii et al., 2013; Ovsepyan et al., 2019; Sandor et al., 2008). For example, abandoned soils under succession of local vegetation such as grassland and forest show similar physicochemical and biological properties as a result of similarities in their history, i.e. agricultural land use (Jangid et al., 2011; Kalinina et al., 2019; Kurganova et al., 2019; Ovsepyan et al., 2019). The flood-irrigated soils in Cave Creek, Arizona, support only the growth of the creosote bush even about 700 years after abandonment. This contrasts with the presence of seven species of shrubs and cacti in areas between such soils. The reason is substantial changes in soil texture, i.e. via siltation, thus reducing the water-holding capacity in the flood-irrigated soils and leading to a shift in the vegetation com-

munity toward more drought-resistant species, in this case the creosote bush (Hall et al., 2013). Whereas establishing a no-till system on former pasture-land leads to a decrease in SOM, changing a formerly ploughed land to no-till had no such effect (Francis and Knight, 1993). The amidase activity in Colca soils, Peru, is still high 400 years after land abandonment due to the remaining effect of applied organic amendments on microorganisms (Dick et al., 1994). We argue that during agropedogenesis the multidimensional space of master soil properties will continuously narrow when approaching the attractors. This multidimensional space resembles a funnel (Fig. 9), meaning that the broad range of all properties in initial natural soils will be narrowed and unified to a (very) small range in agricultural and subsequently degraded soils. Identifying the attractors of master properties and the relations among them in this multidimensional space yields diagnostic characteristics for identifying and classifying agrogenic soils (Gerasimov, 1984; Kozlovskii, 1999).



**Figure 9.** Conceptual schema of convergence of soil properties by agropedogenesis. The very broad range of natural soils and their properties will be tailored for crop production by agricultural use, resulting in Anthrosols with a very narrow range of properties. Note that the soils within the funnel are mentioned exemplarily, and not all World Reference Base (WRB) soil groups are presented. The sequence of soils within the funnel does not reflect their transformations during agropedogenesis to Anthrosols. (The extended version of this figure, reflecting multiple pathways to Anthrosols, e.g. formed and used under completely different climate and management conditions, is presented in Fig. S3.)

## 2.7 Changes in the attractors by specific land use or climatic conditions

Despite the principle of attractors – the convergence of a property of various soils to one value by degradation – we assume that these attractors may differ slightly depending on climate, parent material and management (Fig. S3). This means that the multidimensional attractor space can exhibit some local minima – metastable states (Kozlovskii, 1999). If the initial natural soil is close to such a minimum, or the management pushes the trajectory in such a direction, then agropedogenesis may stop at local minima. Thus, the global minimum will not be reached.

For example, no-till farming may increase SOM in the Ap horizon (Lal, 1997) and cause SOM contents to level off at higher values compared to tillage practices (Fig. 10). However, periodically tilling the soil to simplify weed control quickly destroys the improvements in soil properties during the no-till period (Cannell and Hawes, 1994). This results in degradation stages similar to soils under conventional tillage. The ultimate effect of irrigation on soil degradation is expected to be similar to that of dry-land farming. Despite more organic C input into irrigated systems, the SOM content remains unchanged (Troost et al., 2014) due to accelerated decomposition (Denef et al., 2008). The state of soil properties in the tropics is predictable based on pedotransfer functions commonly used in temperate regions, which, even though

tropical soils are usually more clayey, have a lower available water capacity and exhibit a higher bulk density. The explanation lies in the similarities in relations among soil properties under various climatic conditions (Minasny and Hartemink, 2011). This makes the concept of attractors generalizable to all cultivated soils (Kozlovskii, 1999), although geo-climatic conditions and specific management may modify the attractor values and affect the rates of soil degradation following cultivation (Tiessen et al., 1994).

## 3 Conclusions and outlook

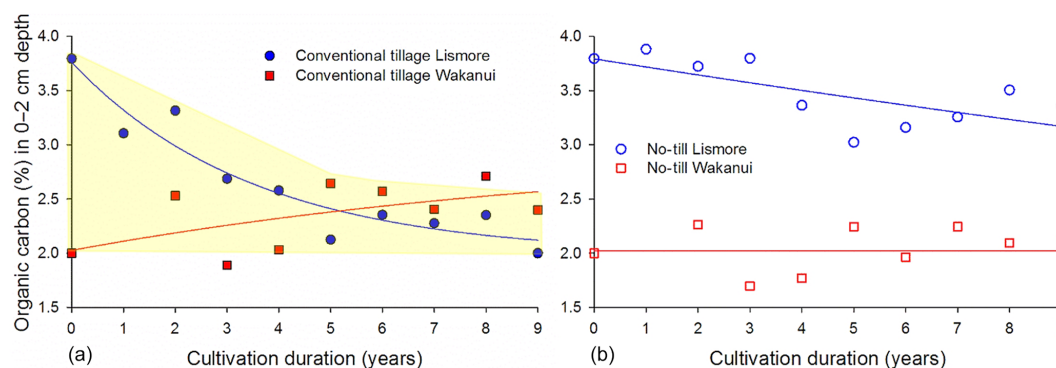
### 3.1 Conclusions

We state that (1) human activities are stronger in intensity and rates than all other soil-forming factors (Liu et al., 2009; Richter et al., 2015). Because humans exploit mainly one soil function – crop production – they optimize all soil processes and properties toward a higher yield of a few agricultural crops. Because most crops have similar requirements, the range of measured values for any soil property becomes narrower during agropedogenesis. Therefore, human activities for crop production lead to the formation of a special group of agrogenic soils with a defined and narrow range of properties – Anthrosols. The range of properties moves toward the attractor: specific for each property but similar for various soils. (2) Analysing the properties of soils from various geo-climatological conditions and types of management in relation to cultivation periods reveals (i) the dynamics of soil properties by agropedogenesis and (ii) demonstrates the final stage of agrogenic degradation when the values of various soil properties reach the attractor.

By analysing the soil development and the properties' dynamics under agricultural use, we develop for the first time the basic theory of agropedogenesis. This theory is based on (1) the modified classical concept of factors → processes → properties → functions and back to the processes, (2) the concept of attractors of soil degradation, (3) identifying master soil properties and analysing their dynamics by agropedogenesis, (4) analysing phase diagrams of master soil properties to identify the thresholds and stages of soil degradation, and finally (5) defining multidimensional attractor space. We defined the attractors and provided the basic prerequisites for elucidating the nine master properties responsible for the trajectory of any soil during agropedogenesis within multidimensional attractor space.

### 3.2 Outlook

We developed a new unifying theory of agropedogenesis based on the long observation of soil degradation under agricultural use and on experiments with agricultural soils under various land-use intensity under a broad range of climatic conditions. The presented examples of soil degradation trajectories and of attractors of soil properties clearly do not re-



**Figure 10.** Nine years of continuous cropping and conventional tillage (a) led to similar soil organic carbon (SOC) contents in contrast to no-till soils (b) (Francis and Knight, 1993). The Lismore no-till soil either needs longer cultivation duration to reach the C content characterizing soils under conventional tillage or the attractor of SOC has already been reached, i.e. local minima for this soil. Note that the Wakanui no-till soil was cultivated for 10 years before beginning the trial and thus shows similar values, i.e. similar attractor for SOC as under conventional tillage. Thus, changing the conventional tillage to no-till had no effect on SOC content. Lismore soil is an Umbric Dystochrept, containing 5 % stones, with rapid draining, which was cultivated for 5 years under mixed rye grass and white clover pasture. Wakanui soil is an Udic Ustochrept, with slow draining, and 10-year rotation of wheat, barley and peas.

flect the full range of situations. This theory therefore needs to be filled with more observational and experimental data. Various emerging topics can be highlighted.

- *Confirmation of master soil properties.* The master properties presented here represent suggested entities. This calls for clarifying whether these are sufficient (or excessive) to describe the stages of soil degradation under agropedogenesis. The degree of orthogonality of these properties also remains to be determined. Defining the master soil properties and their multidimensional attractor space will clearly simplify the modelling of degradation trajectories.
- *Identification of attractor values.* The suggested attractor values (Figs. 3, 6 and 7b; Table 3) are mainly based on a few chronosequence studies and expert knowledge. These values should be defined more precisely based on a larger database. The challenge here is that the average values are not suitable as attractors because only the maximal or minimal values – the attractors – of a variable are of interest. Therefore, specific statistical methods should be applied, e.g. the lower (or upper – depending on the property) 95 % confidence interval or envelope testing should be used instead of means to set the attractor value.
- *The determination of local minima.* The determination of local minima is necessary (and is closely connected with the identification of the multidimensional attractor space). Arriving at such local minima will temporarily stop soil degradation, and knowing their values can help simplify the measures to combat degradation and accelerate soil recovery.
- *Threshold investigation.* Investigating the thresholds and stages of soil degradation, along with identifying the main mechanisms dominating at each stage, should be done based on the phase diagrams of various soil properties – at least those of the master properties. These stages of agropedogenesis with their corresponding main mechanisms are crucial for understanding, modelling and combating soil degradation.
- *Model development.* Only a few models of natural pedogenesis in its full complexity are available (Finke, 2012; Finke and Hutson, 2008; Keyvanshokouhi et al., 2016), and the models addressing soil degradation describe more or less individual or a selected few processes but not overall agropedogenesis. For example, various models are available for erosion (Afshar et al., 2018; Arekhi et al., 2012; Ebrahimzadeh et al., 2018; Millward and Mersey, 1999; Morgan et al., 1998; Pournader et al., 2018; Rose et al., 1983), SOM decrease (Chertov and Komarov, 1997; Davidson et al., 2012; Del Grosso et al., 2002; Grant, 1997; Liu et al., 2003; Smith et al., 1997), density increase (Hernanz et al., 2000; Jalabert et al., 2010; Makovnikova et al., 2017; Shiri et al., 2017; Taalab et al., 2013; Tranter et al., 2007) and other processes due to land use. This calls for complex theory-based models of agropedogenesis.

*Data availability.* No data sets were used in this article.

*Supplement.* The supplement related to this article is available online at: <https://doi.org/10.5194/bg-16-4783-2019-supplement>.

*Author contributions.* YK and KZ contributed equally to writing the paper.

*Competing interests.* The authors declare that they have no conflict of interest.

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