Cover page

Title: **Agropedogenesis: Humankind as the 6th soil-forming factor and attractors of agricultural soil degradation**

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# Agropedogenesis: Humankind as the 6th soil-forming factor and attractors of agricultural soil degradation

## Abstract

Agricultural land covers 5100 million 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*, urgently needed. We introduce a theory of *anthropedogenesis* – soil development under the main factor 'humankind' – the 6th 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 – Processes – Properties with the addition of 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 multi-dimensional 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 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 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 to a multi-dimensional attractor space enables predicting the trajectory and the final state of agrogenic soil development and to develop measures to combat soil degradation. In conclusion, the suggested new theory of anthro- and agropedogenesis is a prerequisite for merging various degradation processes to a general view, and for understanding the functions of humankind not only as the 6th soil-forming factor but also as an ecosystem engineer optimizing its environment to fulfil a few desired functions.

*Keywords*: Anthropogenic soil change, Soil-forming factors, Land-use, Intensive agriculture, Anthropocene, Human impact, Ecosystem engineer, Global change

# 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, ...) (see the copy-paste history of the equation in Supplementary Materials).

The processes of additions, losses, transfers/translocation, and transformations of matter and energy over centuries and millennia produce a medium – soil (Simonson, 1959), which supports plant roots and fulfills 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 as 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 Amazonian Basin (Glaser et al., 2001), *Plaggen* in northern Europe (Pape, 1970) as well as *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 human populations (Carozza et al., 2007) and technological progress. Increasing food demand requires either larger areas for croplands or/and 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 + grasslands) cover 5100 million ha, corresponding to about 34% of the global land area. Huge areas are located in very cold regions that are continuously covered by ice (1500 million ha), in hot deserts, mountainous areas, or barren regions (2800 million ha), as well as sealed in urban and industrial regions and roads (150 million ha). Accordingly, agricultural lands cover about 50% of the area potentially suitable for agriculture (*https://ourworldindata.org/yields-and-land-use-in-agriculture*). 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 – anthropedogenesis and its subcategory agropedogenesis – is absent. This paper therefore presents for the first time a unifying theory of *anthropedogenesis* – soil development under the main factor 'humankind' – the 6$^{th}$ factor of soil formation. Moreover, we expand it to encompass *agropedogenesis* as a key aspect of general anthropedogenesis.

## 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 (18$^{th}$ to 6$^{th}$ centuries BC) (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, loosening soil by tillage, run-off irrigation, draining, and terracing), (ii) altered soil chemical conditions through fertilization, liming, 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., 2016a; 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 3 of them – corn, wheat, and rice – supply 2/3 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 (Supplementary Fig. 1) 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 Mollisol (~ Chernozems or Phaeozems), for example, turns into an Inceptisol (~ Cambisols) by decreasing total SOM (Lo Papa et al., 2013; Tugel et al., 2005) or/and thinning of the mollic epipedon by tillage and erosion and destroying granular and sub-polyedric 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), Hortic Anthrosols (long-term fertilized soils with household wastes and manure) and Irragric Anthrosols (long-term irrigated soils in dry regions) (WRB, 2014). These effects have stimulated the on-going 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 of 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 'humans' (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.

Agropedogenesis should be clearly separated from the natural pedogenesis because of: (1) strong dominance of the factor 'human' over all 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, (5) much higher intensity of many specific processes compared to natural developments and consequently faster rates of all changes.

Agropedogenesis and natural pedogenesis are partly 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; Supplementary Materials). Here, soil formation will reach the quasi-steady state typical for the combination of the five soil-forming factors (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. Agropedogenesis is partly 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 even less) 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: (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.

## 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 very well describes the visible morphological soil properties in the field and measurable parameters in the lab, leading to the development of various (semi)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, 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, and thus adapt and modify 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 multi-functionality, 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 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). We define:

**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 ≈ 5-6% for mineral soils), highest increase of clay content in the Bt horizon by a ~ two-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 ~ 0.8 g $cm^3$, 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 multi-dimensional 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 a start from various initial states is evident by comparing soils under long-term (e.g. decades and centuries) cultivation (Sandor and Homburg, 2017). The challenges that ancient farmers faced were fundamentally the same as today, although recent decades are characterized by a major intensification of chemical impacts (fertilization, 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, 1986b; Dalal and Mayer, 1986; Haas et al., 1957; Nyberg et al., 2012) (Figs 3, 4, and the Supplementary Fig. 2).

In reaching the attractor values, however, the process rates and dynamics differ among various soil properties (Fig. 6), in various geo-climatological regions (Chen et al., 2011, p.29011; Guillaume et al., 2016a; 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 content less than organic C because of N and P fertilization (Guillaume et al., 2016b), whereby a strong decrease of 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) 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 partly from the parent material – are: clay mineralogy and $CaCO_3$ content, texture, nutrient content, and bulk density. The master properties that are cumulated or formed during pedogenesis are: soil aggregation/structure, depth of A+B horizons, SOM stock and C:N ratio, pH, electrical conductivity, 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 (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 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 5% SOM contents (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 Acrisoils in Indonesia are resistant to decreasing SOM down to 2.7% of SOM, but strongly dropped beyond that value (Guillaume et al., 2016b). 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. 7). Phase diagrams are very useful to identify 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 (Kozlovskii, 1999). Note that, in reality all soil properties are at least partly dependent on each other. Nonetheless, the last prerequisite – orthogonality – ensures the best separation of soils in multi-dimensional 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+B horizons) and 8 properties as being master (Table 3): Density, Macroaggregates, SOM, C/N ratio, pH, EC, Microbial biomass C, and Basal respiration. We consider these 9 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, erodibility) (Andrews et al., 2003; Nabiollahi et al., 2017; Seybold et al., 1997; Shpedt et al., 2017), chemical (nutrient availability, sorption capacity, pH) (Lal, 2006; Minasny and Hartemink, 2011), and biological (biodiversity, microbial biomass, basal respiration) (Raiesi, 2017) properties. The values of the mentioned secondary properties can 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., 2016b).

**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 intensities. One option to understand and analyze soil degradation *independent of time* is to use phase diagrams. Generally, a phase diagram is a type of chart to show the state and simultaneous development of two or more parameters of a matter[1]. Phase diagrams present (and then analyze) properties against each other, without the time factor (Figs 7c and 8). Thus, various properties measured in a chronosequence of soil degradation are related to each other on 2D or even 3D graphs (Fig. 9), 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 intensities and even various land-uses. (2) Such diagrams enable identifying the *thresholds* and stages of soil development and degradation.

We define:

***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. 7c)**.**

[1] 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.

Importantly, soil degradation does not always follow a linear or exponential trajectory (Kozlovskii, 1999). This means that changes (absolute for linear or relative for exponential) are not proportional to time or management intensity. Soil degradation proceeds in stages of various duration and intensity. The key consideration, however, is that each stage is characterized by the dominance of one (group) of degradation process(es), 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 into analyze not only the dependence (or at least correlation) between individual properties, but also to identify the thresholds of soil degradation. The thresholds clearly show that soil degradation proceeds in stages (Figs 7c, 8 and 9), 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 2D or 3D space (Fig. 7 and 8) and help to evaluate the connections between the properties and the stages of soil degradation. The suggested 9 master soil properties are orthogonal and the phase diagrams can therefore be built in multi-dimensional attractor space – the space defining the soil degradation trajectory based on the master soil properties (Fig. 8 bottom). Therefore, **development of master soil properties during long-term agricultural land-use and degradation forms a multi-dimensional 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 multi-dimensional space of attractors defines the final stage of agropedogenesis.**

The degraded soil will remain within this multi-dimensional 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 after about 700 years 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 community to 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 plowed 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 of land abandonment due to the remaining effect of applied organic amendments on microorganisms (Dick et al., 1994). **We argue that during agropedogenesis the multi-dimensional space of master soil properties will continuously narrow in approaching the attractors. This multi-dimensional 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 multi-dimensional space yields diagnostic characteristics to identify and classify agrogenic soils (Gerasimov, 1984; Kozlovskii, 1999).

## 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 (Supplementary Fig. 3). This means that the multi-dimensional 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. Hence, the global minimum will not be reached.

For example, no-till farming may increase SOM in the Ap horizon (Lal, 1997) and cause them 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 (Trost 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, 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 managements 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 intensities 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) Analyzing the properties of soils from various geo-climatological conditions and managements 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 analyzing 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 analyzing their dynamics by agropedogenesis, (4) analyzing phase diagrams of master soil properties to identify the thresholds and stages of soil degradation, and finally (5) defining multi-dimensional 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 multi-dimensional 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 intensities under a broad range of climatic conditions. The presented examples of soil degradation trajectories and of attractors of soil properties clearly do not to reflect 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 multi-dimensional attractor space will clearly simplify the modelling of degradation trajectories.

Identification of attractor values: The suggested attractor values (Fig. 3, 6, 8b; 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 is necessary (and is closely connected with the identification of the multi-dimensional 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.

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 the master properties. These stages of agropedogenesis with their corresponding main mechanisms are crucial for understanding, modeling, and combating soil degradation.

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.

*Author contribution*

YK and KZ contributed equally to writing the paper.

*Competing interest*

The authors declare that they have no conflict of interest.

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

| | Degradation directions and consequences | Processes and mechanisms | References |
|---|---|---|---|
| Physical properties | Structure:<br>⇩ granular structure<br>⇧ hard clod formation<br>⇧ micro-aggregates and large blocks | - ⇩ SOM content and litter input<br>- aggregate destruction<br>- ⇩ rhizodeposition & mucilage | (Homburg and Sandor, 2011)<br>(Ayoubi et al., 2012; Celik, 2005; Khormali et al., 2009) |
| | Density:<br>⇧ bulk density<br>⇧ subsoil compaction<br>⇧ formation of massive layers | - compaction by heavy machinery<br>- plowing at a constant depth<br>- destruction of aggregates<br>- ⇩ SOM content<br>- ⇩ burrowing animals (earthworms, gophers, etc.)<br>- ⇩ root growth and distribution | (Carducci et al., 2017; Holthusen et al., 2018; Horn and Fleige, 2009; Severiano et al., 2013) |
| | Porosity:<br>⇩ total porosity<br>⇩ water holding capacity<br>⇩ soil aeration | - ⇩ root density<br>- ⇩ burrowing animals<br>- ⇩ large & medium aggregates | (Celik, 2005; Lipiec et al., 2012)<br>(Flynn et al., 2009; Ponge et al., 2013) |
| | ⇩ soil depth | - ⇧ water and wind erosion<br>- ⇧ tillage erosion<br>- ⇧ soil density | (Ayoubi et al., 2012; Govers et al., 1994; Lal, 2001) |
| Chemical properties | ⇩ SOM content<br>⇩ easily available and low molecular weight organic substances | - ⇧ SOM mineralization by increasing aeration<br>- removal of plant biomass via harvesting<br>- residual burning<br>- destruction of macro-aggregates | (Lisetskii et al., 2015; Liu et al., 2009; Sandor and Homburg, 2017) |
| | ⇩ element/nutrient content<br>loss of nutrients<br>narrowing of C:N:P ratio | - removal of plant biomass via harvesting<br>- nutrient leaching<br>- SOM mineralization + NP-fertilization | (Hartemink, 2006; Lisetskii et al., 2015; Sandor and Homburg, 2017) |

| | | | |
|---|---|---|---|
| | <u>Acidification:</u><br>⇩ pH<br>⇧ exchangeable aluminum<br>⇩ CEC | - N-fertilization<br>- cation removal by harvest<br>- ⇩ buffering capacity due to cation leaching and decalcification<br>- acidification and $H^+$ domination on exchange sites<br>- loss of SOM | (Homburg and Sandor, 2011; Obour et al., 2017; Zamanian and Kuzyakov, 2019) |
| | ⇧ salts and/or exchangeable $Na^+$ | - irrigation (with low-quality water or/and groundwater level rise by irrigation) | (Dehaan and Taylor, 2002; Emdad et al., 2004; Jalali and Ranjbar, 2009; Lal, 2015) |
| Biological properties | ⇩ biodiversity<br>⇩ (micro)organism density and abundance | - weeding<br>- pesticide application<br>- monocultures or narrow crop rotations<br>- mineral fertilization<br>- ⇩ SOM content and litter input<br>- ⇩ root amounts and rhizosphere volume<br>- plowing and grubbing<br>- ⇩ total SOM<br>- pesticide application | (Lal, 2009; Zhang et al., 2017)<br>(Breland and Eltun, 1999; Fageria, 2012) |
| | ⇩ microbial activities<br>- respiration<br>- enzyme activities | - recalcitrance of remaining SOM<br>- ⇩ microbial abundance<br>- ⇩ litter & rhizodeposition input<br>- mineral fertilization<br>- ⇩ organism activity, diversity and abundance<br>- shift in microbial community structure<br>- ⇩ soil animal abundance and activity | (Breland and Eltun, 1999) (Bosch-Serra et al., 2014; Diedhiou et al., 2009; Ponge et al., 2013) |

⇧ and ⇩ means increase or decrease, respectively

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

| Additions | Losses | Translocation | Transformation |
|---|---|---|---|
| Irrigation<br>- water<br>- salts ⇧*<br>- sediments | Mineralization ⇧<br>- organic matter<br>- plant residues<br>- organic fertilizers<br>- N (to $N_2O$ and $N_2$) ⇧ | Irrigation<br>- dissolved organic matter ⇩<br>- soluble salts ⇧ | Fertilization<br>- acceleration of nutrient (C, N, P, etc.) cycles<br>- formation of potassium-rich clay minerals |
| Fertilization:<br>- mineral<br>- organic (manure, crop residues) | Erosion:<br>- fine earth erosion ⇧<br>- whole soil material | Evaporation<br>- soluble salt transportation to the topsoil ⇧ | Mineralization ⇧<br>- humification of organic residues ⇩<br>- organo-mineral interactions ⇩ |
| Pest control<br>- pesticides<br>- herbicides | Leaching:<br>- nutrients leaching ⇧<br>- cations ⇧<br>- $CaCO_3$ | Plowing/deep plowing<br>- soil horizon mixing<br>- homogenization<br>- bioturbation ⇩ | Heavy machinery<br>- compaction of top- and subsoil<br>- aggregate destruction ⇧ |
| Amendments<br>- liming<br>- gypsum<br>- sand**<br>- biochar | Harvesting<br>- nutrients<br>- ballast (Si, Al, Na, …) elements | | Pest control<br>- fungal community ⇩ |

* ⇧ and ⇩ imply the increase or decrease, respectively, in rates of processes that may also occur under natural conditions

** To improve soil texture and permeability

**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, $CaCO_3$ 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, $C_{humic}$:$C_{fulvic}$, Gibs energy, $SiO_2$:($10R_2O_3$) | (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., 2016b) |
| pH, Arylsuphatase 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), and available phosphorus | (Rezapour and Samadi, 2012) |
| **Physical:**<br>Bulk density (1.7 g $cm^{-1}$), Macroaggregates (0%), Soil depth (A+B horizons = 20 cm)<br>**Chemical:**<br>SOM content (50% of natural), C/N (8-10), pH (4 or 10), EC (16 dS $m^{-1}$)*<br>**Biological:**<br>Microbial biomass C, Basal respiration | This study** |

* 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.

** 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.

**Figure legends**

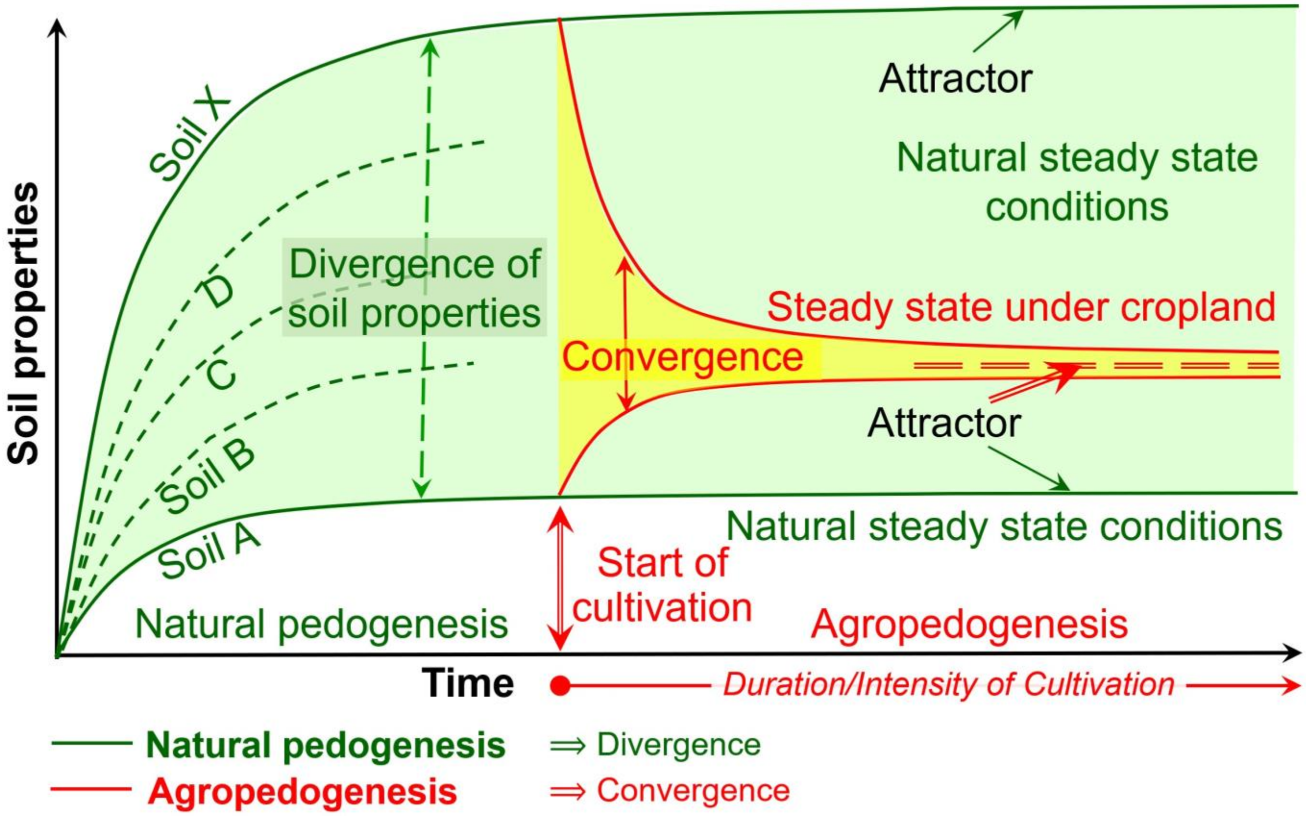


**Figure 1.** Conceptual scheme of soil development, i.e. pedogenesis, under natural conditions (green lines) and agropedogenesis due to long-term agricultural practices (red lines). Green area: the increasing variability of natural soils during pedogenesis. Yellow area: decrease in the variability of soil properties by agricultural use. Double 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 to optimize the production of few crops. Therefore, agropedogenesis leads to *convergence* of soil properties.

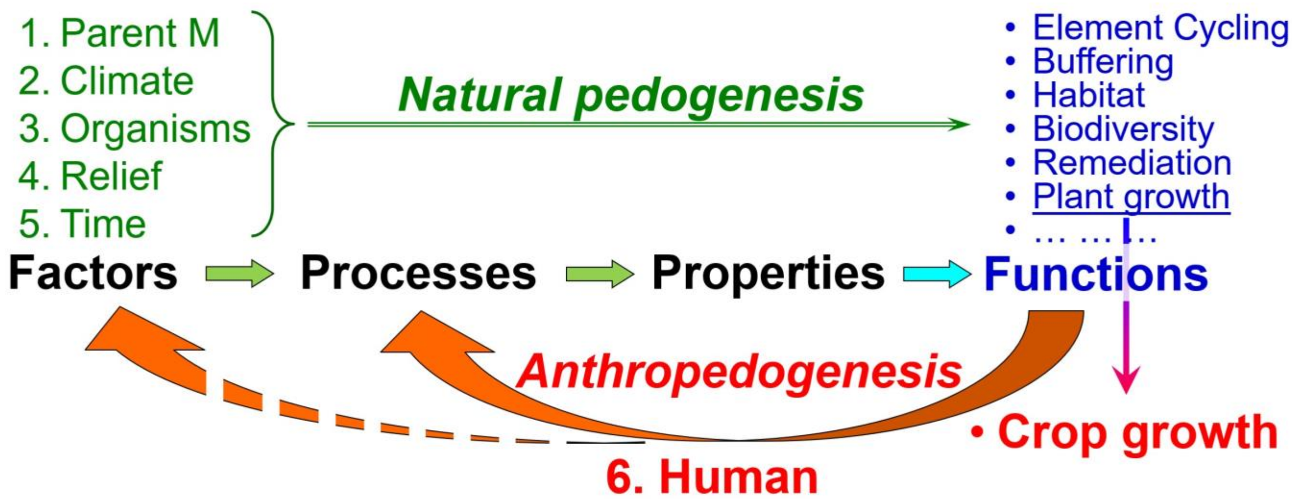


**Figure 2.** Soil genesis based under the five natural factors of soils formation and under the 6$^{th}$ factor: Humans. Natural processes are presented in green, human processes in red.

The concept 'Factors → Properties' was suggested by Dokuchaev (1883) and Zakharov (1927, see Supplementary Materials); and later by Jenny (1941) Our introduced theory 'Factors → Processes → Properties → Functions' considers not only the functions of natural soils, but especially 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 bottom reverse arrows reflect the main specifics of Anthropogenesis: One of the functions becomes a factor of pedogenesis and modifies the processes.

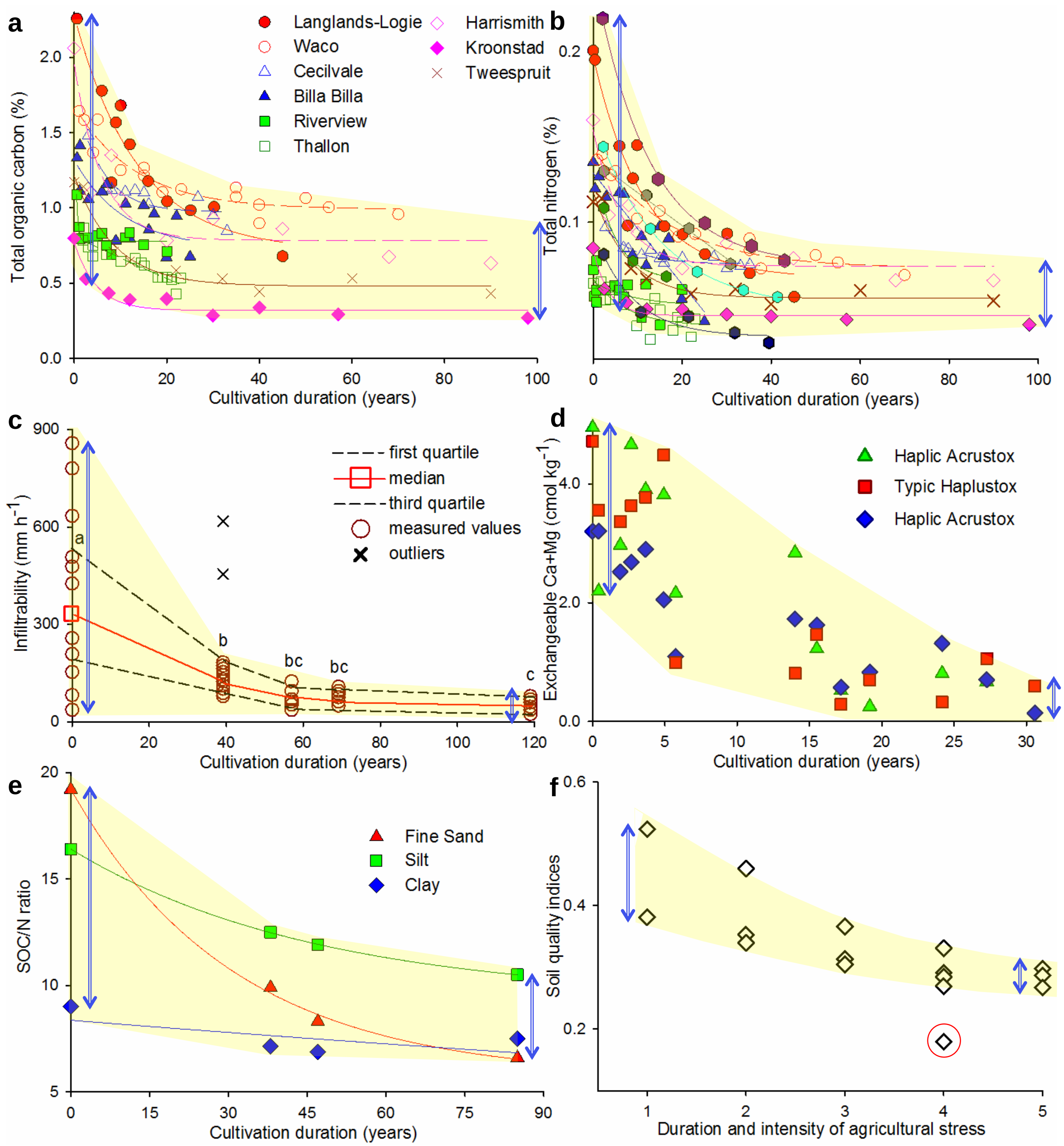


**Figure 3.** Examples for attractors of soil properties by anthropogenic degradation: (a) Soil organic carbon content, (b) Total nitrogen content, (c) Infiltration rates, (d) Exchangeable $Ca^{2+}$ and $Mg^{2+}$ contents, (e) C to N ratio , and (f) overall decrease in soil quality, i.e. degradation over the cultivation period. Yellow shading: area covered by all experimental points, showing a decrease of the area with cultivation duration. Blue double arrows: range of data points in natural soils (left of each Subfigure) and strong decrease of data range due to cultivation.

(a) Narrowing range (blue arrows) of soil organic C over cultivation periods in southern Queensland, Australia (6 sites) (Dalal and Mayer, 1986a) and savanna soils in South Africa (3 sites) (Lobe et al., 2001). The natural soils in different climatic regions have various ranges of properties, e.g. organic C from 0.8-2.3%. During cultivation however, the organic C content strongly narrows to between 0.3-1.0%.

(b) Narrowing range (blue arrows) of total soil N over cultivation periods. Sampling sites similar to (a) plus 5 sites (hexagon symbols) from 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 cultivations (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 $Ca^{2+}$ and $Mg^{2+}$ 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 managements thereafter.

(e) Narrow ranges of C:N ratios in all texture classes (sand, silt, clay) over 85 years of cultivation (Eleftheriadis et al., 2018). Note 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 plowed land, 4- Post-antique idle land, 5- Continually plowed 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).

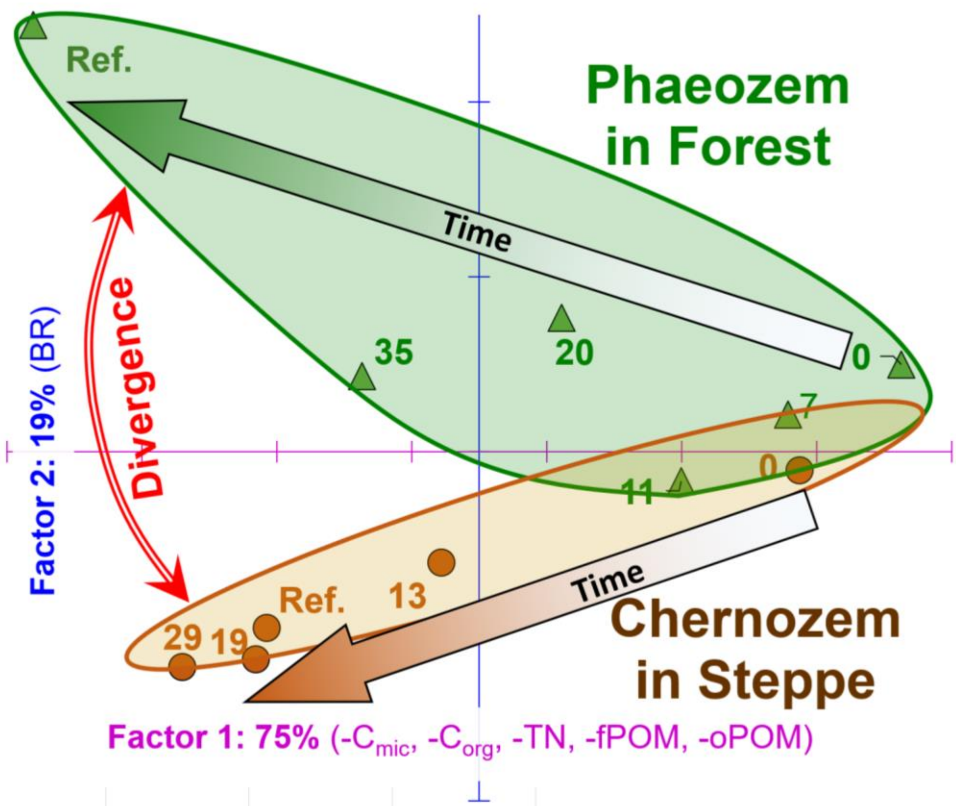


**Figure 4.** Example of the divergence of soil properties of abandoned agriculturally used Chernozem (under steppe) and Phaeozem (under forest) after termination of cultivation (Ovsepyan et al., 2019, modified). The soil properties were analyzed by principal component analysis (PCA). The soils had very 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 (Cmic), soil organic C (Corg), total N (TN), free particulate organic matter (fPOM) and occluded organic matter (oPOM); and on the y axis: basal respiration (BR). (for details see Ovsepyan et al., 2019).

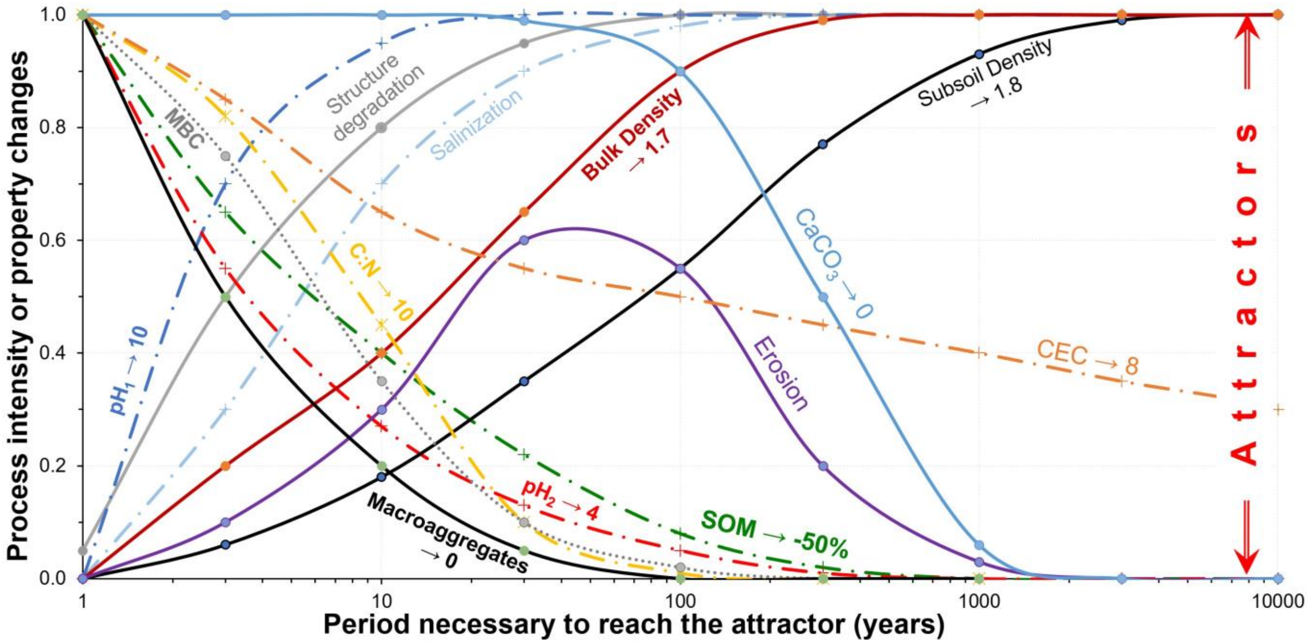


**Figure 5.** Overview on rates of key processes of agropedogenesis and their trajectory in reaching their attractors. Curves start from 0 or 1 (relative values) at the onset of cultivation and go to 1 or 0 to the specific attractors. Each curve is labeled with the specific property. Small arrows after each parameter title show the estimated level of attractor in absolute values. After approach to its attractor, each process slow down and finally stop. The time scale is logarithmic. Curve shape, time to reach attractor, and attractor levels are only estimates and require future adjustment based on experimental data. $pH_1$ is for alkaline, $pH_2$ for acidic soils. Note that not all attractors are defined yet. Properties in bold: master soil properties for agropedogenesis (see Table 3). MBC: microbial biomass carbon, SOM: soil organic matter, CEC: cation exchange capacity. Continuous lines present physical properties or processes, dot-dashed lines correspond to chemical, dotted lines to biological properties.

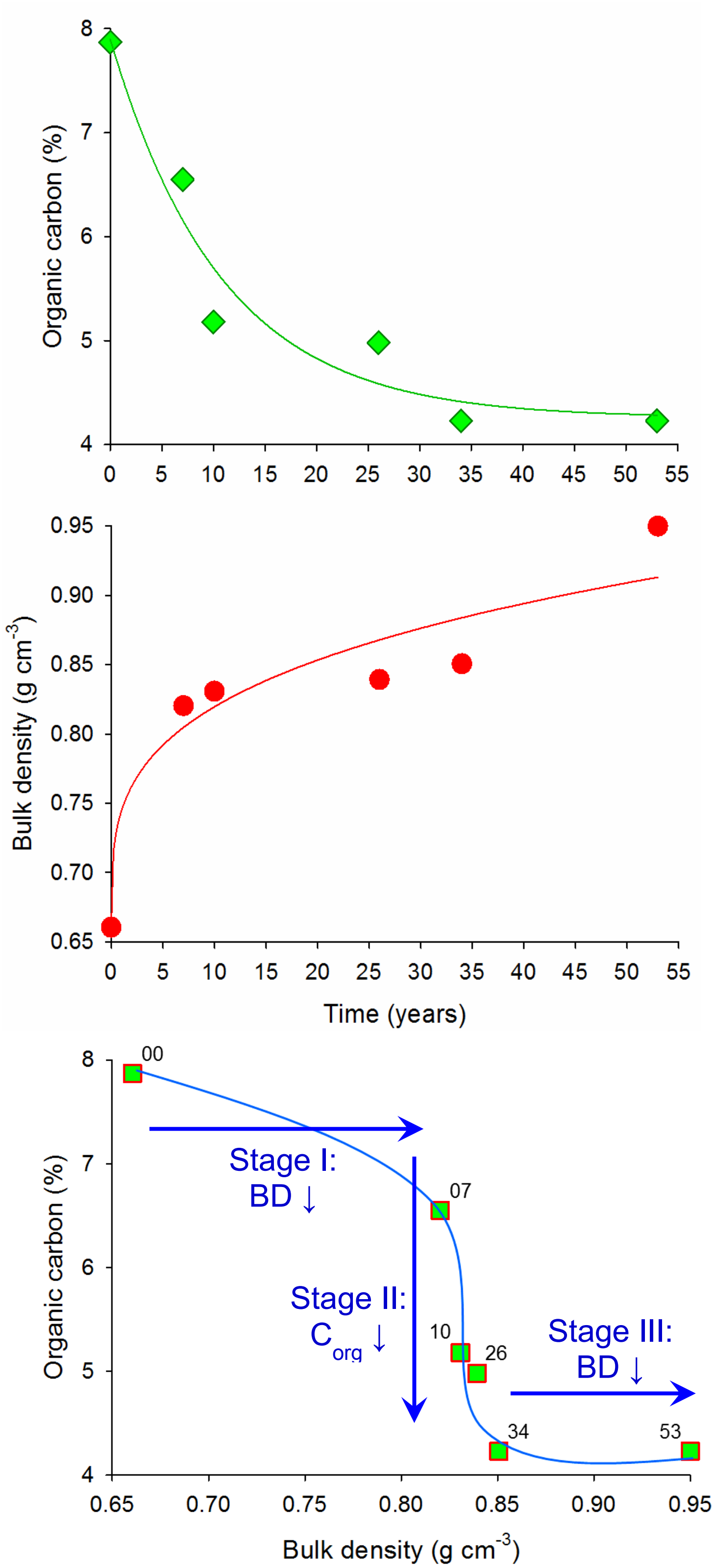


**Figure 6.** Effects of duration of forest conversion to cropland on decreasing soil organic carbon (SOC) (a) and increasing bulk density (b) during 53 years (Southern Highlands of Ethiopia, (Lemenih

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.

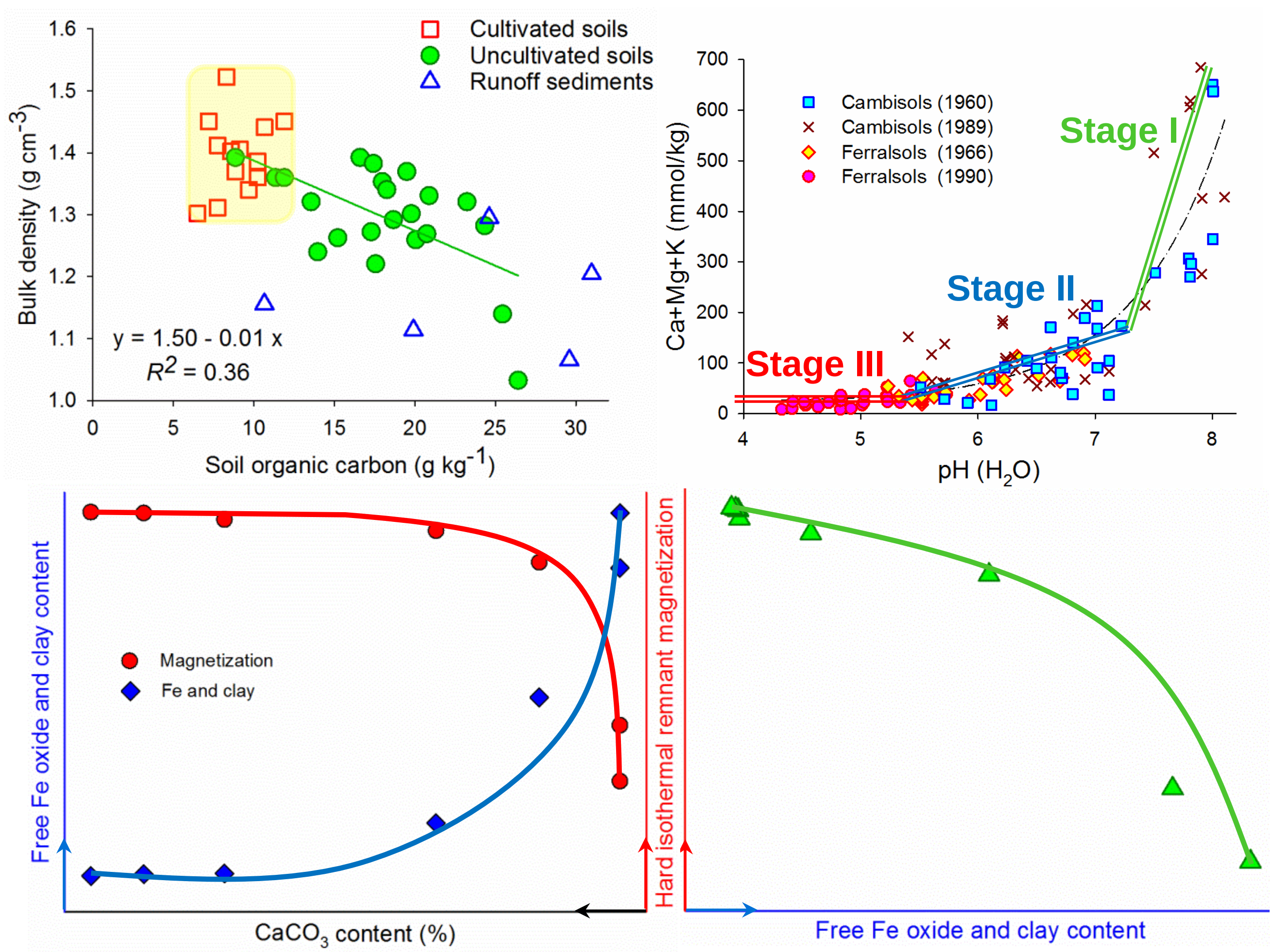


**Figure 7.** Phase diagrams of various properties of agricultural soils. Small arrows at the start or end of the axes show the increase of the corresponding soil property.

(a) Narrow range (yellow-shaded area) of organic carbon and bulk density in ancient agricultural soils cultivated for 1500 y at Mimbres (New Mexico, USA), compared to uncultivated soils and runoff 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 phase 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 ~ 25 mmol+ $kg^{-1}$ (stage III). This value – which corresponds to the amount of exchangeable $Ca^{2+}$ and $Mg^{2+}$ shown on 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 $CaCO_3$ content in soil (adopted from Chen et al., 2011).

(d) The relation between IRMh and free iron oxides vs. clay content.

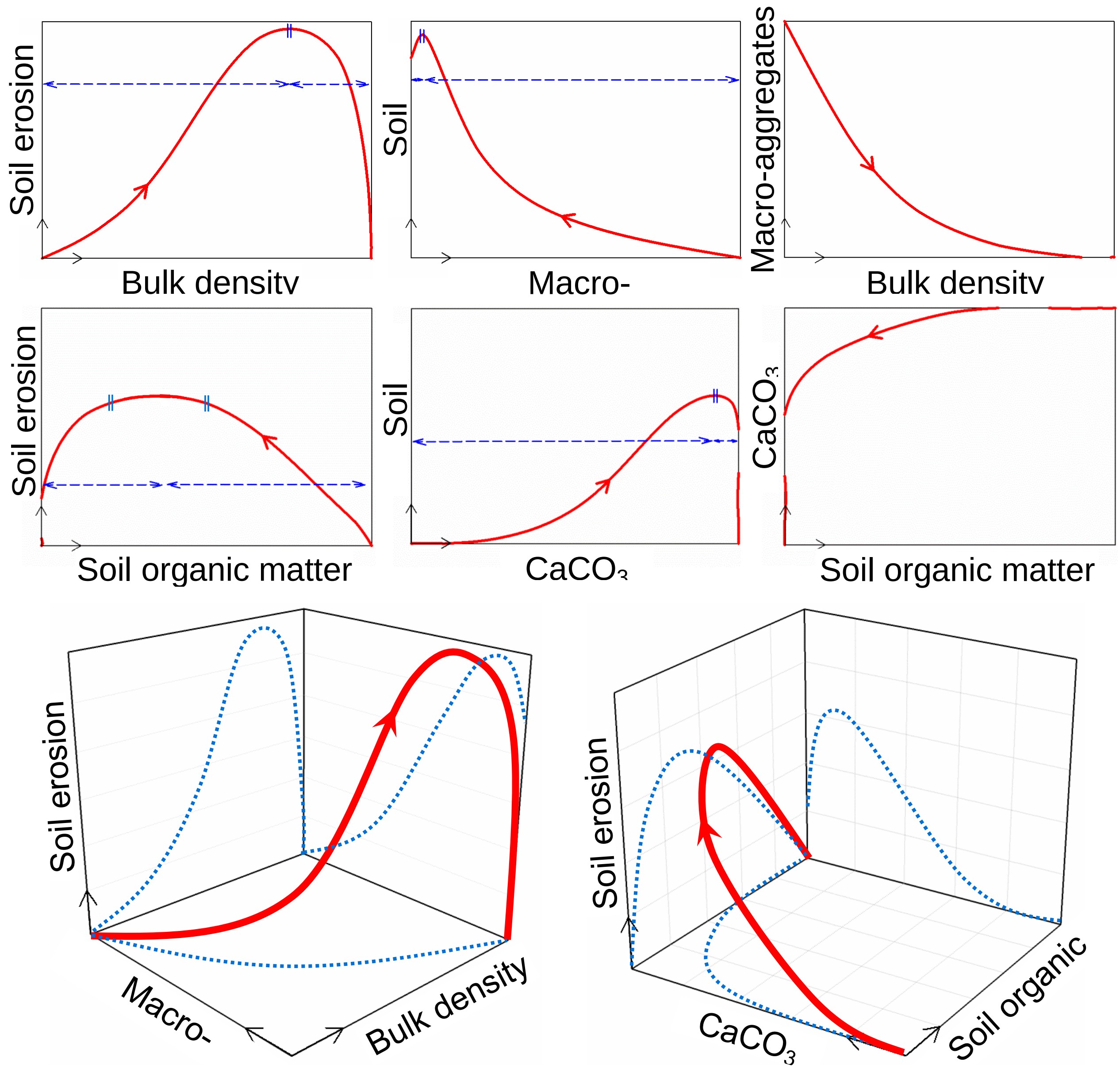


**Figure 8.** Examples of conceptual 2D and 3D phase diagrams linking soil erosion intensity with (top) bulk density and macroaggregates content, (middle) SOM and $CaCO_3$ contents during agropedogenesis. The original curves were taken from Fig. 6. Small red arrows on curved lines show the direction of soil degradation and corresponds to the increasing duration or intensity of agricultural use. Vertical blue double lines show the arbitrary thresholds of soil degradation, horizontal blue dashed arrows the degradation stages. The stages are time laps to reach a threshold for a given soil property. After a threshold the trend may slow down or reverse. Projections of 3D lines (light blue) on last Subfigures (bottom) correspond to the individual lines on the 2D phase diagrams in top and

middle. Similar phase diagrams can be built in multi-dimensional space corresponding to the number of master soil properties (Table 3).

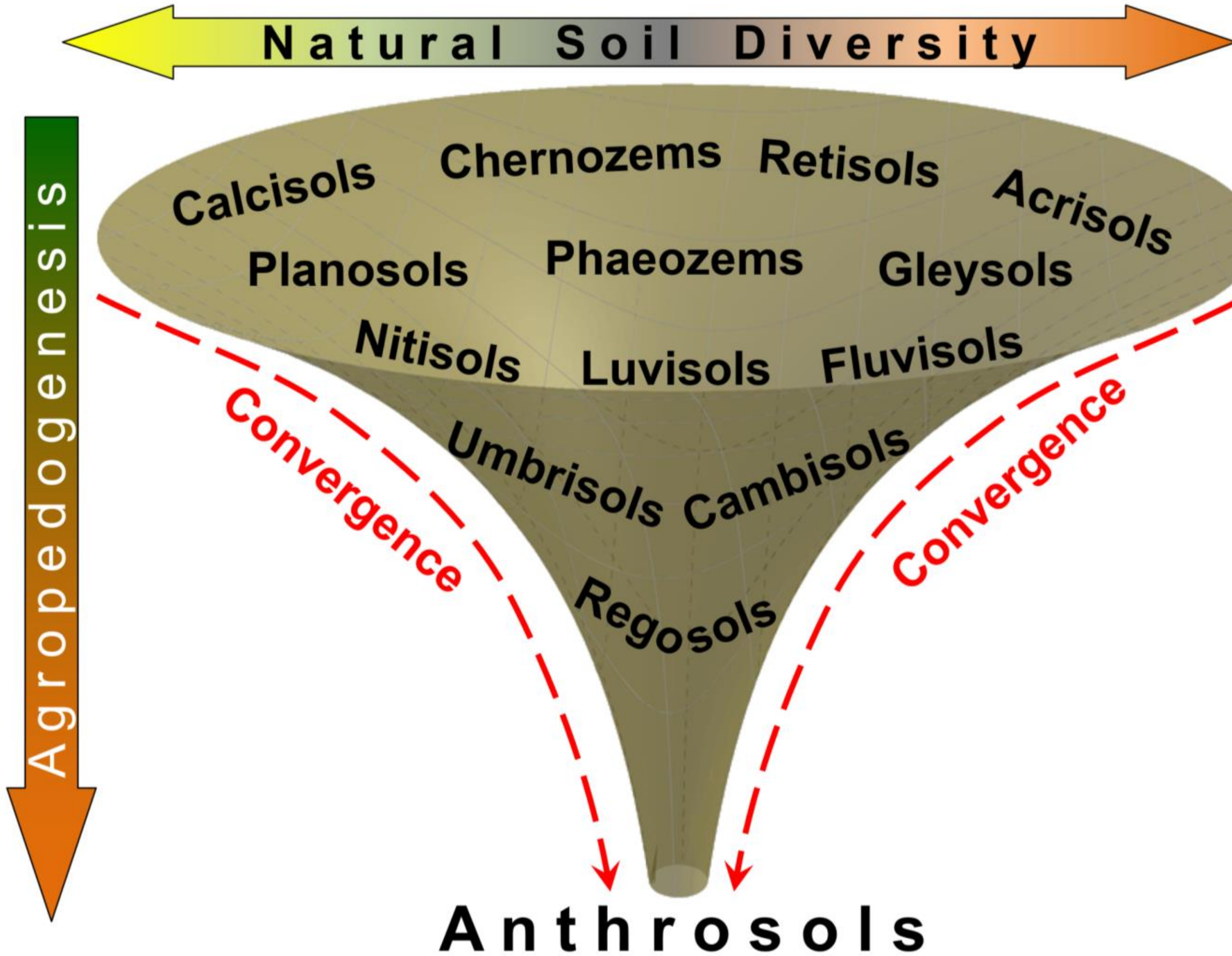


**Figure 9.** Conceptual schema of convergence of soil properties by agropedogenesis. The very broad range of natural soils and their properties will be tailored for crop production by agricultural use, resulting in Anthrosols with a very narrow range of properties. Note that the soils within the funnel are mentioned exemplarily and not all 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 Supplementary Materials, Supplementary Fig. 3).

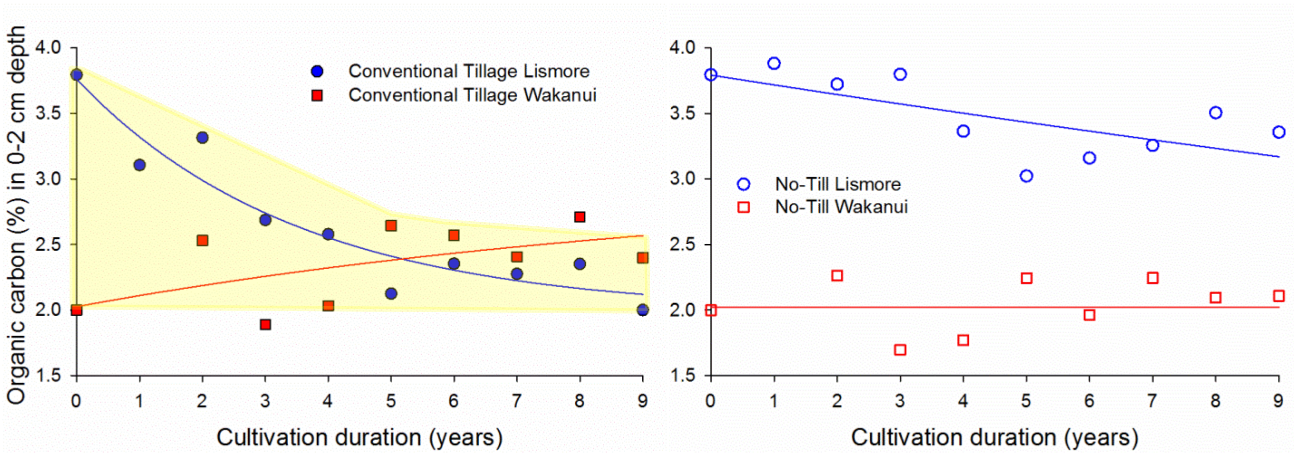


**Figure 10.** Nine years of continuous cropping and conventional tillage (left) led to similar soil organic carbon (SOC) contents, in contrast to no-till soils (right) (Francis and Knight, 1993). The Lismore no-till soil either needs longer cultivation duration to reach the C content characterizing 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. Hence, changing the conventional tillage to no-till had no effect on SOC content. Lismore soil: Umbric Dystochrept, 5% stones, rapid draining, 5 y mixed rye grass/white clover pasture. Wakanui soil: Udic Ustochrept, slow draining, 10 y rotation of wheat, barley, peas.