Response to the Reviewers' comments

Anonymous Referee #1

This review paper addresses humankind impacts on soil development. The authors highlight the importance of humankind impact as new soil formation factor and distinguish it from natural soil formation factor due to the impact that it has on the soil development. As the authors pointed out in their text the importance of humankind impacts on soil formation has been acknowledged by some researchers but what makes the view of authors special here is the way they take into account its contribution in soil development. They argue that the natural soil processes result in soils with diverse functions and properties, while the humankind interferences in the ecosystem result in soils with uniform and similar functions and properties. In this sense, the impact of humankind on soil development is introduced as a convergence factor and neutral soil formation factors as a divergence factor.

The authors' opinion here is mainly supported by some examples at which different land uses (mainly forest) were converted to agricultural use. I found the view of authors interesting and considered it as an emerging topic in the field of fundamental soil science. In general, I do not have any fundamental comments on the concept presented here and believe that this review should be published as a review paper in the journal of Biogeosciences Discussion.

We are very thankful to the Reviewer for his very positive assessment and suggested improvements.
Please see our improvements and answers below.

Given that all the authors are very experienced scientists with a substantial track record, this is a pity, and I cannot refrain from emphasizing that the text and figures need some careful revisions. Some examples are listed below:

Fig.1 is an interesting figure showing the main concept presented in this review. However, it was hard for me to follow its context and would suggest some modifications to this figure as follows: 2) place the legend on the right side of the figure. In its current location is confusing and the readers may relate it to the time, 2) Does the red arrow on x-axis show start of cultivation decades? if yes remove its label out of the figure that one can read it. otherwise, it looks like two different labelings,3) it is not clear what does it show the label " duration/intensity of cultivation. Do you mean a time period between the start of cultivation till now? If yes, show it with an arrows bellow the x-axis, 4) move the label of x-axis more to the bottom and make some space with indicated time.

Many thanks – we can understand well that these points are not clear.
We improved the Fig 1 as suggested by the Reviewer and hope that it is easier to follow now.
We added legend, removed Millenia and Decades, added additional x axis for agropedogenesis.

In fig. 2, what does it mean ‘Soil genesis based on the development of concepts’ in the caption of figure? I would recommend the authors to rearrange this figure and improve its readability. In the current version, it is hard to follow its context and massage. Found a better away of relating this information together, for instance, the factors and parental materials, climate, etc. Here and elsewhere in the figures, I found it annoying for readers to follow a diagram with varying font sizes and styles.

We completely rewrote the caption.
We have unified better the font sizes within each Fig. We still left some various fonts to show the importance of processes.

In Fig. 4: It is hard to understand the message of this figure. What does it mean factors 2: 38% and 1: 48% in the label of x-axis and y-axis. Do you mean a relative increase of 38% and 48%? Where does the 1 start?

This is the results of a principal component analysis on various parameters measured in the abandoned agricultural soils with increasing abandonment periods. We improved the Figure and also add more details to the legend for better understanding. 75% of variation in soil properties is explained by factor 1 and 19% by factor 2.
If the Reviewer mean that this is superfluous Fig., we will move it to Supplementary Materials.

Fig. 5: rephrase the caption, it is a confusing sentence and hard to read. In Fig. 5a and 5b, explain in the legend what do show the solid lines. The legend of Fig. 5c and 5d are confusing. Use a separate legend for every four cases.

The fig. caption has been modified.

Fig. 6: This is an interesting figure. State that this is a hypothetical trend. How do the authors argue on the proposed time? It looked to me that the authors aimed to show here the relative responses of each process with time and the selection of time is not based on any experimental evidence. If that is true I suggest using a normalized time between 0 and 1 to avoid giving a weak impression.

The fig. is actually based on the real values stated for each soil property in various studies (including that presented in the Fig. 3 and 4). Nonetheless, the values written on each curve are our suggestion for the attractor of each soil property over long-term cultivation. See also line 380-385.

Fig. 9: how did the authors generate these figures? Are they hypothetical figures? If yes mention it in the caption. What does it mean stage in these figures? Stage of what?

The figures are conceptual phase diagrams as it is mentioned in the caption. These phase diagrams were made based on the curves in the Fig 6 (now 5), which are experimentally based. The stages show the changing trend in a given soil property over the degradation processes.

The stages are time laps to reach a threshold for a given soil property when after that the trend may slow down or become reversed. See line 291-292 for definition of stages of degradation. The fig. caption has been modified.

Some minor typos:
Line 220: Replace “decreases “ with “decrease “

Decreases in Line 234 has revised

Line 33: replace ‘fulfils’ with ‘fulfills’

It is revised in Line 35

Line 378: replace because with become

The sentence has been modified

Line 279: replace “independent of” with “independency of”

“Independent of” looks grammatically correct here.

Line 149: Do the author mean the function rather than production?

No, the (crop) production is one of the soil functions. So, when only one function can be increased at a time the other functions (other than production) will be decreased.

Line 138: Replace “ develops” with “ develop.”

The sentence has been modified

…………….

Anonymous Referee #2

The authors 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 theory of agropedogenesis is a very important issue in pedology and there is a clear gap in knowledge related to this issue and the outcomes of this research certainly help to better understand the dynamics of soil development under agricultural practices.

We are very thankful for this positive evaluation and suggested improvements.
Please see our improvements and answers below.

Although the contents of the manuscript is fairly good, it would benefit from better editing (e.g. grammar and clarity), which would improve its clarity.

We sent the ms once again for the improvement of the English language.

In addition, some necessary improvements are suggested in the following:

1) More comprehensive literature review on soils [e.g. semi-arid tropical soils] showing no sign of soil degradation by growing agricultural crops in soils.

This point is based on the comments given by Dr. Pal about the necessity to exclude semi-arid tropical soils from the concept of agropedogenesis. The point that Dr. Pal emphasized to be "no-sign-of-degradation" is solely based on stability of SOC content over 25 years of cultivation in semi-arid tropical soils of India. This is however, because of yearly addition of large amount of organic fertilizers which keeps the SOC content at a high level along with the presence of alkaline soils which prohibit soil acidification. This, in our opinion, is temporary condition (i.e. pedogenic inertia) and following decalcification of topsoil (when attractor of $CaCO_3$ is achieved) the mentioned soils will also face acidification and so, degradation and crop reduction. We already addressed in the text that such conditions may also take place (see lines 210-211) due to soil intrinsic master properties which are from their threshold values to cause soil degradation.

2) It is also important to discuss more thoroughly, why these soil properties were selected [Master soil properties]. In particular, a reader would like to know whether these soil properties are intrinsically more important than the others or simply more important in this study due to some identified characteristics and assumptions.

The main characteristic of a soil property to be a master property in agropedogenesis concept is its sensitivity to agricultural use. Further, changes in the values of the so-called master properties should determine the state many other properties over cultivation period. See section 2.4 as we defined the master properties and their particular characteristics. Also the most other studies suggested these properties (see Table 3).
We would like to discuss these soil properties and the reasons in the next paper. This paper is already too long for individual description of each of the nine properties.

3) It is necessary to explain clearly the figures in the main body of the manuscript.

We agree. The Reviewer #1 mentioned the same. In the improved version we presented more explanations and details to the figure legend.

Some other comments are made along with the text:
Keywords: I think five keywords are enough.

We developed a theory which is not only connected to the effects of human on soil conditions but also to the effects of human in general on planet Earth and so, to the Anthropocene. This

includes many aspects which we tried to address by the key-words for a better indexing by the searching programs.
We deleted 4 Keywords (but added 2).

Line 4-5: This first sentence of the abstract should be removed.

This sentence actually shows the relevance and significance of studying the effects of human on agricultural soils. It shows that human through agricultural practices may affect a huge land surface area. Deleting this sentence will raise the question of how significant or relevant is this study.
If the Reviewer insists on it, we will delete this sentence.

Line48-49: Please clarify this sentence "Since the suitable land resources for agriculture are limited and increasingly located in ecologically marginal conditions".

The suitable land areas for agricultural practices are limited. Therefore, many studies are focusing on protecting strategies to save such areas against degradation causing decreasing food production. Furthermore, if intensification in crop production on the available land is not considered then, we have to cultivate the ecologically susceptible areas for example shallow soils on steep slopes. We simplified the sentence.

Line 50: add cit.

Lal et al., 2005 has been added.

Line 73: run-off irrigation and terracing

"and" has been added.

Line 80: add cit.

FAO 2018 has been added.

Line 87: "The human factor can even change soil types as defined by classification systems (Supplementary Fig. 1)".

The sentence is correct similar to what the reviewer has written.

Figure 1 indicates the convergence and divergence of soil properties!

Under natural soil genesis, yes (the green lines) but convergence under agropedogenesis (red lines). The fig. is however, improved for better clarifications.

Line104: add cit.

See Dudal, 2004 (line 101).

Table 2: justify Table 2

We wanted to bold the main soil formation processes under agricultural practices and their consequences on soil properties. Could you please let us know what you mean with justifying the table?

Line 122: climate, organisms, relief and time

It has been revised accordingly.

Line 139: climate, organisms, and relief

It has been revised accordingly.

Line 140: “...over time. Thus, morphological soil properties...”. This sentence should be rewritten.

The sentence is re-written as: Therefore, visible morphological soil properties in the field and measurable parameters in the lab were very well described leading to development of various (semi)genetic soil classifications

Line 143: Figure 2.

Corrected

Line 153:add cit.

This is authors definition of soil degradation and its stages.

Line 180: climate, organisms, and relief

It has been revised accordingly.

Line 201: How is possible to infer the decreasing in the spatial variability of soil properties in figure 5.

The sentence has been corrected.

Line 847: “(c) and(d) total soil carbon”!

The sentence has been corrected.

Lines 273-lines 299: the definition of phase diagrams would be necessary. Not sure that every Biogeosciences reader is familiar with them.

We added the definition of the phase diagrams (see line 277).

Other comments and minor corrections by Peter Kühn

It was a pleasure to read the manuscript. I have some minor remarks, which may improve the strength of the discussion, if considered. Best wishes, Peter Kühn

We are very thankful to Prof. Kühn for his positive assessment and suggested improvements.

General Remarks Chapters 1.2 and 2.1 In this context the scorpan model by McBratney et al. (2003; “On digital soil mapping”) should be discussed as well, which includes more than five soil forming factors and particularly their functions.

The reference McBratney et al. (2003) has been added to the text.

188-190: If the “convergence of soil properties” is not true in all cases, I recommend rephrasing the statement in line 188.

The sentence has been deleted.

Chapter 2.7 Additionally different topographic positions should be discussed: upslope, Mid-slope, toe-slope and even positions. Do not soil properties diverge or converge despite of human impact just related to the topographic position of the soil? E.g. imagine calcareous substrate with a decalcified soil, at upslope positions and human-induced soil erosion; after some time the soil will have many properties of the substrate, particularly regarding carbonate content, pH, EC, and the content of some elements as e.g. Ca and Mg. These are also master properties of agropedogenesis as you defined in chapter 2.4. - And e.g. in toe-slope positions you have often an additional material input from upslope positions, which influences also some master properties and might rule out convergent tendencies. Of course this is different under humid and arid climate conditions.

We assumed that agricultural soils are generally located on flat and leveled grounds or on gentle slopes and there would be terracing on steeper slopes. On the other hand, we hypothesized that there will be an equilibrium between the erosion rate and soil genesis rate over long time farming (see supplementary fig. 1).

Cover page

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

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Keywords: Anthropogenic soil change, ~~Soil formation and degradation,~~ Soil forming factors, ~~Pedogenesis, Agropedogenesis,~~ Land-use, Intensive agriculture, ~~Soil erosion,~~ Anthropocene, Human impact, Ecosystem engineer

Agropedogenesis: Humankind as the 6th soil-forming factor and attractors of ~~agrogenic~~ 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, ~~the~~ we have an advanced mechanistic~~al~~ understanding of individual degradation processes of soils under agricultural use ~~concepts or theories of agropedogenesis have already been advanced,;~~ ~~the~~ general concepts of agropedogenesis are absent.~~,~~ We therefore,~~and webut~~ urgently ~~still~~ need a~~n~~ ~~further consideration to~~ unifying theory ~~better understand the dynamics~~ of soil development under agricultural practices, of~~–~~ ~~the~~ *agropedogenesis*. 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 ~~getting~~becoming the main soil--forming factor. The focus on~~f~~ only one function and disregard of other functions inevitably lead ~~indispensable~~ 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 ~~mainly~~ largely opposite to that of natural soil development and is thus ~~mainly~~ 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~~, and~~ 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 ~~each~~ 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. ~~Concluding~~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~~on~~ few desired functions.

Keywords: Anthropogenic soil change, ~~Soil formation and degradation,~~ Soil-~~–~~forming factors, ~~Pedogenesis, Agropedogenesis,~~ Land-~~–~~use, Intensive agriculture, ~~Soil erosion,~~ Anthropocene, Human impact, Ecosystem engineer

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 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~~ however~~, commonly decrease due to human activities, in particular through agricultural practices because of accelerated~~ing~~ 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 ~~which~~ that~~are~~ lead~~ing~~ to the formation of fertile soils such as *T~~t~~erra P~~p~~reta* in the Amazonian Basin

(Glaser et al., 2001), *P~~p~~laggen* in ~~North~~ northern Europe (Pape, 1970) as well as *H~~h~~ortisols* (Burghardt et al., 2018), soil degradation is ~~in most cases~~ the most common outcome of ~~long-term~~ agricultural practices (DeLong et al., 2015; Homburg and Sandor, 2011). Soil degradation begins immediately after conversion of natural soil ~~coverage and land preparation for cultivation~~ and involves the degradation in all physical, chemical and biological properties (Table 1). The result is a decline in ecosystem functions.

Soil~~This~~ degradation gains importance ~~when~~ ~~considering~~~~by~~with the rapid increase in human populations (Carozza et al., 2007) and technological progress. Increasing food demand ~~necessitates~~ requires either ~~ever~~ larger areas for croplands or/and intensification of crop production per area of already cultivated land. Because~~Since~~ the ~~suitable~~ land resources suitable for agriculture are limited ~~and increasingly located in ecologically marginal conditions~~, ~~any~~ most increases in food production ~~will~~ depend~~s~~ on the second option: intensification (Lal, 2005). ~~This will intensify the imbalance between input to and output from the soil, resulting in faster and stronger soil degradation.~~ 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. ~~Importantly, h~~Huge areas are located in very cold regions that are continuously covered by ice (1500 million ha), ~~located~~ 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, ~~the~~ a theory of soil formation as affected by humankind – anthropedogenesis and its subcategory agropedogenesis – is ~~still far from proper attention~~absent. This paper therefore presents for the first time a~~n~~ unifying theory of *anthropedogenesis* – soil development under the main factor 'humankind' – the 6th 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 ~~with~~ 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 ~~from~~ with Mesopotamia (18th to 6th centuries BC) (Diamond, 2002; Weiss et al., 1993). Notwithstanding all the negative impacts ~~of~~ humans have on soils~~ and on cycles of energy and matter~~, 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 ~~soil~~ 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, ~~corn,~~ and rice – supply 2/3 of this amount (FAO, 2018). These crops (except rice) have similar water and nutrient requirements ~~(except rice) compared~~ in contrast to the plants growing under natural conditions. Consequently, agricultural land-use has always striven to narrow soil properties~~y space~~ to uniform environmental conditions.

~~The h~~Humans~~ factor~~ 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 ~~only~~ 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 ~~very~~ 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), ~~as well as~~ 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 ~~(Bryant and Galbraith, 2003)~~.

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 ~~will~~ are not treated~~be described~~ ~~in this paper~~here, because they are not ~~directly~~ connected with agriculture.

Agropedogenesis should be clearly separated from the natural pedogenesis because of: (1) strong dominance of the factor ‘humans’ over all other five factors of soil formation, (2) new processes and mechanisms that are ~~not pre~~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 ~~processes~~. Natural soil formation involves the development of soils from parent materials under the effects of climate, organisms, relief, ~~organisms~~ and time (Dokuchaev, 1883; Jenny, 1941; Zakharov, 1927; Supplementary Materials). Here, soil formation will reach the quasi-steady state ~~conditions~~ typical for the combination of the five soil-forming factors (Fig. 1). Agropedogenesis, in most cases, is a process involving the loss of ~~losing~~ 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 ~~on~~ 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 ~~in~~ for natural pedogenesis, which involves millennia (Tugel et al., 2005). The range of soil properties at this quasi-steady state ~~condition~~ 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 →~~and~~ Functions

The original concept of “Soil Factors → Soil Properties” was initially suggested by (Dokuchaev (~~,~~ 1883) and ~~;~~ Zakharov (1927~~Jenny, 1941~~) and was modified by “P~~p~~rocesses”, which are dependent ~~s~~ on the factors of soil formation and develop~~s~~ the properties (Gerasimov, 1984; McBratney et al., 2003). This triad: Factors → Processes → Properties enables understanding ~~the~~ soil development ~~of soils~~ from the initial parent materials by the effects of climate, organisms, and relief, ~~vegetation and organisms~~ over time. ~~Thus,~~This very well describes the visible morphological soil properties ~~that are visible~~ in the field and measurable parameters in the lab~~, are very well described and yielded~~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. ~~3~~2). ~~We do not~~Rather than describing~~e~~ 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., ~~but~~ we refer to excellent reviews focused on soil functions (Lal, 2008; Nannipieri et al., 2003).

One function – plant growth~~roduction~~ – is~~, however,~~ 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 ~~crop~~ productivity and crop yields. As it is not possible to simultaneously maximize all functions, the functions other than ‘~~production’~~ crop growth’ decrease or even disappear. Accordingly, *agropedogenesis is driven by processes pursuing the maximization of only one function – crop ~~production~~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 *~~the~~ one function~~s~~ becomes a factor* (Fig. 2). This is because humans tailor the processes of soil development for the main function of agricultural soils – crop production~~vity~~. Based on the example of agropedogenesis, we conclude that all types of anthropedogenesis are directed at the functions ~~which~~ that humans desire from the soil; hence, the *one function~~s~~ is~~are getting~~becomes the factor~~s~~ 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) ~~their range~~ 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 ~~tends to~~ develops from a wide variety of initial or intermediate states of pedogenesis.

An attractor of agricultural~~ogenic~~ soil degradation is a minimal or maximal value, ~~of a soil property~~ toward which the property tends to develop by long-term intensive agricultural ~~practices~~ 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 ~~and organisms~~ (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~~for~~ 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, ~~A~~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 ~~having~~ a start~~ed~~ 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~~albeit with~~ a major~~much stronger~~ intensification of chemical impacts (fertilization, pesticides) and heavy machinery ~~in the last decades~~ (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 ~~J.~~ Mayer, 1986; Haas et al., 1957; Nyberg et al., 2012) (Figs~~.~~ 3, ~~and~~ 4, and the Supplementary fig. 2). ~~Continuous agricultural practices also decrease the temporal and spatial variability of all properties in the topsoil – in the Ap horizon (Jones and Dalal, 2017; Scott et al., 1994) (Fig. 5).~~

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 ~~lead to soil~~ degrade~~ation~~ 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 ~~A selected f~~Few of them~~se properties~~ – 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 ~~which~~ 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~~-~~, ~~do not reflectare unimportant for~~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~~s~~ 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)~~, modified)~~. 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~~A~~ 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 ~~8~~ 9 to be sufficient to describe the degradation state of most other parameters during agropedogenesis~~ and to define their multi-dimensional attractor space (see below). Their definition enables assessing the other properties~~: 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 ~~are~~ 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)**.**

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 ~~different~~ 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 ~~is~~ formed in the previous phase.

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[1] ~~Please n~~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.

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 ~~8~~ 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~~ development of master soil properties during long-term ~~intensive~~ 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 ~~is in contrast to~~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). ~~While~~ 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 ~~relatively~~ high 400 years after of land abandonment due to the remaining effect of applied organic amendments on ~~soil~~ 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 ~~have~~ 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 ~~in~~ at local minima. Hence, the global minimum will ~~be~~ 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~~e~~ results in~~s~~ 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~~vity~~ – they optimize all soil processes and properties toward a higher yield of a few agricultural crops. ~~And b~~Because most crops have similar requirements, the range of measured values for any~~ given~~ 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 ~~the same~~similar for ~~different ~~various soils. (2) Analyzing the properties of soils from various geo-climatological conditions and managements in relation to ~~the respective time since the beginning of ~~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~~ space~~.

By analyzing the soil development ~~of soils ~~and the properties' dynamics ~~of soil properties ~~under agricultural use, we develop for the first time the basic ~~concept ~~theory of agropedogenesis. This theory ~~concept ~~is based on (1) the modified classical concept of F~~f~~actors – P~~p~~rocesses – P~~p~~roperties – F~~f~~unctions and back to the P~~p~~rocesses, (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 ~~of ~~the ~~eight ~~nine master ~~soil ~~properties responsible for the trajectory of any soil during agropedogenesis within multi-dimensional attractor space.

3.2. Outlook

We developed a ~~the suggested ~~new unifying ~~concept ~~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 ~~very ~~broad range of climatic conditions. The presented examples of soil degradation trajectories and of attractors of soil properties ~~are~~ clearly ~~insufficient~~ do not to reflect the full range of situations. This theory ~~concept~~ 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 ~~perhaps~~ 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~~broader~~ database~~range of data~~. The challenge here is that the average values are ~~probably~~ not ~~optimally~~ 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 border of~~ the lower~~upper~~ (or upper~~lower~~ – depending on the property) 95% confidence interval or overlap testing should be used instead of means to set the attractor value.

The ~~detection~~ 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~~their determination~~ can ~~be used to~~help simplify the measures to combat degradation and ~~perhaps even~~ 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~~ in its full complexity are available (Finke, 2012; Finke and Hutson, 2008; Keyvanshokouhi et al., 2016) and the models addressing soil degradation ~~agropedogenesis~~ describe more or less individual or a selected few processes, but not ~~the~~overall agropedogenesis ~~in its complexityof soil degradation~~. 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. ~~Thus~~This~~,~~ calls for complex theory-based models of agropedogenesis~~ are required~~.

Author contribution

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

	Acidification: ⇩ pH ⇧ exchangeable aluminum ⇩ CEC	- N-fertilization - cation removal by harvest - ⇩ buffering capacity due to cation leaching and decalcification - acidification and H$^+$ domination on exchange sites - 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 ⇩ (micro)organism density and abundance	- weeding - pesticide application - monocultures or narrow crop rotations - mineral fertilization - ⇩ SOM content and litter input - ⇩ root amounts and rhizosphere volume - plowing and grubbing - ⇩ total SOM - pesticide application	(Lal, 2009; Zhang et al., 2017) (Breland and Eltun, 1999; Fageria, 2012)
	⇩ microbial activities - respiration - enzyme activities	- recalcitrance of remaining SOM - ⇩ microbial abundance ~~activity~~ - ⇩ litter & rhizodeposition input - mineral fertilization - ⇩ organism activity, diversity and abundance - shift in microbial community structure - ⇩ 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 - water - salts ⇧* - sediments	Mineralization ⇧ - organic matter - plant residues - organic fertilizers - ~~nitrogen~~ N (to N_2O and N_2) ⇧	Irrigation - dissolved organic matter ⇩ - soluble salts ⇧	Fertilization - acceleration of nutrient (C, N, P, etc.) cycles - formation of potassium-rich clay minerals
Fertilization: - mineral - organic (manure, crop residues)	Erosion: - fine earth erosion ⇧ - whole soil material	Evaporation - soluble salt transportation to the topsoil ⇧	Mineralization ⇧ - humification of organic residues ⇩ - organo-mineral interactions ⇩
Pest control - pesticides - herbicides	Leaching: - nutrients leaching ⇧ - cations ⇧ - $CaCO_3$	Plowing/deep plowing - soil horizon mixing - homogenization - bioturbation ⇩	Heavy machinery - compaction of top- and subsoil - aggregate destruction ⇧
Amendments - liming - gypsum - sand** - biochar	Harvesting - nutrients - ballast (Si, Al, Na, …) elements		Pest control - 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: Bulk density (1.7 g cm^{-1}), Macroaggregates (0%), Soil depth (A+B horizons = 20 cm) **Chemical:** SOM content (50% of natural), C/N (8-10), pH (4 or 10), EC (16 dS m^{-1})* **Biological:** 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.

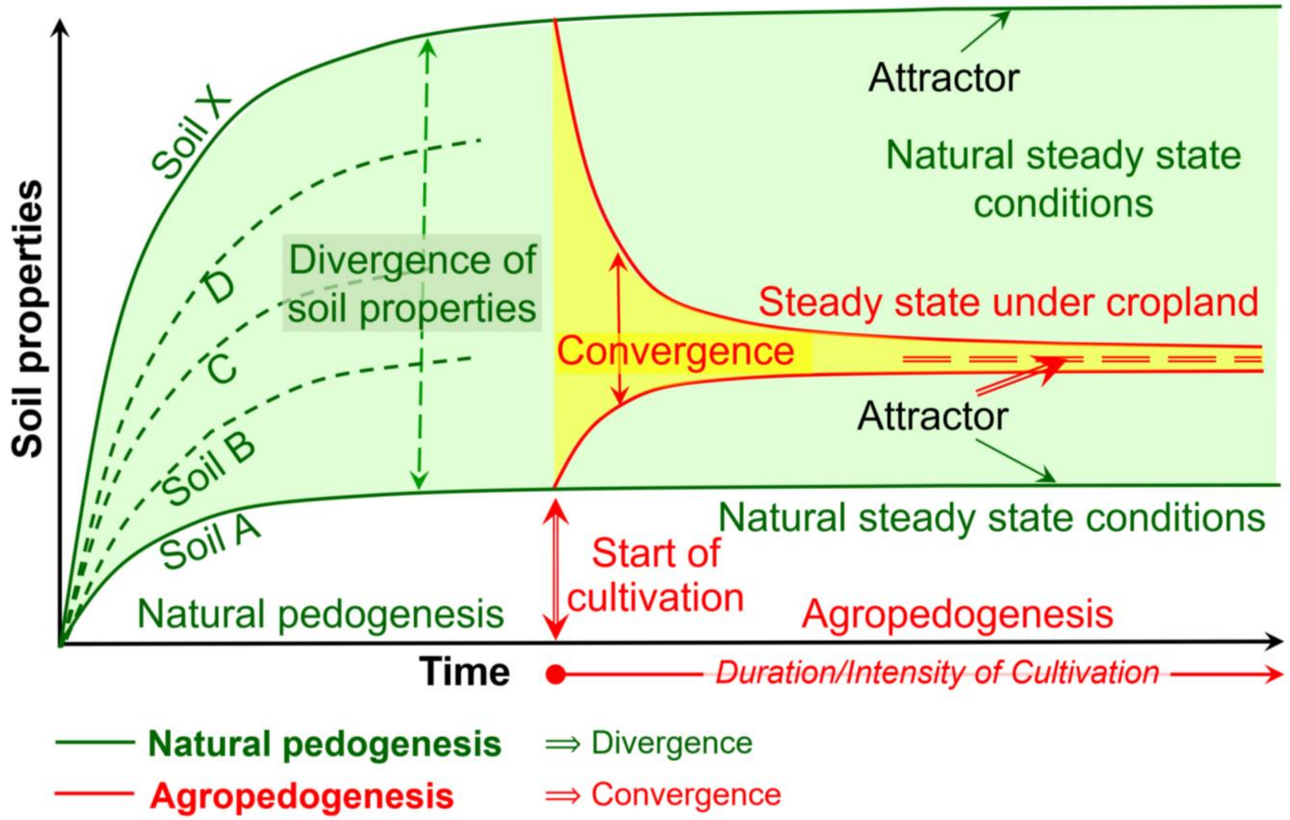


Fig. 1: Conceptual scheme of soil development, i.e. pedogenesis, under natural conditions (green lines) and agropedogenesis due to long-term agricultural practices (red lines). ~~The green~~Green area: ~~corresponds to~~ the increasing variability of natural soils during pedogenesis. ~~The y~~Yellow area: ~~reflects the~~ decrease ~~of~~in the variability of soil properties by agricultural use. ~~The d~~Double vertical arrow: ~~shows~~ the start of cultivation. ~~The x~~X axis: ~~reflect~~ 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 t~~f~~o~~r~~ optimize~~ation of crop~~ the production of few crops. Therefore, agropedogenesis leads to *convergence* of soil properties.

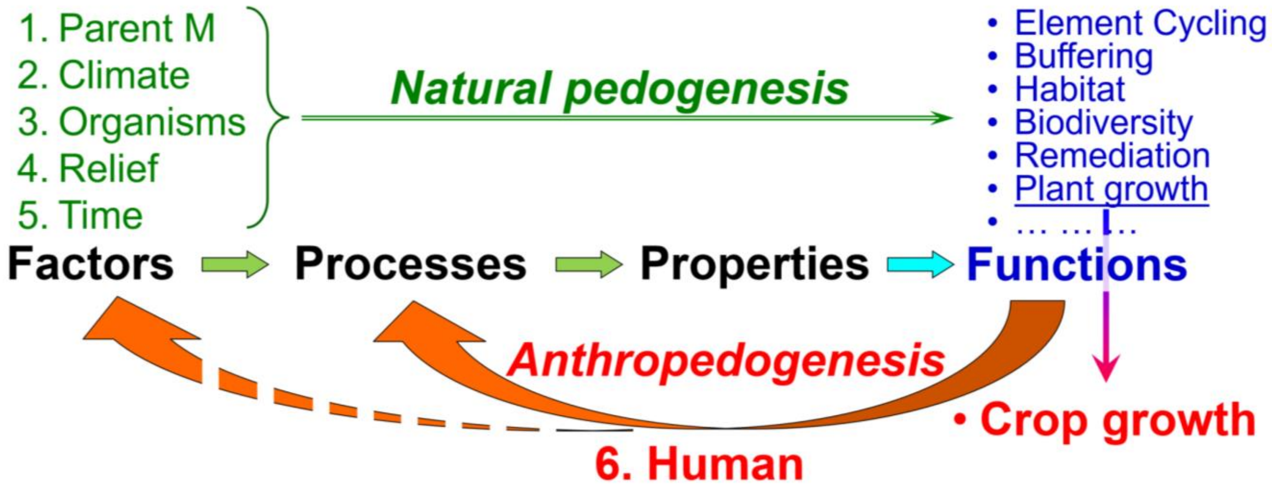


Fig. 2: Soil genesis ~~concepts~~ based under ~~natural~~the five natural factors of soils formation~~on the development of conceptsorder~~ and under the 6th factor: Humans. Natural processes are presented in green, ~~and~~ human processes in red.

The concept~~①~~ 'Factors → Properties' was~~ere~~ suggested by ~~(~~Dokuchaev (~~,~~1883) and ~~;~~ Zakharov (1927, see Supplementary Materials); and later by Jenny (~~,~~1941) ~~– green arrow, ② 'Factors → Processes → Properties' (along the blue arrows) (Gerasimov, 1984), ③~~ O~~o~~ur introduced ~~concept~~ theory 'Factors → Processes → Properties → Functions'~~ (along the red arrows) . The latter concept~~ considers not only the functions of natural soils, but especially human modification of soils toward only one function of interest (here, C~~c~~rop growth). Anthropogenic optimization of only one function involves strongly modifying processes and factors, leading to formation of a new process group: Anthropedogenesis. The ~~bot~~bottom reverse arrows reflect the main specifics of Anthropogenesis: One of the functions ~~is getting~~becomes a factor of pedogenesis and modifies~~y~~ the processes.

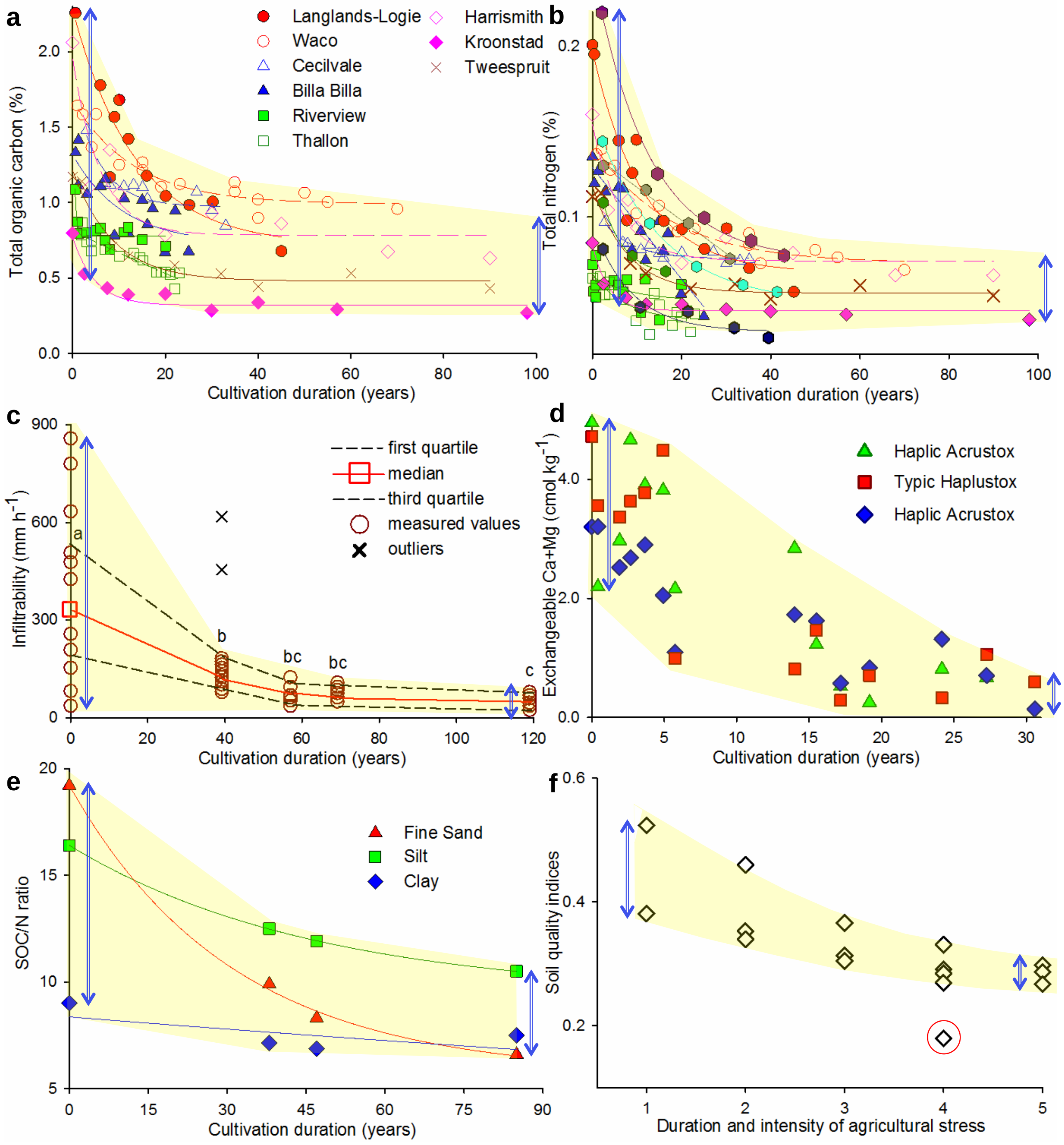


Fig. 3: Examples for attractors of soil properties by anthropogenic degradation: (a) Soil organic carbon content, (b) Total nitrogen content, (c) Infiltration rates, (d) Exchangeable Ca^{2+} and Mg^{2+} contents, (e) C to N ratio ~~in soil particles~~, and (f) overall decrease in soil quality, i.e. degradation 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 ~~carbon~~ 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 ~~carbon~~ C from 0.8-2.3%. During cultivation however, the organic ~~carbon~~ C content strongly narrows to between 0.3-1.0%.

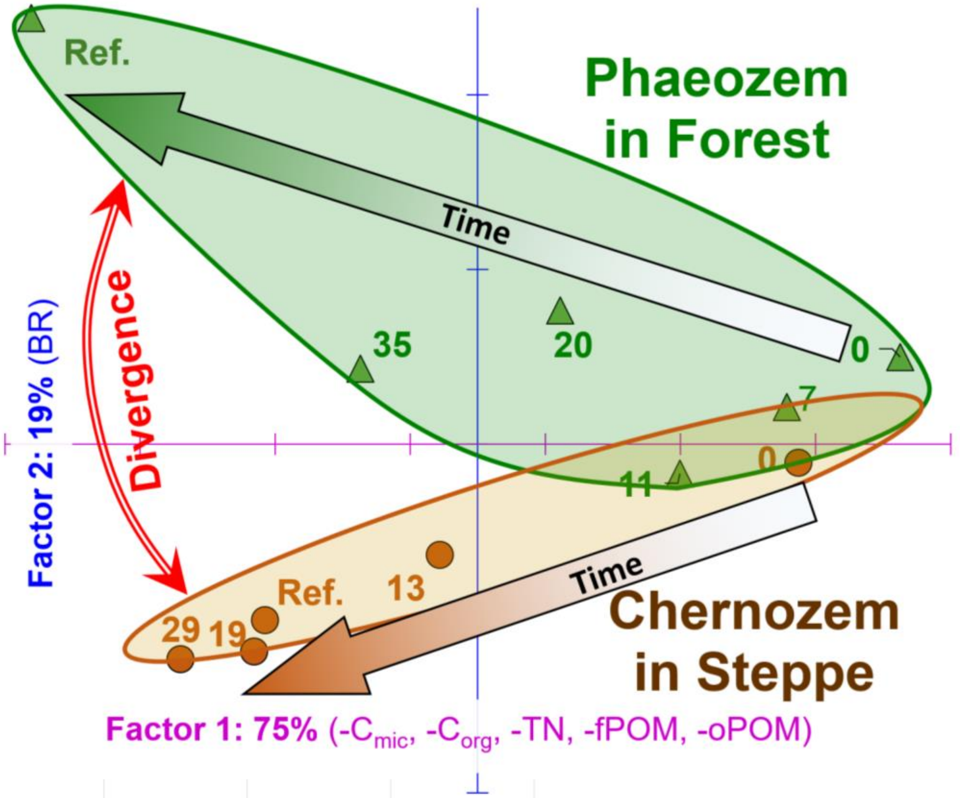
(b) Narrowing range (blue arrows) of total soil ~~nitrogen~~ N over cultivation periods. Sampling sites similar ~~as~~ to (a) plus 5 sites (hexagon symbols) from Great Plains, USA (Haas et al., 1957). Before ~~commencing~~ agriculture start, the Great Plains soils had a wide range of texture classes (silt loam, loam, clay loam, and very fine sandy loam), an initial organic ~~carbon~~ C content of 1.13-2.47%, and a total N~~nitrogen~~ content of 0.05-0.22%. Nonetheless, the total N~~nitrogen~~ 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~~nitrogen~~ (i.e. the attractor for N~~of nitrogen~~) 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 (~~the~~ blue arrows) ~~in measured values~~ from forest (t = 0) toward long-term cultivations (t = 39, 57, 69 and 119 years since conversion). The ~~measured~~ 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 ~~different~~ various natural vegetation prior to cultivation and received different managements 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 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).



~~Fig. 4: Example of dDivergence of properties of agriculturally used Chernozem (CH) and Phaeozem (PH) after abandonment analyzed by principal component analysis (PCA, Kurganova et al., 2019, submitted). The soils had very similar properties due to long-term (> 100 years) cropping. After abandonment, they started to develop to their natural analogues (∞), leading to strong divergences of their properties. This figure reflects the divergence, i.e. the opposite situation to agricultural use. Numbers close to points: duration of abandonment, 0 is agricultural soil and ∞ is natural analogues (not cultivated). The soil parameters primarily driving the divergence are: microbial biomass C (C_{mic}), soil organic C (C_{org}), total N (TN), free particulate organic matter (fPOM), occluded organic matter (oPOM), basal respiration (BR), metabolic coefficient (qCO$_2$), BR/C_{org} ratio, and portion of microbial biomass (MB%).~~

Fig. 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).

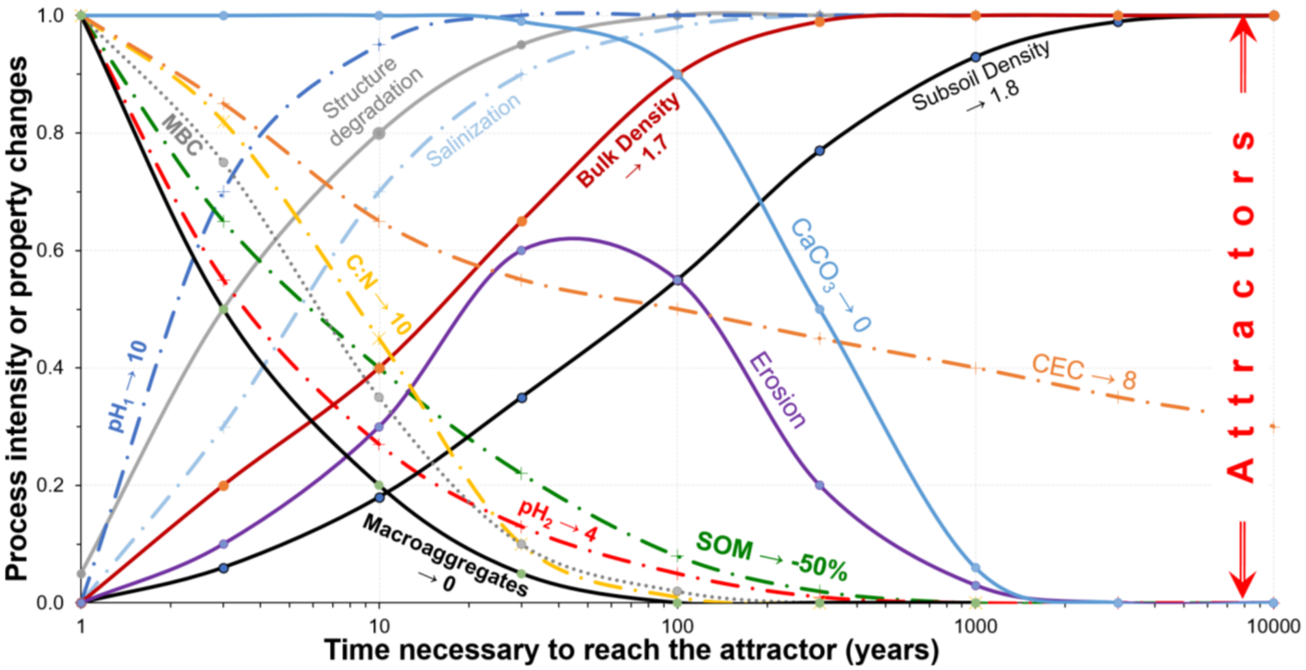


Fig. 5: Overview on rates of key processes of agropedogenesis and their trajectory in reaching their attractors. Curves start from 0 or 1 (relative values) at the onset of cultivation and go to 1 or 0 to the specific attractors. Each curve is labeled with the specific property. Small arrows after each 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.

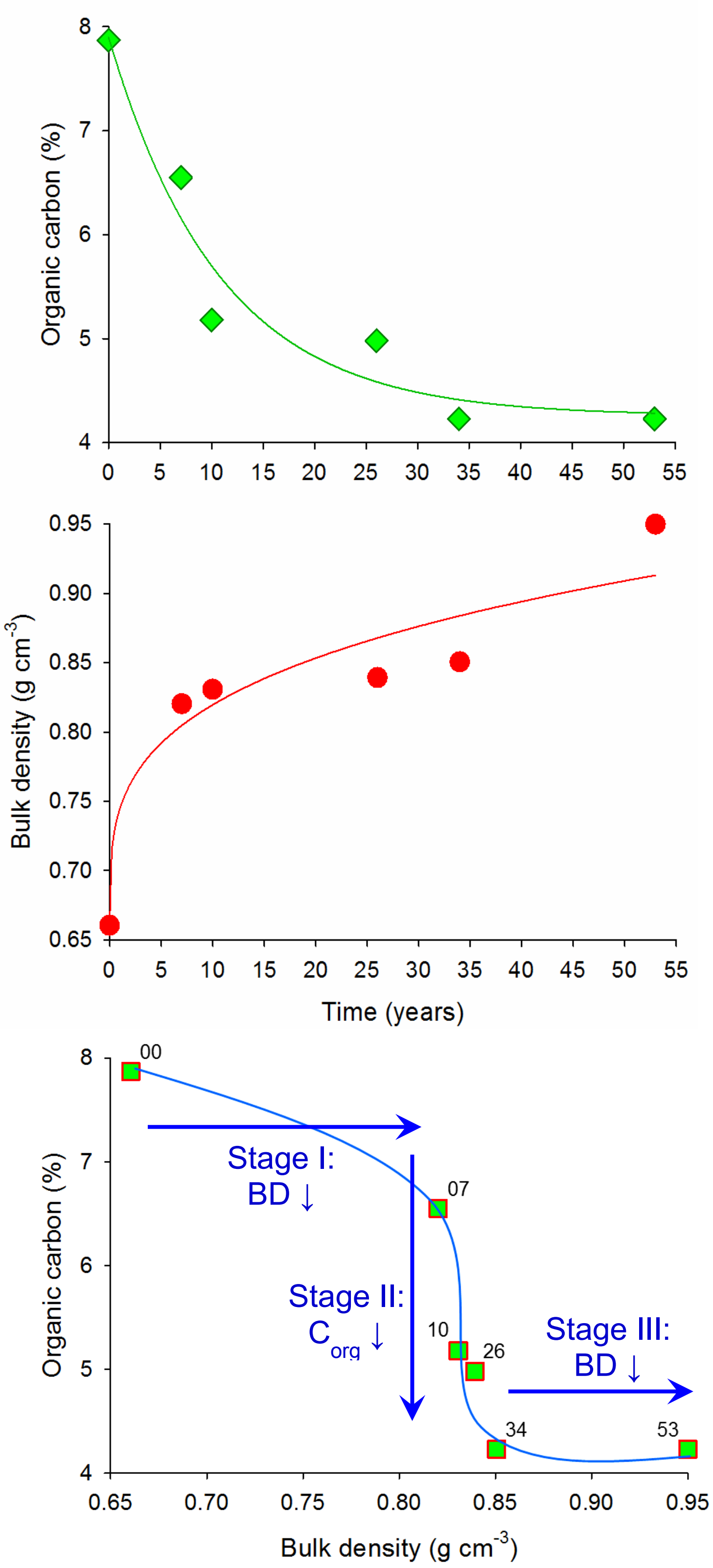


Fig. 6: Effects of duration of forest conversion to cropland on decreasing soil organic carbon (SOC) (a) and increasing bulk density (b) during 53 years (Southern Highlands of Ethiopia, (Lemenih et al.,

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.

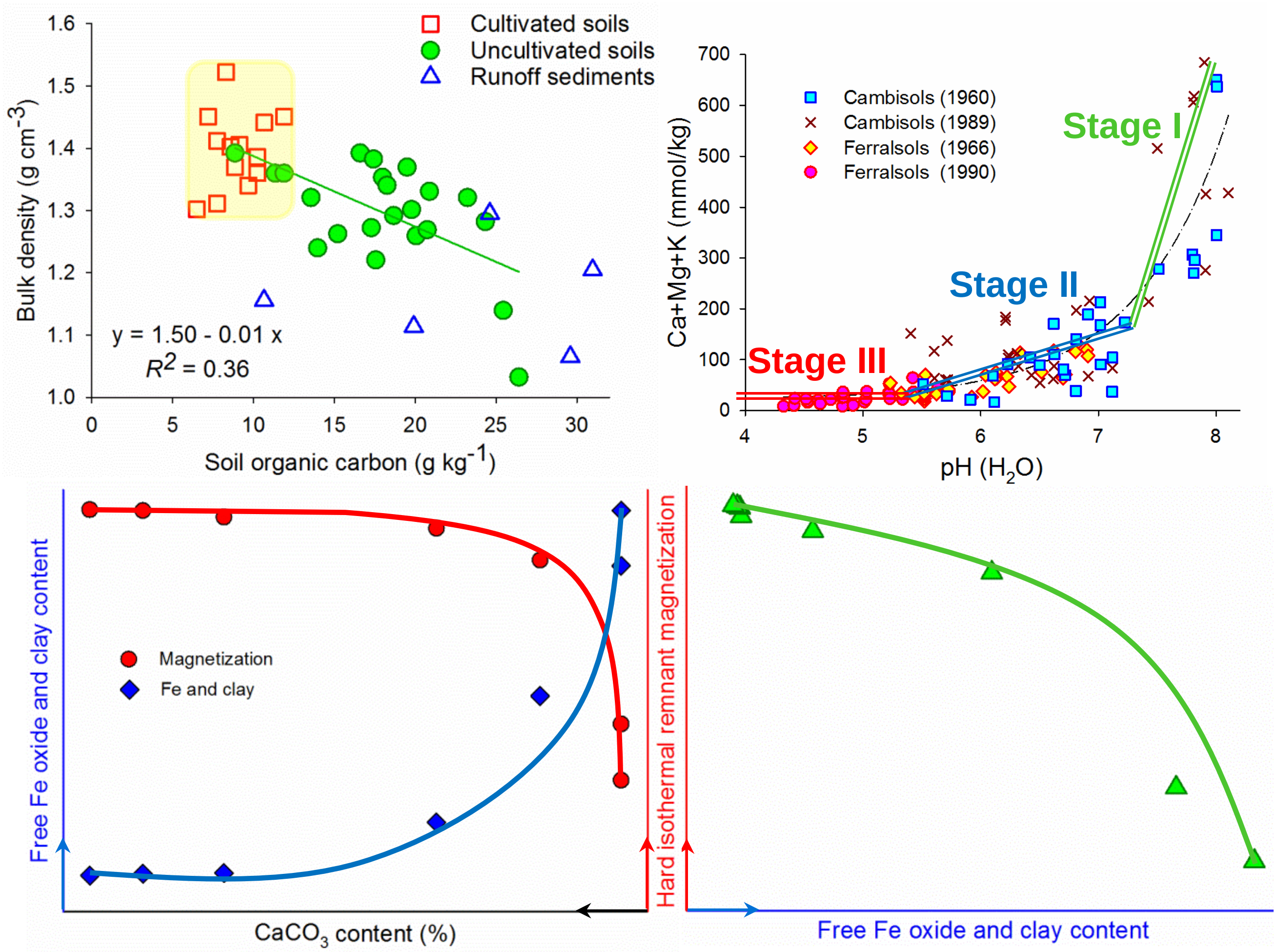


Fig. 7: Phase diagrams of various properties of agricultural soils. Small arrows at the start or end of the axes show the increase of the corresponding soil property.

(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~~ing~~ 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.

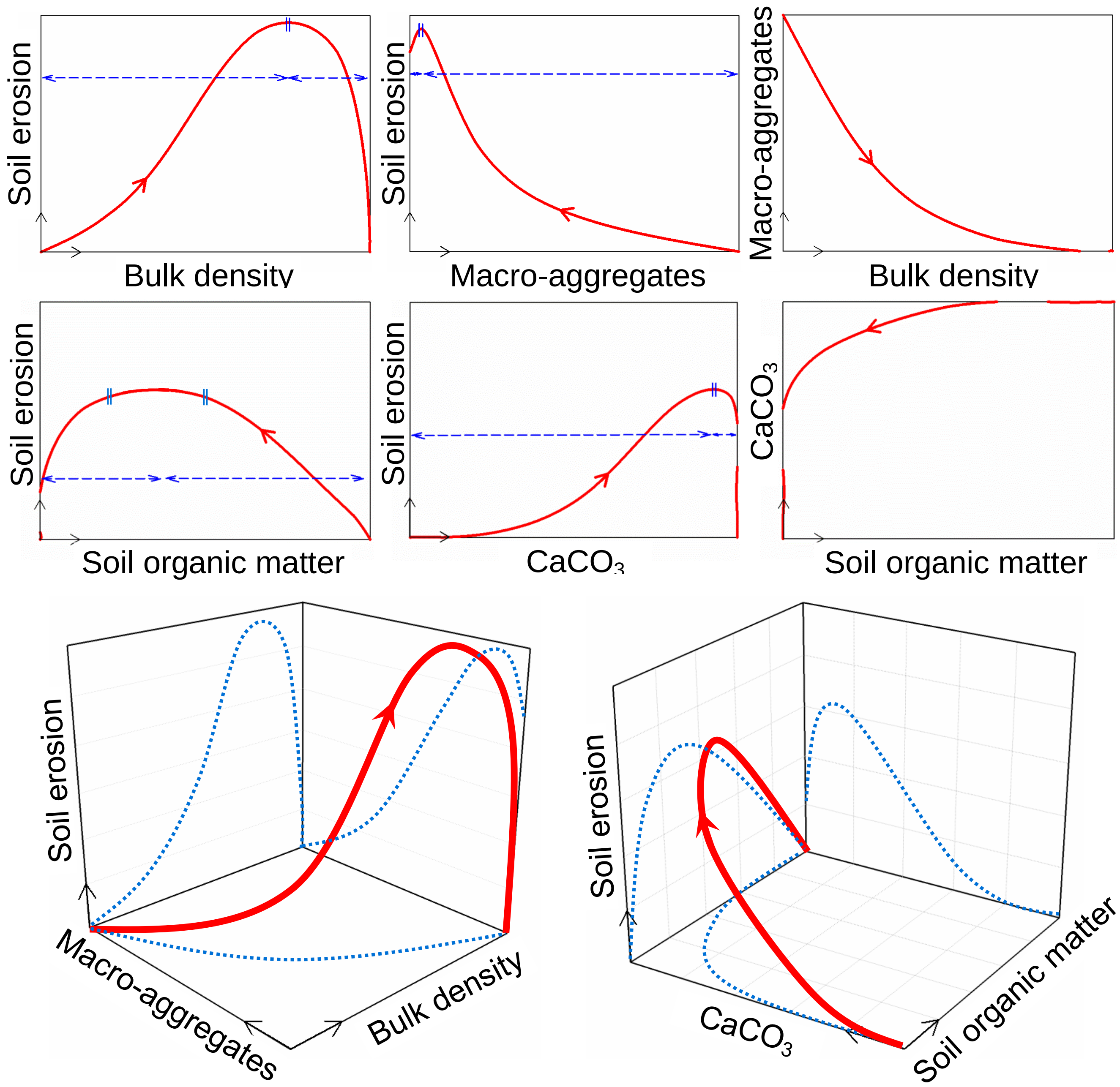


Fig. 8: Examples of conceptual 2D and 3D phase diagrams linking soil erosion intensity with (top) bulk density and macroaggregates content, (middle) SOM and CaCO$_3$ contents during agropedogenesis. The original curves were taken from ~~the~~ Fig. 6. Small red arrows on curved lines show the~~:~~ direction of soil degradation and corresponds to the increasing duration or intensity of agricultural use.~~-~~ ~~Horizontal blue dashed arrows show the stages, and vertical~~ 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 ~~when~~

~~after that~~ 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 ~~the~~ master soil properties (Table 3).

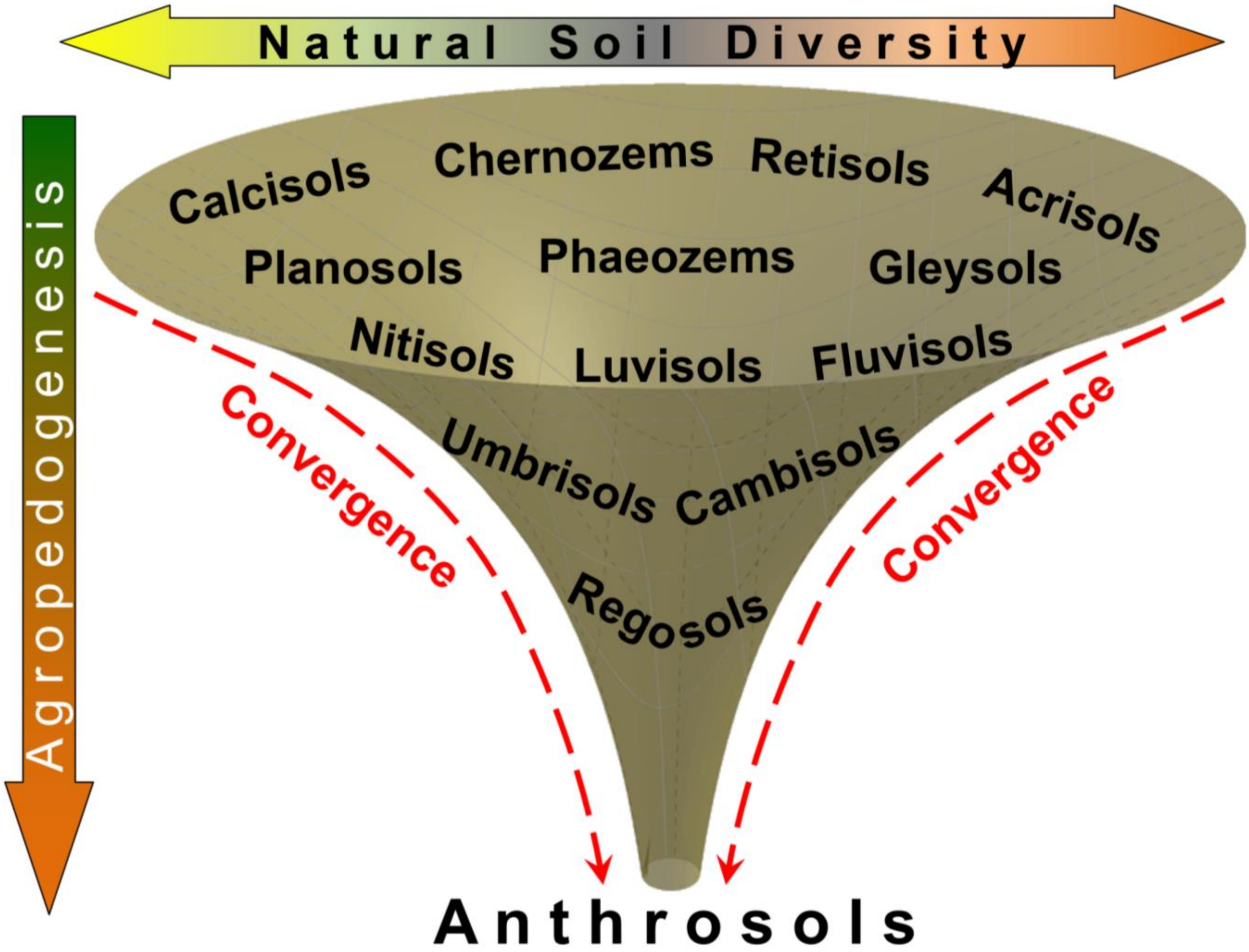


Fig. 9: Conceptual schema of convergence of soil properties by agropedogenesis. The very broad range of~~in~~ natural soils and their properties will be tailored for crop production by agricultural use, resulting in Anthrosols with a very narrow range of properties. Note that the soils within the funnel 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).

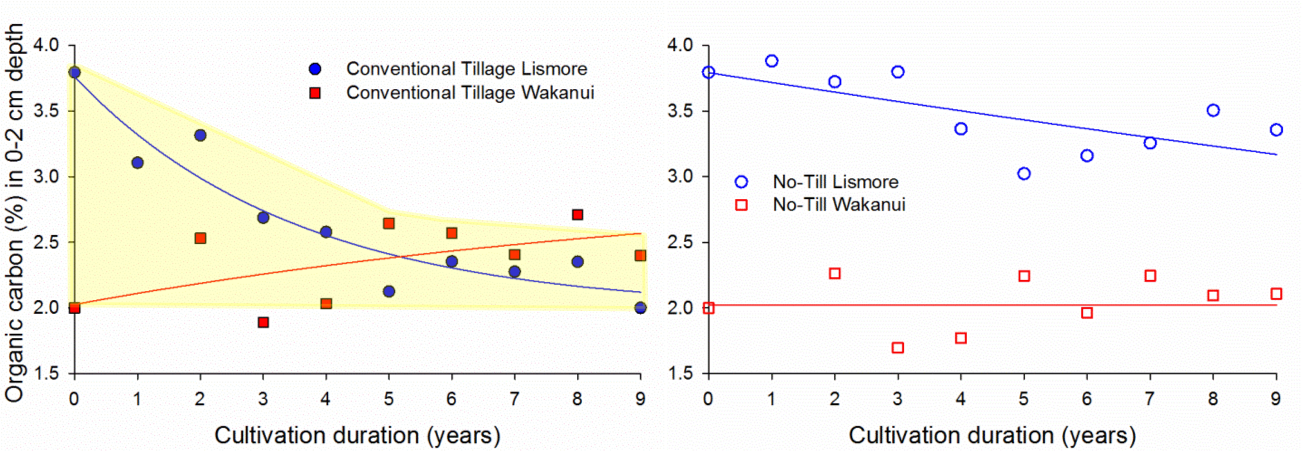


Fig. 10: Nine years of continuous cropping and conventional tillage (left) led to similar~~ities in~~ soil organic carbon (SOC) contents, in contrast to no-till soils (right) (Francis and Knight, 1993). The Lismore no-till soil either needs a longer cultivation duration to reach the ~~carbon~~ C content 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 ~~organic carbon~~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.

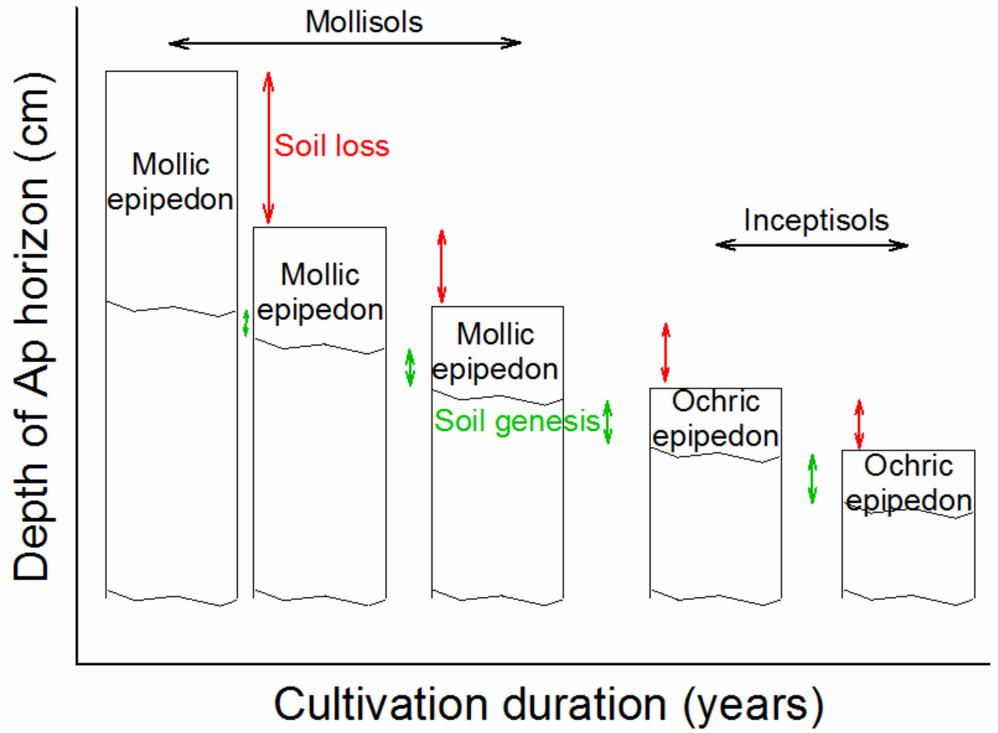
Supplementary Materials

for

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

by Yakov Kuzyakov and Kazem Zamanian

Florinsky, I.V. 2012. The Dokuchaev hypothesis as a basis for predictive digital soil mapping (on the 125th anniversary of its publication). Eurasian Soil Science 45 (4), 445-451.



Cambisols $\xrightarrow{\text{irrigation in arid environments}}$ Solonchaks

Plinthic Acrisols $\xrightarrow{\text{erosion until plinthite and its hardening}}$ Plinthosols

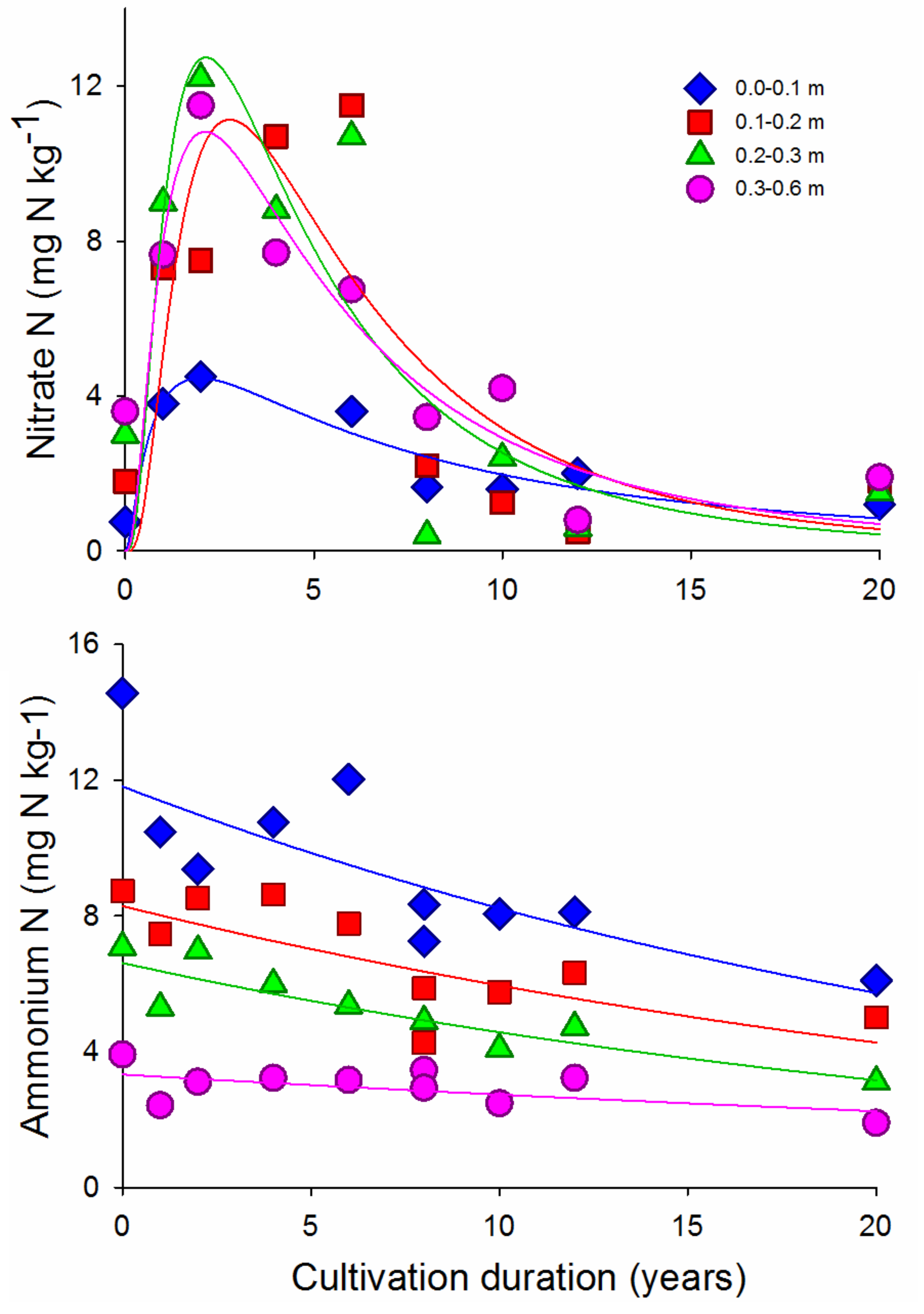
Luvisol $\xrightarrow{\text{total truncation until deep loess}}$ Regosols

Haplic Nitisols $\xrightarrow[\text{rice irrigation}]{\text{surface waterlogging with long lasting}}$ Anthraquic Nitisols

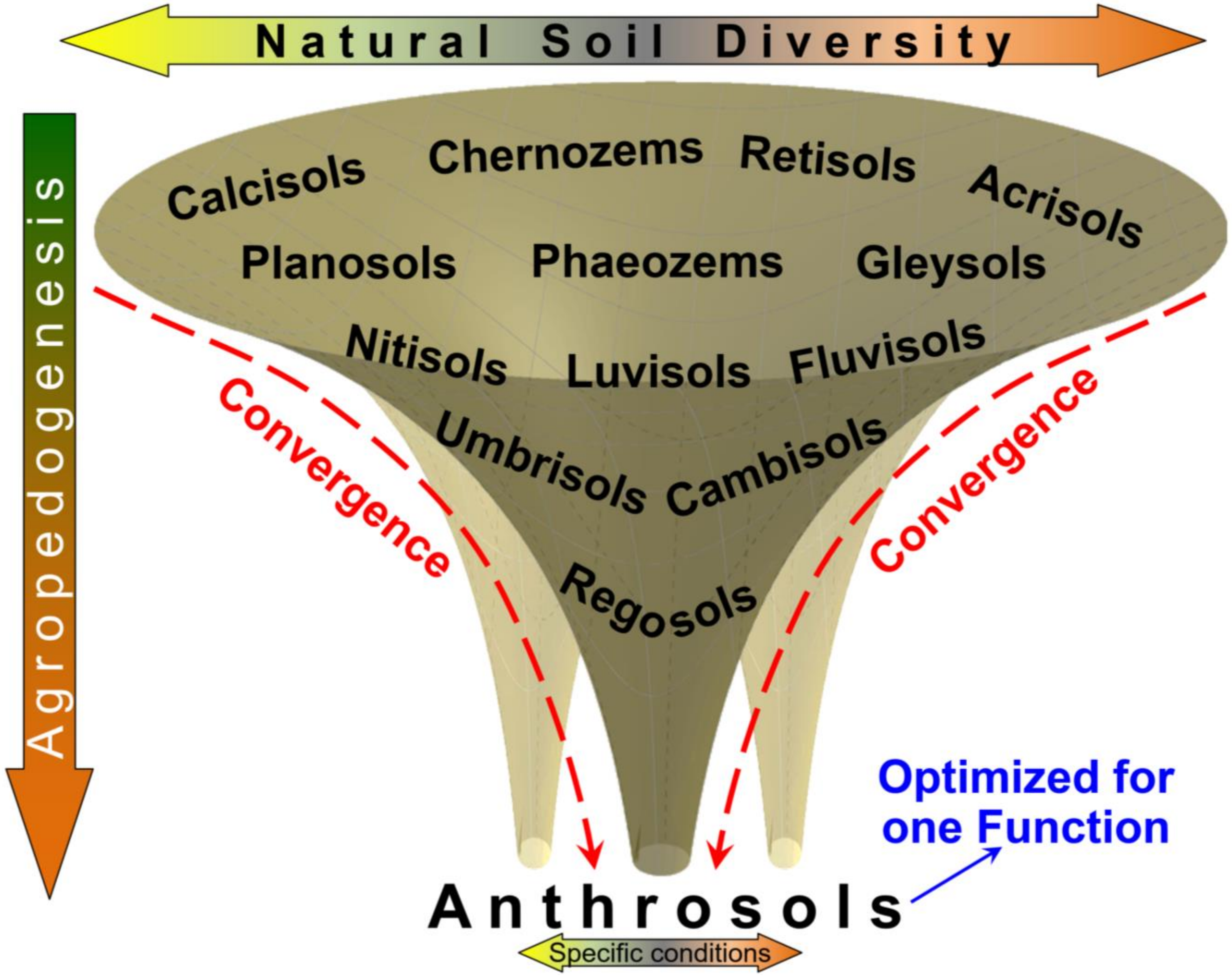
Gleysols $\xrightarrow{\text{drainage}}$ Cambisols

Protothionic Fluvisols $\xrightarrow{\text{drainage}}$ Orthithionic Fluvisols

Supplementary Fig. 1: Soil depth decrease due to erosion. The erosion rate decreases with cultivation duration due to depletion of easily erodible materials. It reaches steady state conditions when erosion becomes equal to soil genesis. After major erosion, the soil taxonomic group changed due to a strong decrease in the Ah / Ap horizon depth, which led to new qualifiers and master properties. Other frequent examples of soil class changes are presented in Dudal (2004)



Supplementary Fig. 2: Examples of convergence of soil properties as a result of cultivation duration: (top) Nitrate content, (bottom) ammonium content depending on soil depth during 20 years of cultivation (Jones and Dalal, 2017). The solid lines are added to better visualize the changing trends in nitrate and ammonium contents as a function of cultivation duration.



Supplementary Fig. 3: Extended conceptual schema of convergence of soil properties by agropedogenesis (see also Fig. 9). 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 – the convergence of properties by agropedogenesis. 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. This extended version reflecting multiple pathways to Anthrosols and their variability. Nevertheless, the variability of all soil parameters is much lower compared to natural soils.