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Soil lifespans and how they can be extended by land use and management change

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Abstract

Human-induced soil erosion is a serious threat to global sustainability, endangering global food security, driving desertification and biodiversity loss, and degrading other vital ecosystem services. To help assess this threat, we amassed a global inventory of soil erosion rates consisting of 10 030 plot years of data from 255 sites under conventional agriculture and soil conservation management. We combined these with existing soil formation data to estimate soil sustainability expressed as a lifespan, here defined as the time taken for a topsoil of 30 cm to be eroded. We show that just under a third of conventionally managed soils in the dataset exhibit lifespans of <200 years, with 16% <100 years. Conservation measures substantially extend lifespan estimates, and in many cases promote soil thickening, with 39% of soils under conservation measures exhibiting lifespans exceeding 10 000 years. However, the efficacy of conservation measures is influenced by site- and region-specific variables such as climate, slope and soil texture. Finally, we show that short soil lifespans of <100 years are widespread globally, including some of the wealthiest nations. These findings highlight the pervasiveness, magnitude, and in some cases, the immediacy of the threat posed by soil erosion to near-term soil sustainability. Yet, this work also demonstrates that we have a toolbox of conservation methods that have potential to ameliorate this issue, and their implementation can help ensure that the world's soils continue to provide for us for generations to come.

1. Introduction

Soils have underpinned the health and longevity of every society. They are a critical global resource, providing the basis of food production, a store and filter for our water resources, the largest organic carbon store and a platform for development (Blum 2005). Pressures on the soil resource grow as food demands rise and land degradation increases. To date, 36% of the world's cultivable land has been farmed (FAO 2015) and in many areas of the world conventional plough-based agriculture is accelerating local soil degradation (Montgomery 2007). The United Nations' Food and Agriculture Organisation (FAO) estimates that 66% of the world's soils suffer from some form of degradation (Bot *et al* 2000), with soil erosion estimated at between 25 and 40 Pg y^{-1} globally (Quinton *et al* 2010).

Rates of human-induced soil erosion are estimated to outpace soil formation rates by more than an order of magnitude (Montgomery 2007). The consequential trajectory of soil thinning is one that, left uninterrupted, leads to the removal of the soil cover and the exposure of the underlying parent material. Given that the thickness of the pedosphere is a first-order control on soil functioning, with thicker soils having a greater capacity for water, carbon and nutrient storage (Power *et al* 1980), the continued thinning of near non-renewable soil profiles is one of the most significant threats to soil sustainability (FAO and ITPS 2015, UNCCD 2017). It is important that land managers, policy makers, and society as a whole understand the timeline over which soil ecosystem services may be severely degraded by complete loss of topsoil.

Thus far, we have not quantified the longevity of our remaining soil resource. Media reports (e.g. Arsenault 2014, Wong 2019) have repeatedly stated that there are as little as 60 years of topsoil left, but there appears to be no scientific basis for these claims. Here, we provide the first scientifically robust, globally relevant estimate of soil lifespans and the degree to which changes in land use or management can extend them. We define a first-order upper physical limit on the productive lifespan of soils as the time it would take for the uppermost 0.3 m of soil to erode, assuming current rates of soil erosion and soil formation remain constant. We argue that a 0.3 m surface horizon is essential for the delivery of ecosystem services, and has been previously used to define the thickness of topsoil which is enriched with nutrients and organic matter (IPCC 2006, Nachtergaele *et al* 2008, FAO 2014) (see *Data and Methods*). We then employ this definition with a global dataset (10 030 plot years of annual water erosion rates, derived from 1103 erosion plot-based records) to quantify typical soil productive lifespans and examine the extent to which land use change and management practices can extend the timescales over which soils remain productive. This is a critical step in motivating and informing land management decisions that secure and sustain food, water and climate services from soils.

2. Data and methods

2.1. Data collation

A compilation of 4285 plot-based gross erosion rates representing 10 030 plot years, were amassed from 240 studies, comprising 255 unique locations across 38 countries (figure 1; sources are listed in Supplementary Information (available online at stacks.iop.org/ERL/15/0940b2/mmedia)). These data were obtained in a series of steps. First, previously published erosion rate inventories were obtained from a Web of Science search, using the search term TS = (‘soil erosion’ AND ‘plot’). As part of the inclusion criteria, studies had to report at least a year’s worth of empirical soil erosion data. Papers based on modelled data and/or those that were based on data collected during singular erosion events were discarded. Second, references within each published inventory were investigated in a snowball sampling strategy. Likewise, those that did not comply with the inclusion criteria set out above were discarded. Subsequently, data from USLE plots and a Chinese dataset were added. To avoid biasing the analysis towards studies with long timeseries or many replicates, we averaged plot replicates and multi-year studies such that all data points represent one erosion rate for each treatment at a single location. Throughout this paper, we use n to denote the number of these gross erosion rates and PY to denote the number of plot years.

The data were assigned into three categories with respect to land management: bare, non-bare conventional agriculture and conservation-based agriculture. The bare soils dataset was from soils that are kept free of vegetation on experimental plots ($n = 62$; $PY = 470$; supplementary table 1). These are often used to gauge erosion in a worst-case scenario. Whilst instances of constantly bare soil are only likely to occur periodically (e.g. prior to crop emergence), the use of bare soil data provides a worst-case baseline against which conventional agriculture and soil conservation practices can be assessed. The non-bare conventional agriculture dataset includes observations from plots undergoing non-conservation agricultural practices, including downslope cultivation, non-terraced cropland and conventional tillage ($n = 320$; $PY = 4816$; supplementary table 1). The conservation-based agriculture dataset comprises an array of plots that have been subject to soil conservation techniques, such as land-use change and modifications to agricultural practices ($n = 721$; $PY = 4744$; supplementary table 1).

Gross erosion rates in the study’s native units were compiled along with details of the respective management or soil conservation practice. Additional information about the study site were noted, including: soil type (FAO World Reference Base), textural data, mean annual precipitation, slope and location co-ordinates. Bulk density was recorded if it was provided; otherwise, the lower and upper values from bulk density ranges were used from accepted standards for each soil texture (US Department of Agriculture 2018). Cultivation notes, including ploughing depth, mulching technique and crop species, were recorded wherever applicable (supplementary table 1). The dataset includes soils from 14 of the 26 soil orders as recognized by the World Reference Base. All soil textures apart from ‘Silt’ and ‘Sandy Clay’ soils are represented within this inventory (supplementary figure 1), with the modal texture being ‘Silt Loam’ ($n = 182$; $PY = 1865$).

2.2. Lifespan model

To permit a valid comparison between gross erosion rates and soil formation rates, all erosion data were converted from their native unit to mm y^{-1}. This involved a two-step approach whereby data in native units were first converted into t ha^{-1} y^{-1} and then, with the bulk density estimate, into mm y^{-1}, following standard approaches (Montgomery 2007). Bulk densities were either taken directly from original papers or, in the case of these data being absent, a lower and upper bulk density were estimated based on accepted standards (US Department of Agriculture

Figure 1. Number and spatial distribution of plot years for the 255 unique locations in this study. Full dataset can be found in supplementary table 1.

2018). A lower and an upper gross erosion rate were thus calculated (supplementary table 1).

A previously compiled global dataset ($n = 264$) of soil formation rates was used in this study (Evans *et al* 2019). This dataset comprises ^{10}Be-derived rates of soil formation measured at ten unique locations across Australia, USA, Chile and the UK, representing five different climates (according to the Köppen classification system) and all three major rock types (igneous, sedimentary and metamorphic) (Heimsath *et al* 1997, 1999, 2000, 2001a, 2001b, 2005, 2006, 2012; Wilkinson *et al* 2005; Dixon *et al* 2009; Owen *et al* 2011; Riggins *et al* 2011). The mean soil formation rate was 0.053 ± 0.005 mm y^{-1}. The 25th and 75th percentiles of this dataset (0.011 and 0.059 mm y^{-1}, respectively) were employed into the lifespan model in order to provide a representation of uncertainty and variation in the formation rate (supplementary table 2).

Where gross erosion rates exceed those of soil formation, soil profiles thin; over time, assuming these rates remain imbalanced, the soil profile will eventually erode beyond a critical depth required for the delivery of ecosystem services. We argue that the surface horizons of the soil are critical for ecosystem service delivery as they are enriched with nutrients and organic matter, and critical for plant growth. In line with the FAO Harmonised World Soil Database, the World Reference Base Soil Classification and the IPCC (IPCC 2006, Nachtergaele *et al* 2008, FAO 2014) we set the topsoil depth as 0.3 m. We chose a single topsoil depth as few of the plots where the erosion rates were measured had detailed soil descriptions. Global spatially explicit estimates of soil depth exist, such as the International Soil Reference Information Centre Global Soil Information System '*SoilGrids*', however, the representativeness of these data products for the individual sites compiled in the erosion rate dataset is unknown (Hengl *et al* 2017; Shangguan *et al* 2017). Hence, we employ the simplest assumption and calculate the lifespan assuming a productive 0.3 m topsoil layer at all sites. This also provides the advantage of allowing us to harmoniously compare the estimated lifespans across locations, land uses and management practices.

Following Stocking and Pain (1983), soil productive lifespans (L) were calculated for bare, non-bare conventional and conservation-based land use regimes using equation (1) (supplementary table 2):

$$\frac{D}{E-F} \tag{1}$$

where D is depth (mm) (set at 300 mm), E is the gross annual soil erosion rate (mm y^{-1}) and F is the gross annual soil formation rate (mm y^{-1}).

For each land use and management type, calculated lifespans were pooled and an Anderson Darling test for normality was conducted. All were found to be non-normal, leading to the median being used as the most appropriate measure of central tendency. Interquartile ranges and the 5th and 95th percentiles were calculated. Percentages of lifespans <100 years were calculated, with these percentages referring to the number of plot studies.

Where gross erosion rates fall below those of soil formation, the soil is thickening and equation (1) no longer applies (the lifespans are indefinite). In these instances, the net annual soil gain was calculated using the gross soil erosion and formation rates. The proportions of <100 year, finite, and indefinite lifespans were calculated for each land use and management type. A two proportion Z test (both one-tailed and two-tailed at 95% confidence) was then used to assess whether these <100 year, finite, and indefinite lifespan proportions from conservation managed plots were significantly different to those from bare and conventionally managed plots.

2.2.1. Limitations of the soil lifespan analysis. The lifespans calculated here are based on a single proxy (net erosion), which is just one form of degradation that threatens the sustainability of soils globally. There are a range of retrogressive processes that can degrade the soil's capacity to deliver ecosystem services in shorter time frames (Heimsath *et al* 2009). For example, soil compaction can bring about adverse effects on water regulation and nutrient cycling, without a substantial loss of soil thickness (Batey 2009). The soil formation and erosion rate (and, therefore, the net annual soil loss and gain) were assumed to remain constant over time. This does not account for the year-to-year fluctuations observed in long-term soil erosion studies (Martínez-Casasnovas *et al* 2002), the potential acceleration of soil erosion rates as precipitation intensity increases, nor the extent to which soils may become armoured by coarse fragments (e.g. pebble beds) in the future (Evans *et al* 2019). Moreover, the use of constant soil formation rates do not account for potential variations in bedrock weathering rates as the overlying soil mantle progressively thins (Heimsath *et al* 1997) or climatic or biotic variations. In addition, the bedrock-derived soil formation rates account neither for allochthonous additions (aeolian and alluvial deposits) nor the thickening of an organic layer on the mineral soil surface, observed as a product of some management practices, such as conservation tillage (Sharratt *et al* 2006). As aforementioned, we selected a generalized critical soil depth of 0.3 m, but in reality, depending on the soil and the environment, the critical soil depth threshold may be lower or higher than this. Furthermore, we do not account for any adaption of the subsoil: if surface erosion rates are sufficiently low, the underlying subsoil (if it exists) could be transformed, chemically and biologically, into topsoil (Bakker *et al* 2004).

Assumptions were also made in the collation of input data used in the lifespan calculation. First, the lifespans presented here have been calculated from erosion rates measured at the plot scale, which are not wholly representative of the erosional processes observed at the landscape scale, such as gully erosion (Takken *et al* 1999, Cerdan *et al* 2010). Erosion plot experiments tend to be located in areas suffering from erosion, likely leading to bias in our calculated lifespans. In addition, the erosion rates included in this analysis are only for water-based erosion; the redistribution of soil by tillage was not considered, although this is a significant erosion process (St. Gerontidis *et al* 2001). Therefore, it is likely that estimates of lifespans are overestimated for soils on slope convexities, where tillage reduces soil depth, and underestimated on slope concavities, where tillage leads to soil accumulation (Van Oost *et al* 2006).

Finally, there is an imbalance between the number of observations in the soil erosion dataset and within the inventory of soil formation: 18 940 papers were found in Web of Science (25 March 2020) following a search for 'soil erosion' compared to 2785 for the term 'soil formation'.

3. Lifespans for bare and conventional agricultural soils

Here, we consider soils that are devoid of vegetation (bare) and under conventional cropping (e.g. inversion tillage, seedbed preparation followed by cereal or vegetable cropping), representing the worst-case and business-as-usual conditions respectively. The cumulative distribution of the estimated soil lifespans is illustrated in figure 2.

For plots kept bare, 34% of the dataset reported lifespans of <100 years and the median lifespan for thinning soils ($n = 60$; $PY = 447$) was 333 years. For the bare soils that were classed as thickening ($n = 2$; $PY = 23$), the mean annual estimated soil gain was 0.03–0.04 mm y^{-1}. For soils from non-bare, conventionally managed plots, 16% of the dataset ($n = 298$; $PY = 4737$) reported lifespans of <100 years, with a median of 491 years for thinning soils, and a mean annual estimated soil gain was 0.03 ± 0.001 mm y^{-1} for thickening soils ($n = 22$; $PY = 79$). These estimates demonstrate the magnitude of the threat that soil thinning can place on relatively near-term soil sustainability.

The analysis also shows that all regions of the world have a predominance of thinning soils (table 1, finite lifespans), with soils with <100 years present on all continents. The location of sites with lifespans <100 years include some of the wealthiest nations (Australia, Brazil, China, Italy, Mexico, Spain and the USA), as defined by gross domestic product (World Bank 2019) demonstrating the pervasiveness of this issue.

Our analysis suggests that a sizeable proportion of our soil resource under conventional management practices have lifespans <100 years comparable to human timescales (16% with lifespans <100 years). This is not in line with the popular claim that there

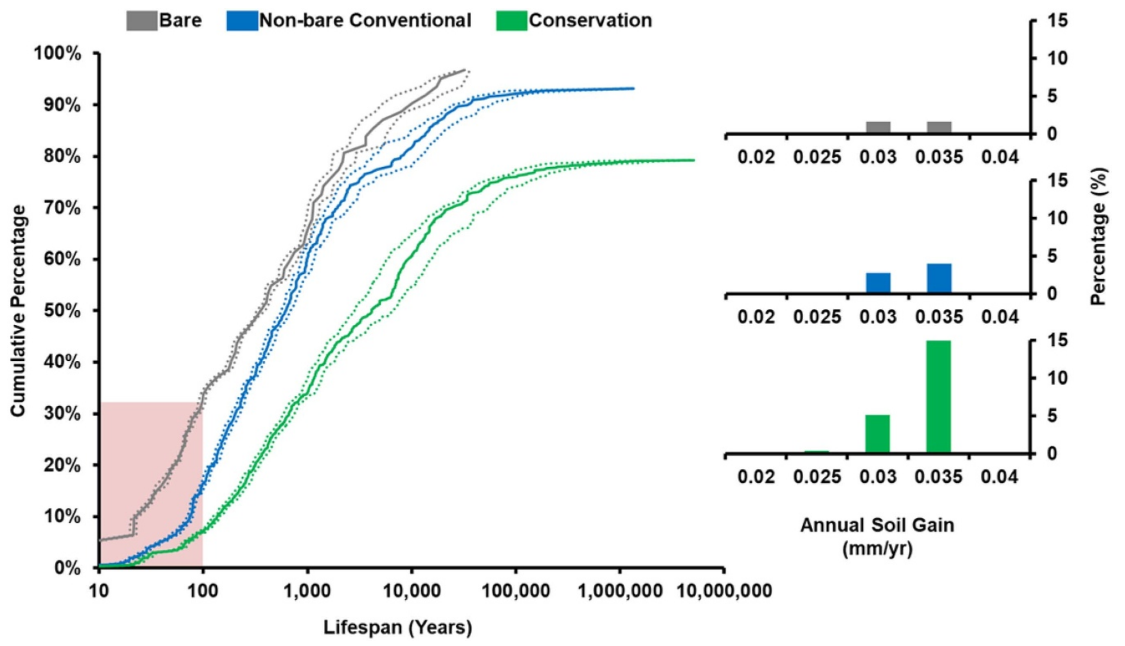

Figure 2. Cumulative distribution of soil lifespans ($n = 929$; $PY = 9168$ for thinning and $n = 174$; $PY = 862$ for thickening soils) and annual soil gain for bare soils (grey), non-bare conventionally managed soils (blue) and conservation management (green). Bold lines on the cumulative distribution chart represent median lifespans; dotted lines represent the lower and upper bounds of lifespans when the uncertainties in soil formation and soil erosion data are taken into account (see *Methods*). The shaded red box highlights the lifespans <100 years. Full dataset can be found in supplementary table 2.

are 60 years of global topsoil left (e.g. Arsenault 2014, Wong 2019). Our analysis suggests that this claim may be too alarmist given that 79% of the worst-case bare soils had lifespans longer than 60 years, and that rises to >90% for conventionally managed soils. However, it should also be noted that these lifespans were spread across five orders of magnitude and were heavily dependent on the management in operation and the local environmental conditions at each site. Hence, quoting a single lifespan estimate does not effectively acknowledge the range of lifespans that exist under a number of different land management practices.

4. Extending soil lifespans by changing land use and agricultural practice

The lifespans of soils under conservation management, including changes both in land use and agricultural practice, were estimated using measured erosion rates ($n = 721$; $PY = 4744$) drawn from 201 plot-based studies. These plots include those adopting conservation-based agricultural practices (e.g. contour cultivation) and different types of land use, including forest and grassland. In the majority of studies, forest and grassland sites were established prior to the commencement of the study, although some studies were not explicit in this regard. Gross soil erosion rates were lower than soil formation in 21% of cases ($n = 150$; $PY = 760$), leading to a net annual soil gain (figure 2). Compared with the bare and conventionally managed plots, the proportion of thickening soils from the conservation management plots was significantly greater ($p < 0.05$) with these soils more than twice as likely to be thickening rather than thinning.

Pooling all data for plots managed with conservation practices, 7% of lifespans were <100 years. This represents a statistically significant reduction of more than half in the proportion of lifespans <100 years compared with the conventionally managed plots in the dataset ($p < 0.05$; figure 2). The distribution of lifespans for the plots under conservation management was shifted towards longer lifespans when compared to conventionally managed soils. For conservation managed soils, 48% of the estimated lifespans exceeded 5000 years compared to 23% for conventional agriculture, and 39% exceeded 10 000 years compared to 18% for conventionally managed soils.

4.1. Land use change

Analysing by land use suggests that land use change towards a forested site would be the most effective land use change for extending soil lifespans (figure 3). The shortest lifespan in the forested dataset was 420 years, compared to 16 years for cropland soils. In 50% of cases, gross erosion rates in forests fell below those of soil formation, promoting soil thickening (0.032 ± 0.000 mm y^{-1}). This proportion of thickening soils was significantly greater than that for bare plots (15 times greater) and cropland plots (six times greater) ($p < 0.05$). These findings concur with similar work that has concluded that croplands erode, on

Table 1. Global distribution of finite, lifespans <100 years, and infinite lifespans for five regions.

	All Data			Finite Lifespans			Lifespans <100 years			Infinite Lifespans			
	n	*PY*	Median lifespan (years)	*n*	*PY*	% of dataset in the region	*n*	*PY*	% of dataset in the region	*N*	*PY*	% of dataset in the region	Mean soil gain (mm y^{-1})
North America	217	2487	583	181	2346	83	39	755	18	36	141	17	0.033
South America	201	3221	7101	147	3019	73	24	134	12	54	203	27	0.031
sub-Saharan Africa	105	1219	671	100	1198	95	17	212	16	5	21	5	0.035
Europe and Middle East	107	963	6270	83	689	78	5	24	5	24	274	22	0.032
Asia and Australia	473	2140	1397	418	1917	88	40	162	9	55	223	11	0.031

[a] Comprises bare, non-bare conventional, and conservation land use management.

[b] Full data can be found in supplementary table 2.

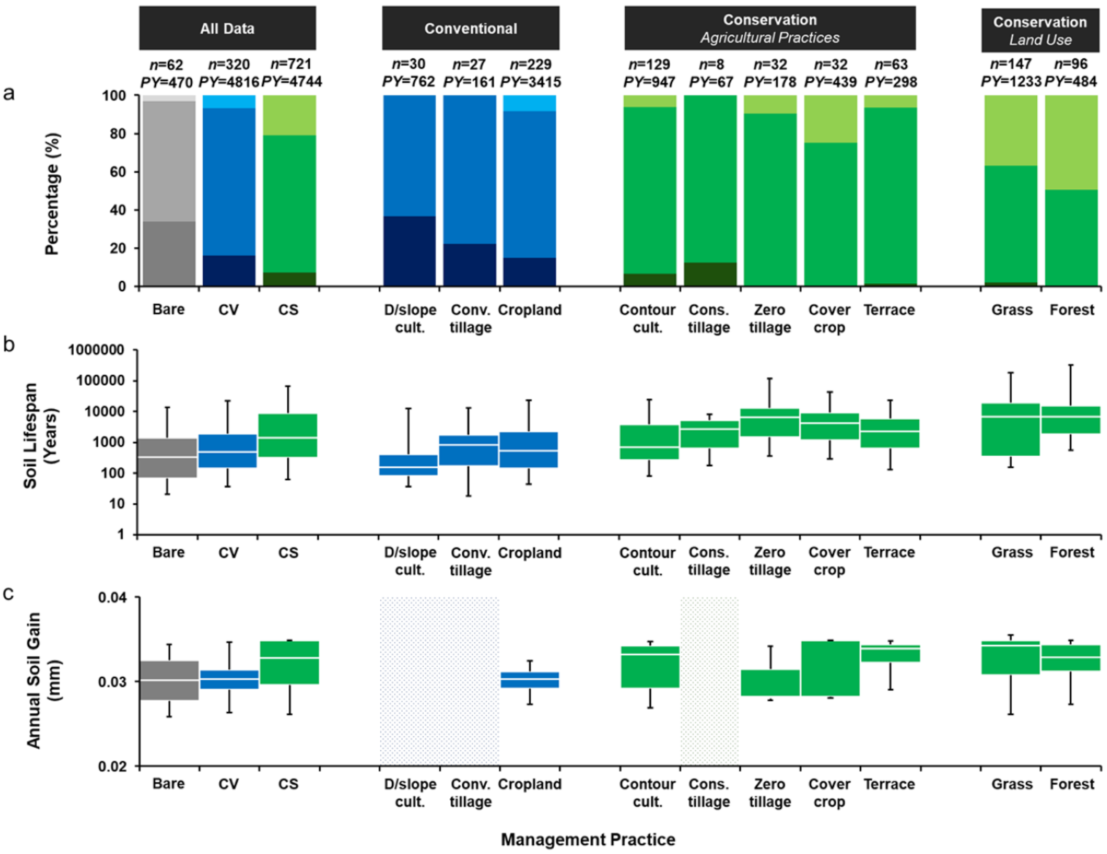

Figure 3. (a) Distribution of lifespans <100 years (*lowermost bars*), finite (>100 years; *middle bars*) and infinite (thickening; *uppermost bars*) lifespans for bare, conventional and conservation-based management ($n = 1103$; $PY = 10\,030$). (b) Soil lifespans for conventional (blue) and soil conservation (green) management practices ($n = 929$; $PY = 9168$), excluding those soils that are thickening. (c) Net annual soil gain for conventional (blue) and conservation-based (green) management practices ($n = 174$; $PY = 862$). Dotted bars denote incidences where either annual soil gain did not occur or there were not enough data. All lifespans in the dataset were calculated by accounting for the uncertainty in soil formation and erosion rates (see *Methods*). Boxplots represent the interquartile range of these pooled lifespans; error bars refer to the 5th and 95th percentiles, within each management shift category. A description of management practices can be found in supplementary table 3. Full dataset can be found in supplementary table 2.

average, more than an order of magnitude faster than forest soils (Zhao *et al* 2016).

The analysis suggests that land use change from bare or conventional cropland to grassland would be similarly effective in lengthening soil lifespans. For grassland plots, we found that 2% of lifespans were <100 years, a 17-fold reduction in the proportion of <100 year lifespans compared to plots kept bare ($p < 0.05$) and a seven-fold reduction in comparison to cropland soils. In 37% of cases, gross soil erosion rates fell below those of soil formation, promoting soil thickening (0.032 ± 0.000 mm y^{-1}). This represents an 11-fold increase in the occurrence of thickening soils ($p < 0.05$) compared to bare soils, and a four-fold increase ($p < 0.05$) compared to cropland soils.

4.2. Changing agricultural practices

Without reducing the area of land designated for agriculture, we found that cover cropping was an effective method of extending lifespans. No plot in the cover-crop dataset had lifespans of <100 years (figure 3(a)). In 25% of cases, gross soil erosion rates fell below those of soil formation, promoting an estimated net annual soil gain of 0.031 ± 0.001 mm y^{-1}. The proportion of thickening soils from cover crop plots was significantly greater than that of conventional management practices ($p < 0.05$). These results accord with previous work showing the importance of cover cropping in reducing erosion (Nyakatawa *et al* 2001, Verstraeten *et al* 2002, Gyssels *et al* 2005).

Whilst cover cropping is one of the most effective agricultural practices for lengthening soil productive lifespans, a suite of additional practices both prior to and during the cropping season can extend these further. In our dataset, conservation tillage led to a two-fold reduction in the proportion of cases with lifespans <100 years compared to conventional tillage, although this was not statistically significant ($p > 0.05$). Moreover, we found that zero tillage practices also substantially lengthened soil lifespans, with a significant reduction in the proportion of <100 year lifespans compared to conventional tillage ($p < 0.05$) (figure 3(b)).

For cultivation direction, we found that contour cultivation compared to downslope practices brought about an extension of the soil lifespan, and a significant reduction in the proportion of <100 year lifespans ($p < 0.05$), with 7% of the former having lifespans of <100 years compared to 37% for the latter. For 6% of the contour cultivation dataset, soil thickening led to an estimated net annual soil gain of 0.032 ± 0.001 mm y^{-1}. On particularly steep gradients, contour cultivation may not be practical and the most effective conservation-based management strategy may be terracing. For terraced soils, 2% of the dataset reported lifespans of <100 years, which compared to downslope cultivation represents a 23-fold reduction in lifespans <100 years ($p < 0.05$). However, terraces can lead to a reduction in the cropping area (Herweg and Ludi 1999), although some have argued that the risers are potentially cultivable (Sahoo *et al* 2015) and their success as a soil conservation measure is fundamentally dependent on their maintenance.

5. Decision making at the site scale

Underpinning the variability in the efficacy of soil conservation management across different regions are local, site-specific variables including climatic, topographic and pedological factors (see supplementary information for a detailed analysis of the effects of precipitation, slope, and soil texture on soil lifespans) and it is important that these are taken into consideration when planning soil conservation measures. The decision about which conservation practice is most likely to be more effective in sustaining soils at a given location is also dependent on an array of social and economic factors. For example, land use change to either forest or grassland would not be appropriate if agricultural activity is displaced to more erosive locations, and the selection of specific agricultural practices is also likely to be partly determined by the social context, financial and resource capability of the land manager in question. Issues such as the duration of land tenancies and the existing policies, incentives and advisory services provided at a regional and national level will influence the adoption of soil conserving approaches. In addition, the approaches to sustain, improve, or restore soil health in the short-term may not always be the most effective strategies of protecting the soil from erosion. Our dataset reported 25 instances where soil lifespans are shorter than 25 years. In ten of these cases, the soils had been subject to conservation management practices, and in seven of these, fallowing had been adopted. Some researchers have found that fallowing for a period after agriculture is necessary to restore soil aggregation and biological health (Aboim *et al* 2008, Zeleke *et al* 2014). In water-limited environments, leaving crop residues or stubble on otherwise uncultivated soil is one of the ways of increasing soil moisture prior to the sowing of the subsequent crop. Whilst the soil is not wholly bare during the fallowing period, the sparseness of vegetation cover can lead to increased erosion. Our analysis showed that, for the majority of cases, fallowing increased soil erosion rates by more than an order of magnitude compared to those during the cropping period. This demonstrates that incorporating a protective cover into the fallowing period is essential to minimize soil erosion. Furthermore, the land use changes and agricultural practices presented in this paper vary in their ‘establishment time’: the time for a selected conservation management regime to be set up, launched and become effective. For soils with lifespans <100 years, and especially the 25 instances in our dataset where lifespans are shorter than 25 years, it could be argued that the most effective management decision is to adopt a strategy with a short establishment time. In this context, conversion to grass, cover cropping and/or contour cultivation may be most appropriate, as the establishment time for these strategies is in the order of months to a year. By contrast, the planting of trees to convert cropland to forest incurs a significant lag time whilst forests mature.

6. Conclusions

In this paper, we have presented the first broad quantitative estimates of the productive lifespans of soils and the degree to which these may be extended by land management change. By compiling globally distributed soil erosion and soil formation rate data and applying the soil lifespan concept, we can contribute the following conclusions.

First, an assessment of soil lifespans using soil loss rates measured from non-bare soils under conventional management systems suggest that, under a worst-case scenario, 93% were thinning and 16% had lifespans <100 years. At these sites, soil erosion is a significant threat to the soil’s capacity to grow food, support ecosystems, store and regulate water, cycle carbon and nutrients and thus to the overall functioning of the soil system.

Second, we have shown that land use and land management practices can extend the soil lifespan and, in many cases, promote the onset of soil thickening. Only 7% of the conservation plot dataset had lifespans <100 years, with 48% of the estimated lifespans exceeding 5000 years and 39% exceeding 10 000 years. The estimates for forested and grassland sites suggest that conversion to these land uses would be most effective in achieving both of these outcomes, closely followed by the introduction of cover cropping. However, given the need to meet the growing demand for food, cover cropping is arguably the more attractive option. A suite of additional strategies to extend soil lifespans and promote annual soil gain include conservation and zero till practices, contour cultivation and terracing. In general, conservation practices extend soil lifespans and may promote soil thickening, increasing the potential for water, carbon and nutrient storage, and thereby soil conditions which could enhance crop yields.

Third, we have shown that there is a wide distribution of soil lifespans globally, encompassing five orders of magnitude, partly reflective of an extensive variation in the underlying driving variables such as climate, slope and soil texture, which in turn can influence the efficacy of soil management techniques. However, soils with human-scale lifespans shorter than 100 years are present in all of the observed regions, including many of the world's wealthiest nations. This clearly demonstrates that soil erosion is one of the most critical threats to soil sustainability globally, and that urgent action worldwide by land managers, policy makers and society is imperative to prevent the collapse of soil ecosystem service provision.

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Author contributions

D L E, J N Q. and J A C D designed research; D L E performed research; D L E, J N Q and J A C D analysed data and D L E wrote the paper with contributions from J N Q, J A C D, J Z, and G G

Competing Interests

The authors declare no competing interests

Data Availability

The authors declare no restrictions on the availability of materials or information.

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