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Scratching the critical zone: the global footprint of agricultural soil erosion

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Abstract

Agricultural activities have drastically increased soil erosion rates and it is therefore likely to have important effects on the Earth's Critical Zone. In this paper we first investigate to what extent agricultural soil erosion can be quantified. We then combine this information with our current understanding of Critical Zone processes to assess the impact of agricultural soil erosion on soil functioning (biogeochemical cycling, hydrology, crop productivity) and to identify areas where additional research is needed to complete our understanding of how agricultural soil erosion affects the Earth's Critical Zone at different spatial and temporal scales.

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1. Introduction

Humans affect the functioning of the Earth's Critical Zone through a range of their activities: large areas are sealed and/or reshaped to allow for urban and non-urban construction and land use changes affect major elements of soil functioning. Agricultural soil erosion may be defined as the accelerated removal of topsoil on land used for agricultural processes by water, tillage or wind is undoubtedly one of the major processes through which humans affect the Critical Zone. While agricultural activities may also lead to increased mass transport on steeplands when forests are removed, this process is usually not included when agricultural soil erosion is considered.

Here we intend to present an overview of the impact of agricultural soil erosion on the Earth's critical zone. We first review the problems associated with assessing rates of accelerated soil erosion due to human action. Then, we discuss the impact soil erosion may have on Critical Zone functioning and we conclude by exploring pathways for

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future research that should enable us to fully understand how agricultural soil erosion relates with other Critical Zone processes.

2. Rates of agricultural soil erosion

At the point scale, rates of soil loss may be simply defined as the amount of soil lost per unit of time. At large spatial scales, assessments is less straightforward. Tillage erosion, for instance, redistributes soil within a single field parcel: very significant soil losses on convexities and downslope of field boundaries are entirely compensated for by deposition in concacivites and upslope of field boundaries. Re-deposition of eroded soil and sediment is also very important in the case of water erosion: often, over 80% of the eroded sediment is re-deposited within a relatively small distance (< 5 km) of the source area, in colluvial or alluvial sediment stores[1]. While erosion rates on agricultural land may be similar to those observed in high mountain areas, agricultural landscapes operate in fundamentally different way. The response of tectonically active mountain areas is primarily driven by river incision: hillslope response primarily occurs through mass wasting directly or indirectly triggered by this incision and a very large fraction of the mobilized sediments rapidly reaches the river network. Agricultural soil erosion is triggered by vegetation and soil disturbance in upland areas: sediments may therefore take a very long time to reach the river network through a cascade of colluvial and alluvial stores leading to a long response time.

Large-scale assessments of soil erosion rates are often made without consideration of sediment re-deposition and storage: yet, this is only one reason why global agricultural soil erosion diverge widely (Table 1). All too often, erosion rates are directly extrapolated from measurements on bounded plots of limited dimensions: such a direct extrapolation almost inevitably leads to an overestimation of soil losses over large areas as erosion plots are generally located on relatively steep slopes in erosion-sensitive areas[2]. Another issue is how erosion scales with slope length: while scaling relationships are relatively well known and understood for arable land, they are not for other land uses with more permanent vegetation. Even when arable land is considered, an adequate calculation of the effective slope length is a prerequisite for a meaningful estimate of regional soil erosion rates. Finally, care has to be taken that soil properties are correctly accounted for: direct measurements of a soil's sensitivity to erosion may diverge by an order of magnitude from model estimates.

Table 1. Estimates of global soil erosion rates (adapted from [3] and [4])

Source	Total soil erosion rate ($Pg\ y^{-1}$)	Water erosion rates on agricultural land ($Pg\ y^{-1}$)
Oldeman et al., 1991[5]	50	
Myers, 1993[6]	75	50
Pimentel, 1995[7]		73.5
Stallard, 1998[8]		23.7-64.9
Lal, 2003[9]	201.1	
Yang et al., 2003[10]	132.7	81
Ito, 2007[11]	172.2	
Wilkinson and Mc Elroy, 2007[12]		28.1-39.9
Van Oost et al., 2007[13]		28.3
Doetterl et al., 2012[3]		17.4

Despite these limitations, significant progress has been made over recent years with respect to the estimation of soil losses by water and/or tillage erosion. Most current estimates set global topsoil losses due to water erosion (rill, interrill and ephemeral gully erosion) at *ca.* 20-30 Pg to which *ca.* 5 Pg of tillage erosion may be added (Table 1). Losses by wind erosion are much smaller (< 2 Pg, data not shown). These estimates should be considered as the total amount of soil lost from the eroding parts of agricultural landscapes: sediment delivery rates are, logically, significantly lower.

3. Implications of soil erosion for the Critical Zone

3.1. Biogeochemical cycles

The impact of lateral fluxes of soil and associated C has been an active field of research over the last decades. A consensus is now emerging that early estimates suggesting that soil erosion leads to the emission of significant amounts of C to the atmosphere (primarily due to the mineralization of eroded C) are not correct and that erosion leads, on the short term, probably to a (minor) sink of atmospheric C. In essence, this is due to the relatively rapid dynamic replacement of soil organic carbon (SOC) at eroding locations and the relatively slow decomposition of SOC buried by deposition[13]. Over longer time scales, the effect of erosion may be different and the legacy effect may be very important: if sediment burial rates are reduced, e.g. due to the implementation of effective soil conservation measures such as no-tillage or conservation tillage, the excess soil carbon store that has been built up by erosion over a millennial timescale may gradually be released to the atmosphere.

Evidently, the timescale at which this would happen is of crucial importance to assess the effects this might have on atmospheric $C0_2$ levels. Recent findings suggest that for agricultural soils in temperate areas, it may take 200-300 years before half of the SOC buried by erosion becomes mineralized (Figure 1)[14]. However, there are currently far too little data available to fully constrain the response of buried SOC reservoirs at the global scale and further research is necessary before reliable estimates on the response of buried SOC can be made.

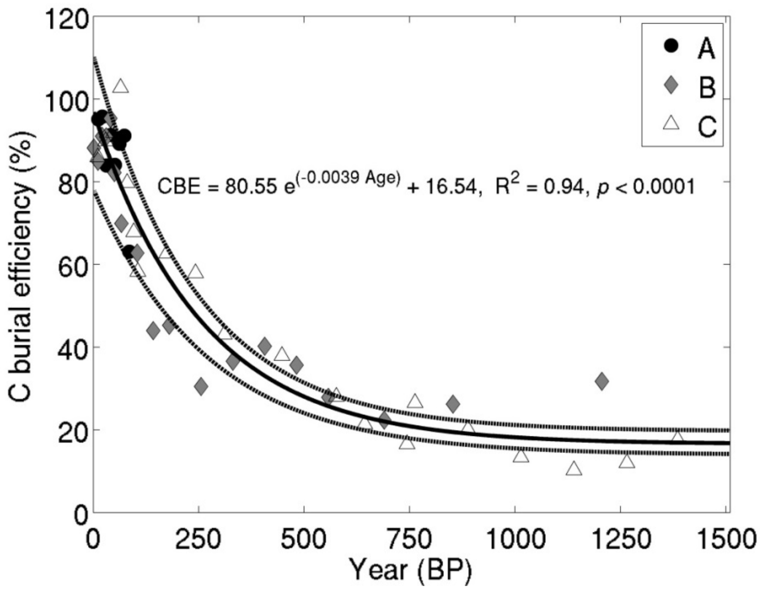

Fig. 1. Variation of C burial efficiency (CBE) with time for the three sites. The solid line is fitted to the medium scenario while the dotted lines show the effects of uncertainty on both original C content and deposition rate as calculated from a low (lower line) and high (upper line) scenario. From Wang et al [14]

As soil organic matter generally contains 5-10 % of N, erosion also affects the N cycle: the amounts of N redistributed by soil erosion are, on a global scale, similar to the amount of N supplied to soil through mineral fertilizers (i.e. *ca.* 100 Tg). In areas where nutrient inputs are low such as sub-Saharan Africa, N losses due to erosion strongly exceed the N supply through fertilization. The fate of the eroded N is strongly controlled by the fate of the SOC in which it is incorporated: the rate at which buried N will be released to the groundwater and/or the atmosphere will be controlled by the rate of soil organic matter decomposition.

Agricultural soil erosion also redistributes significant amounts of P. Soil organic matter holds variable amounts of P, making it more difficult to estimate the total amount of P that is redistributed by erosion. Current estimates suggest that, as for N, the order of magnitude is similar to the amount of P that is supplied to soils by mineral fertilization, i.e. *ca.* 20 Tg.

Recently, the role of vegetation and soils in the global Si cycle has been highlighted in several papers: soils contain a significant amount of highly soluble amorphous Si(ASi), consisting of both a biogenic (BSi) and a pedogenic (Psi) fraction. The amount of ASi that is directly delivered to aquatic ecosystems through agricultural erosion appears to be relatively limited in comparison to the amount of ASi that is released from the soil in dissolved form due to land use change. Forest soils usually contain a significant inventory relatively soluble BSi: this resource is no longer fully replenished under arable agriculture as a large fraction of the biomass is removed by harvesting. Furthermore, the conversion of a foest to arable land use may increase soil drainage. The combination of both mechanism can lead to the release of significant amounts of ASi from soils to aquatic environments[15].

3.2. Soil hydrology, geochemical processes and weathering

Water movement in soils is to a large extent controlled by soil depth: changing the latter by redistributing soil will therefore alter hydrological pathways. Realistic simulations show that, when realistic erosion rates are assumed, hillslope responses to erosional events in terms of runoff generation and sediment production may be fundamentally altered over millennial timescales, leading to a switch from sedimentation of hillslope-derived sediments in first-order drainage lines to net erosion.

Although the precise mechanisms are not always well understood, it is now well established that soil production rates depend on soil depth[16]. One may therefore hypothesize that, as soil depths are modified through agricultural erosion and redeposition, weathering processes and soil production rates may also be affected. Such changes, which are likely to happen over millennial time scales, may be confounded by other effects of human land use such as the effect of deforestation on soil acidity and the replenishment of soluble cations by mineral and organic fertilization. Available studies show that weathering rates under current land use and conditions may indeed be significantly different from long-term weathering. At present, we do have very little, if any, information on how large the impact of agricultural erosion on soil production and weathering may be.

3.3. Crop productivity

Crop production is most likely the most important ecosystem service that soils deliver to mankind and one would therefore expect that factors affecting the potential of a soil to grow a crop would have been studied in detail. However, the available information is noticeably sketchy. The most comprehensive studies until today conclude that crop productivity losses due to erosion are, on a short time scale, relatively small. Bakker et al.[17] concluded that, under intensive agriculture, such losses were, on average, ca. 4 % of total crop yield per 10 cm of soil lost for crops under intensive agriculture, which is a result similar to those obtained by Den Biggelaar et al[18]. Relative losses were higher under low-intensity agriculture in Africa an Asia, which may be related to fact that in such systems nutrients lost by erosion are not replenished.

Some areas such as the Mediterranean or parts of the Ethiopian highlands have been used for agriculture for millennia: here, the cumulative effect of such small losses may have greatly reduced, if not completely destroyed, the productivity of a significant fraction of the hilly cropland in these areas. We do have too little information at present to fully assess to what extent this has indeed happened: this does require the quantification of the amount of soil lost as well as a careful reconstruction of the crop production potential of these areas before significant amounts of soil were removed.

4. Conclusions

Agricultural soil erosion has altered the global soil resource in fundamental ways over large parts of the globe. Rates of agricultural soil erosion are now relatively well constrained although further refinement of our current estimates is still necessary. We also have gained important insights in the role of agricultural erosion in biogeochemical cycling, at least over relatively short time scales. While there is little doubt that agricultural soil erosion affects soil hydrology as well as soil chemical processes, we have, until present, far less information on the magnitude and direction of such changes. Our understanding of how such changes may affect the most important soil ecosystem service, i.e. agricultural production, is also quite limited:there is a need for more detailed studies on the effect of erosion on crop productivity, both in terms of losses on the cropland that is currently used and in terms of the amount of cropland area that is lost for production due to irreversible degradation. Addressing these questions will necessitate the combination of a wide range of approaches allowing to assess not only current soil functioning but also how such functioning has changed due to land use change and soil redistribution by erosion and deposition.

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