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SUPPLEMENTARY INFORMATION

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Countries and the global rate of soil erosion

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Supplementary Materials
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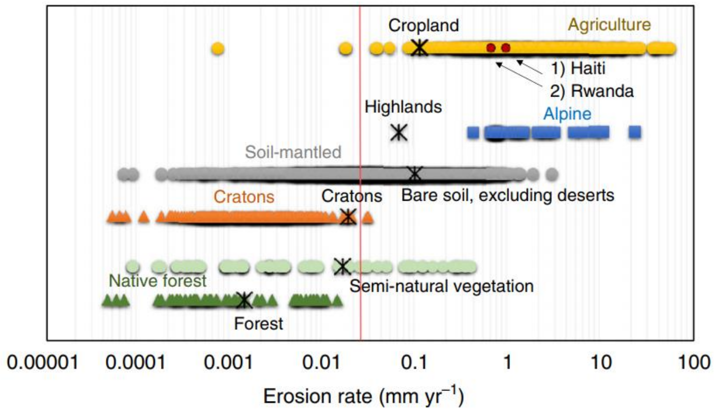
Content:

Supplementary Section 1

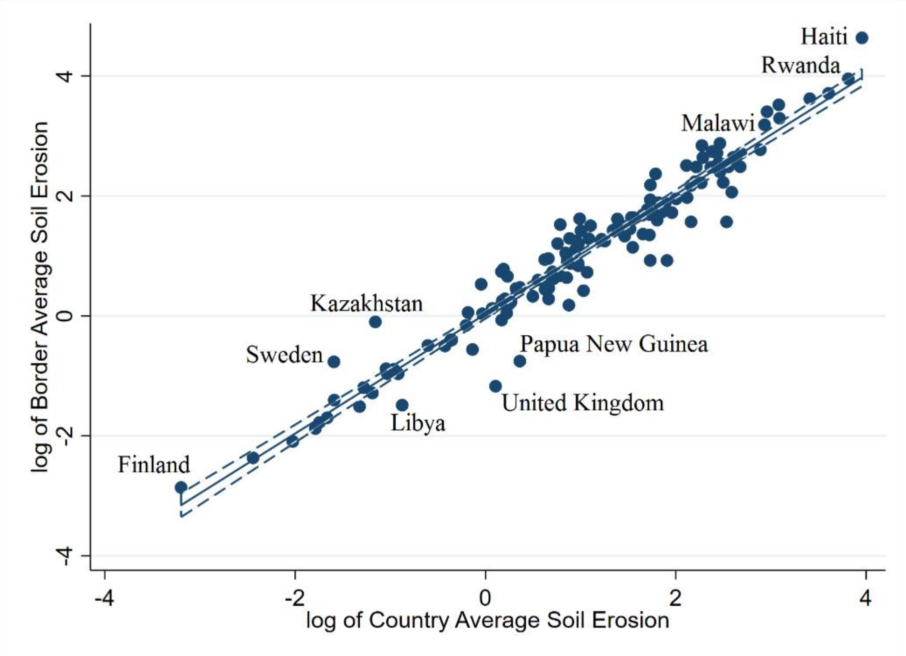
Among the extensive tests and cross-validation exercises of Borrelli, et al. [1] is a comparison of the RUSLE estimates with field measurements (**Fig. 6** in the original article). There is generally a high degree of consistency, but e.g. for highlands, model estimates are lower than what has been measured in the field. Erosion modelling in highlands tends to be more uncertain than elsewhere, but an alternative explanation for the deviation seen here is that there are only 44 field measurements available, and these are unlikely to be representative, as they are not randomly sampled (see supplementary materials of Borrelli, et al. [1]).



Supplementary Figure 1. A Comparison of measured and modelled erosion rates. The figure shows soil erosion rates measured on agricultural fields under conventional agriculture (n = 779), geologic erosion rates measured on alpine terrain (n= 44), soil-mantled landscapes (n = 1456), low gradient continental cratons (n = 218), grassland and scrublands (n = 63), native forests (n = 46) and averages of RUSLE predictions indicated by an asterisk. Reproduced from ref. 1

Supplementary Section 2

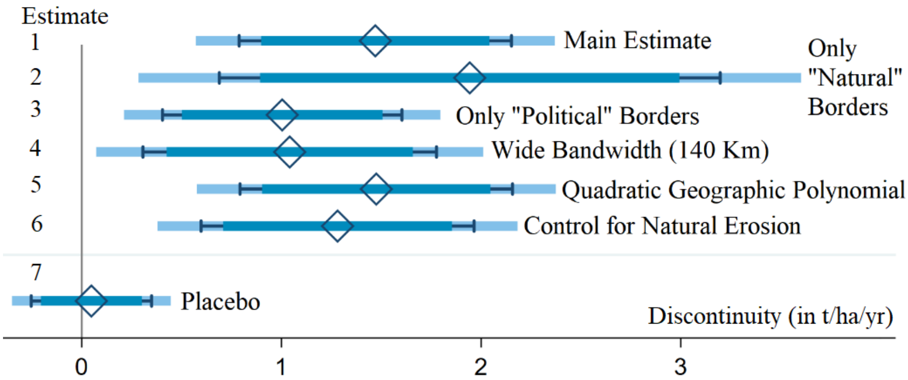
In the regression discontinuity design, we only use data-points that are within a rather narrow bandwidth around international borders. This reduces unobserved heterogeneity but motivates an investigation into how much the rate of soil erosion differs between areas close to international borders and areas further inland. **Supplementary Figure 2** shows that there is a strong correlation between countries' average soil erosion rate and their average soil erosion rate close to international borders. This suggests that we can interpret our findings as findings for countries, not just border areas.



Supplementary Figure 2. Comparing Border Areas to the Rest of the Country. The soil erosion rate in border areas is strongly correlated with country's overall average soil erosion rate. Thus, our analysis that focuses exclusively on border areas is plausibly representative for the countries at large.

Supplementary Section 3

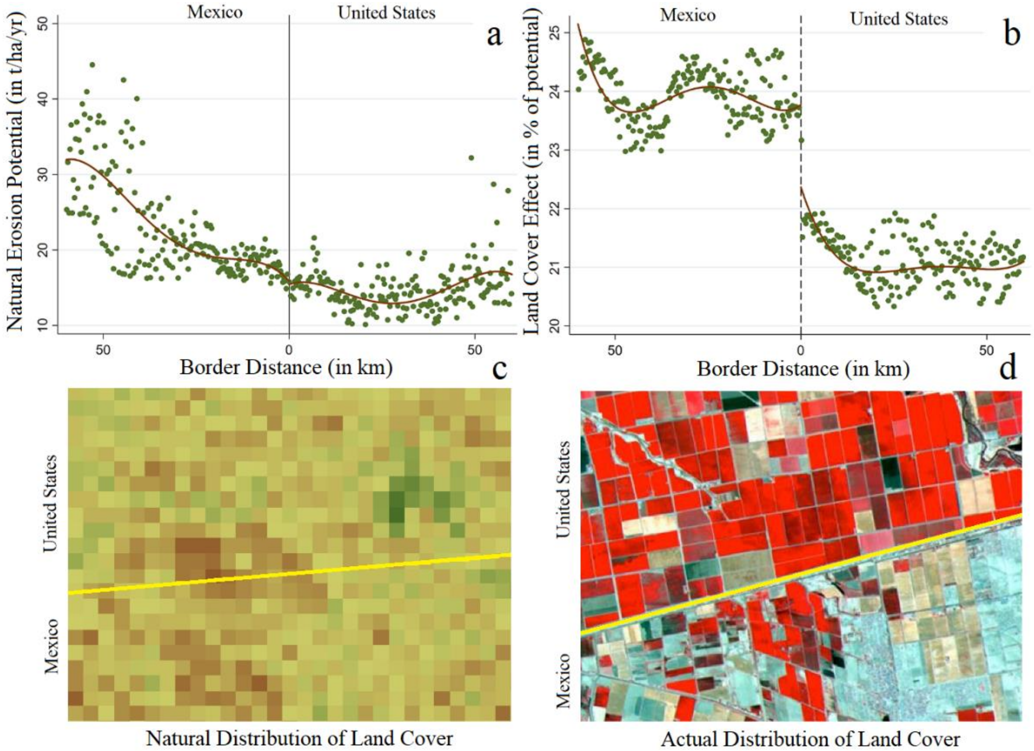
The coefficient plot of **Supplementary Figure 3** below graphs the estimated global border discontinuities in the rate of soil erosion. The estimates on all types of land vary between 1.1 and 1.9 tons per hectare and year. A placebo exercise shows that these discontinuities can only be found at really existing borders. Not shown for brevity, the estimate on cropland alone is slightly larger, at 1.8 tons per hectare and year.



Supplementary Figure 3. Estimating the Global Average Discontinuity. We sort countries according to their individually estimated discontinuities, to estimate a global average. We include border fixed effects and border distance on each side of the border. The bandwidth is 17 km, standard errors are clustered by border. The global average country effect is 1.4 t/ha/yr. To test the robustness of our estimate, we also estimated separate specifications for “natural” and “political” borders, widened the bandwith to 70 km border distance on each side, included a quadratic polynomial of longitude and latitude, controled for the natural erosion rate, and estimated a placebo estimation for non-existent borders that we placed 8 km parallel to the real borders. For the real borders, we consistently estimate a discotninuity between 1.1 and 1.9 t/ha/, whereas we estimate no discotninuity at the placebo borders.

Supplementary Section 4

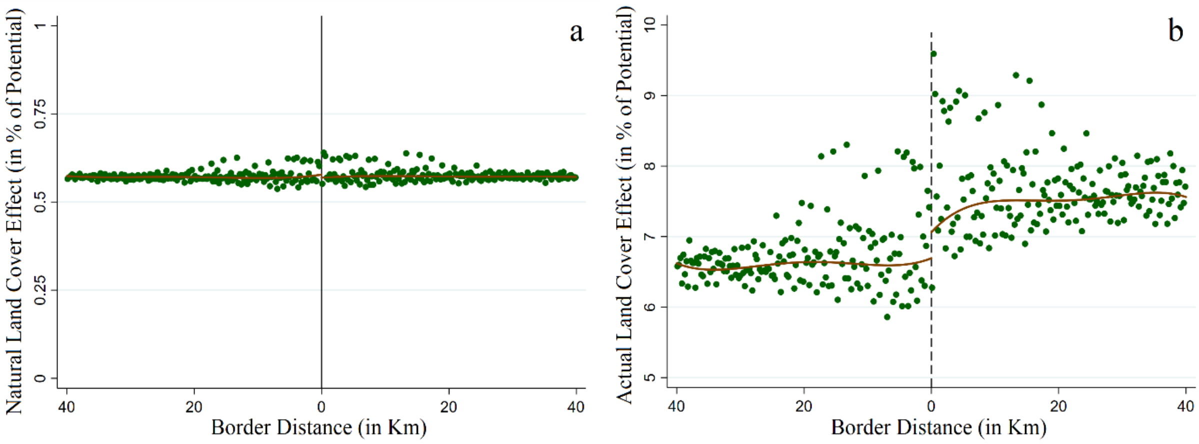
In addition to our first example in the main text where we show the soil erosion discontinuity between Haiti and the Dominican Republic (**Fig.1**), we like to present here a second example (**Supplementary Figure 4**), which illustrates an alternative way to estimate countries' impact on soil erosion. The example is the border between Mexico and the US and here, we exclusively focus on cropland. The maximum erosion potential[1] in the border area of Mexico and the United States changes continuously across the border (i.e. the rate of soil erosion that would occur without any soil cover, based on the effects of rainfall, soils, and topography)(**a**). In contrast, the share of the maximum erosion potential that is actually realized (in %)[1] shows a clear discontinuity right at the border (**b**). When we look at the hypothetical natural vegetation[2] in the area, there is no difference between the side of the US and the side of Mexico (**c**). However, this is currently largely irrelevant, because the area is now predominantly used for agriculture (on both sides). When we look at the area from space[3], we see that actual soil cover is quite dense on the side of the US (vegetation is colored red) and less so on the side of Mexico (**d**).



Supplementary Figure 4. The Border between Mexico and the United States. The border is purely political in the sense that there is no discontinuity in the natural soil erosion potential[1] (based on rainfall, topography and soil characteristics combined with no soil cover, which is the configuration that leads to the maximum soil erosion rate)(**a**). How much of this continuously distributed soil erosion potential actually occurs[1] changes discontinuously at the border (**b**). Importantly, this is not because naturally the vegetation potential[2] is distinct in the two countries (**c**). The reason is that the fields in the US are more intensively farmed, leading to a dense soil cover, whereas most fields on the Mexican side are less intensively farmed, leading to a barer soil cover[3] (**d**). Image credit: NASA/GSFC/METI/ERSDAC/JAROS, and U.S./Japan ASTER Science Team.

Supplementary Section 5

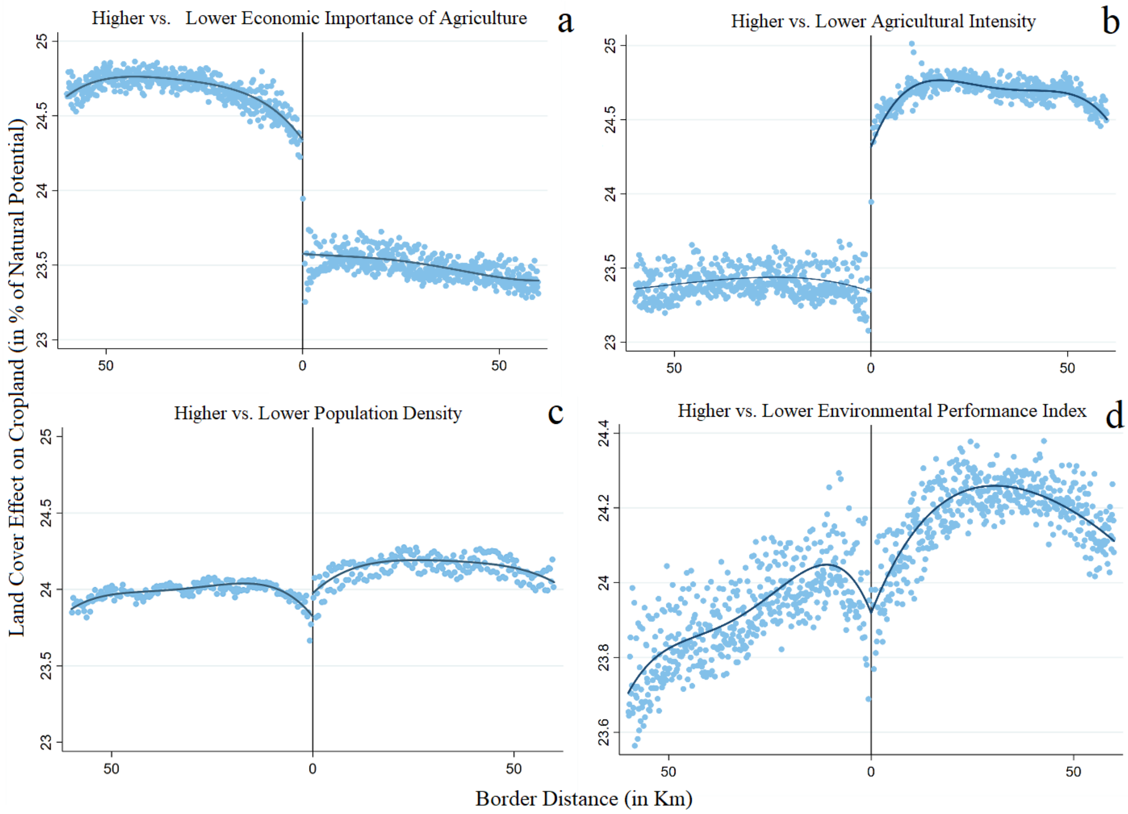
To visually illustrate the global magnitude of our estimated difference between the country effect and the natural rate of soil erosion, consider **Supplementary Figure 5**. Naturally, soil cover would mitigate almost all soil erosion (~99%), continuously distributed in space (**a**). In contrast, the actual soil cover mitigates significantly less soil erosion (~93-94%), and this differs discontinuously by country (**b**).



Supplementary Figure 5. Globally, The *Natural* Land Cover Effect on Soil Erosion is Continuously Distributed around International Borders but the *Actual* Land Cover Effect shows a Discontinuity. It is apparent that naturally, there is no difference in the natural land cover effect, which is large. Without human impact, countries would have erosion rates well below 1% of their natural potential, because an established vegetation would effectively protect the soil (**a**). In reality, however, there are important land-use differences between countries and this leads to large erosion differences (**b**).

Supplementary Section 6

An approach to test for mechanisms is to sort countries according to potential mechanisms. This can be graphically illustrated, as seen in **Supplementary Figure 6**. When we sort countries with a higher agricultural GDP share to the left and countries with a lower agricultural GDP share to the right, we see a clear border discontinuity (**a**). The magnitude of the discontinuity looks very similar when we sort countries with more intensive agriculture to the left and more extensive agriculture to the right (**b**). In contrast, both for population density (**c**), and for the environmental performance index (**d**), there is no obvious discontinuity at the border.



Supplementary Figure 6. Graphical illustrations for the Explanatory Power of Different Mechanisms. We find that between country differences in agriculture explain about 50% of the country impact on soil erosion, whereas many other candidate mechanisms seem to operate at other (often more local) levels. As an example, there is a clear discontinuity discernable when we sort countries that rely economically more on agriculture to the left, and countries that rely economically less on agriculture to the right (**a**). As another example, the graph looks very similar, but basically reversed when we sort countries that farm more intensively to the left and those that farm less intensively to the right (**b**). We do not see clear discontinuities when we sort countries e.g. by population density or environmental performance index (**c** and **d**, respectively).

Supplementary Section 7

This table lists our explanatory variables and their sources

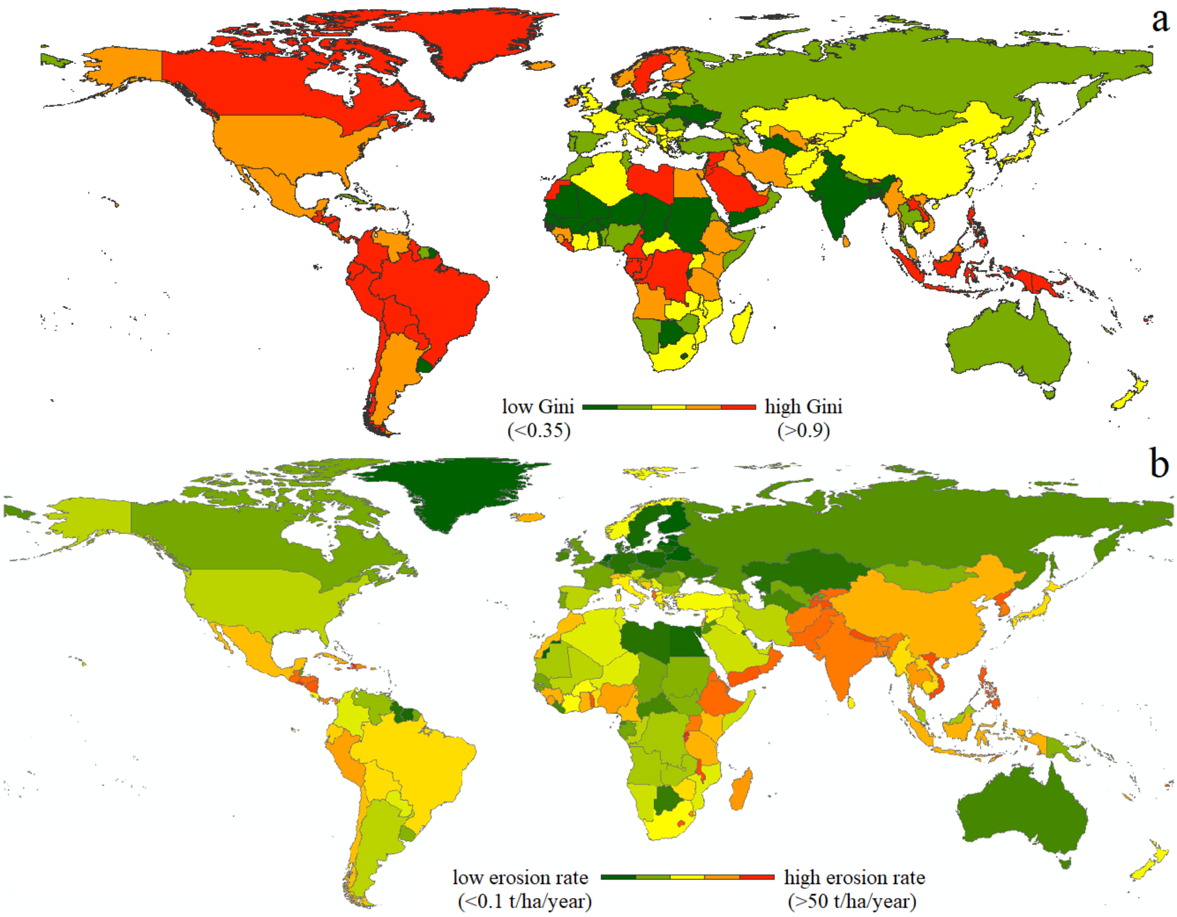
Supplementary Table 1. List of Potential Explanations for a Country Effect

Variable	Description	Source	Prior Results / Hypotheses
gdp	Gross domestic product per capita	data.worldbank.org	Mirzabaev, et al. [4] find no relationship with land degradation but Borrelli, et al. [1] observe a positive relationship with soil erosion.
education	Years of schooling	data.worldbank.org	Aldy, et al. [5] reports a positive relationship between education and environmental preferences
long-term orientation	Opposite to short term orientation. Societies with a long-term orientation value e.g. thrift and education.	worldvaluessurvey.org	Wuepper [6] reports a positive relationship between long-term orientation on soil erosion mitigation
savings rate	gross disposable income less final consumption expenditure	data.worldbank.org	Possibly an alternative indicator for a long-term orientation
ethnic fract	Probability that two randomly sampled individuals in a country are from different ethnicities	anderson.ucla.edu/faculty_pages/romain.wacziarg	Alesina, et al. [7] find a negative relationship between ethnic fractionalization and forest conservation
interpersonal trust	Percentage of the population that states others can generally be trusted	worldvaluessurvey.org	Dietz, et al. [8] emphasize the positive effect of inter-personal trust for the management of natural resources
institutions	World Governance Indicator, based on several hundred individual variables measuring perceptions of governance, such as control of corruption and political stability	info.worldbank.org/governance/wgi	Mirzabaev, et al. [4] find a positive relationship with land degradation, whereas Nkonya and Anderson [9] find a negative one.
government constraints	Strength of constraint on government powers	worldjusticeproject.org/our-work/research-and-data	Alternative measure for the role of institutions
state fragility	The fragility of a state is related to its government's capacity to manage conflict and implements its policies	systemicpeace.org/inscrdata	Alternative measure for the role of institutions
bayesian corruption index	Bayesian Corruption index, with a higher score reflecting that a country is perceived to be less affected by corruption	users.ugent.be/~sastanda/BCI/BCI.html	Alternative measure for the role of institutions
environmental performance index (epi) score	Multi-dimensional Environmental Performance Index. Indicators include environmental risk exposure, air quality and pollution, sanitation, drinking water quality, nitrogen balance and use efficiency, change in forest cover, species protection, trends in carbon intensity, and several others	epi.envirocenter.yale.edu	One would expect that countries with a better general environmental performance also cause less soil erosion, but there is no prior research on this

sustainable development goals index	Sustainable Development Goals Index. Can be interpreted roughly as progress of a country towards achieving the SDGs, in percentage	sdgindex.org	Similar to above
Stringency of Environmental Policies	Business learders' perception of environmental policy stringency	Browne, et al. [10]	Similar to above
Enforcement of Environmental Policies	Business learders' perception of environmental policy enforcement	Browne, et al. [10]	Similar to above
infrastructure	The quality of a country's roads	reports.weforum.org	For infrastructure and market access both positive and negative relationships with land degradation have been found, see literature discussions and own findings in Mirzabaev, et al. [4] and Nkonya and Anderson [9]
population density	Population per unit area	sedac.ciesin.columbia.edu/	Same as for infrastructure. See also Lambin, et al. [11]
agric intensity	Fertilizer use in kg per hectare	fao.org/faostat/en/#data	Positive relationship with land degradation in Sub-Africa and America and a negative one in Europe and Asia[9]
agric va	In percentage, value added in the agricultural sector	data.worldbank.org	Hypothesized to be associated with an erosion reduction because it increases the value of the soil
agric productivity gap	the difference in value added between the agricultural and the non-agricultural sector	Gollin, et al. [12]	Hypothesized to be associated with an increase in erosion because it indicates management issues and lack of resources
agric empl share	Percentage of the workforce of a country that works in agriculture	fao.org/faostat/en/#data	Relationship not clear. Possibly associated with more soil erosion if mostly indicator for low agricultural productivity
forest harvest	Amount of wood harvested in m^3	fao.org/faostat/en/#data	Hypothesized to be associated with an increase in soil erosion because it reduces soil cover

Supplementary Section 8

To understand the global distribution of soil erosion within and between countries, we conduct analyses of variance (ANOVA) and compute Gini indices[13], the latter using the program of Zeileis and Kleiber [14]. In the analyses of variance, we investigate the soil cover effect and the overall soil erosion, and only include country fixed effects as explanation. We estimate that countries explain ~28% of the global variance in land cover related soil erosion (the C-factor) and ~7% of overall soil erosion (in t/ha/yr). On croplands, these numbers are considerably higher, because the human influence is more direct. Turning to our measures of soil erosion inequality, we use Gini indices, which are commonly used to measure income inequality[13] but can just as well be used to understand the distribution of soil erosion. The Gini index ranges from zero (most equal distribution) to one (most unequal distribution). Part **a** of **Supplementary Figure 7** shows the erosion Gini per country. The average is 0.7. part **b** shows the average erosion rate per country. When computing the erosion Gini based on the country averages, it is 0.6. Thus, the distribution of soil erosion follows globally a roughly similar pattern as the distribution within countries.



Supplementary Figure 7. Distribution of Soil Erosion *Within* and *Between* Countries. Part **a** shows the Gini index for the soil erosion distribution within countries. The index goes from zero (most equal distribution) to one (most unequal distribution). Within countries, the Gini has a mean of 0.7. part **b** of shows countries' average rate of soil erosion. Between countries the Gini has a mean of 0.6. This suggests that the distribution of soil erosion is similar within and between countries, with a little bit more inequality within than between countries.

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