

The long-term effects of soil erosion: a global economic analysis

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Abstract

This study employs an interdisciplinary approach to assess the long-term structural economic and non-economic impacts of soil erosion at the global scale. Country-level estimates of soil erosion at the year 2070 are then converted into land productivity losses, to feed the Modular Applied GeNeral Equilibrium Tool (the MAGNET global CGE model) (Woltjer and Kuiper, 2014), recently enriched with several non-market indicators (land usage, GHG emissions, water abstraction, SDGs). Future rates of global soil erosion (Borrelli et al. 2020) are predicted by the high spatial resolution Revised Universal Soil Loss Equation (RUSLE)-based semi-empirical modelling approach under three alternative combinations of Shared Socioeconomic Pathway and Representative Concentration Pathway (SSP-RCP) scenarios (i.e., SSP1-RCP2.6, SSP2-RCP4.5, and SSP5-RCP8.5).

For each single region considered, the study will show the impact of future soil erosion on national income, agricultural markets, international food prices and food security, as well as land and water use change, and the most relevant SDG indicators.

Keywords: soil erosion, land productivity loss, computable general equilibrium, model integration, global economy, agriculture, virtual land flows.

JEL codes: C68, Q24, Q10.

1. Introduction

The biophysical effects of land degradation processes are well-recognized (e.g., Borrelli et al., 2017; Lugato et al., 2018; Poesen, 2018). For example, soil erosion by water causes the loss of topsoil and nutrients, reduces soil fertility and releases carbon dioxide, exacerbating global warming (Telles et al., 2011; Zhao et al., 2013). On the contrary, its indirect socio-economic consequences are much less investigated, though significant (Panagos et al., 2018). Less soil fertility reduces land productivity and crop yields, affecting agricultural production, food security, international agri-food markets and the whole global economy. Sartori et al. (2019) estimate that the annual global cost of soil erosion by water at 33.7 million tonnes of agricultural and food losses, equivalent to a global loss of eight billion US\$. International agri-food prices rise by 0.4%–3.5%, depending on the food product category. Indirect environmental effects are also relevant. The same study shown that abstracted water volumes are driven upwards by an estimated 48 billion cubic meters yearly. Even under the (strong) assumption of existing compounded rates of soil erosion over time, coupled with projected rising rates of population, the future implications for food security, natural resource management practises (i.e., land, water) and stable societies, particularly in the poorest parts of the world, are worrying.

Pioneer in the literature, this study employs an interdisciplinary approach to assess the long-term structural economic and non-economic impacts of soil erosion at the global scale. Country-level estimates of future soil erosion by water are estimated by Borrelli et al. (2020), who employ a high spatial resolution Revised Universal Soil Loss Equation (RUSLE)-based semi-empirical modelling approach. They predict future rates of global soil erosion at the year 2070, under three alternative combinations of Shared Socioeconomic Pathway and Representative Concentration Pathway (SSP-RCP) scenarios (i.e., SSP1-RCP2.6, SSP2-RCP4.5, and SSP5-RCP8.5). Soil erosion rates are then converted into land productivity losses, to feed the Modular Applied GeNeral Equilibrium Tool (the MAGNET global CGE model) (Woltjer and Kuiper, 2014), well-known for its improved treatment of agricultural factor markets and the provision of several non-market indicators in the model output (in particular, land usage, GHG emissions, water abstraction, SDGs). The counterfactual thus captures the resulting marginal market (and non-market) impacts in agricultural (and non-agricultural) activities, which arise in each region due to land productivity losses caused by future soil erosion, under different scenarios of GHG emissions and socio-economic development.

For each single region considered, the study will show the impact of future soil erosion on national income, agricultural markets, international food prices and food security, as well as land and water use change, and the most relevant SDG indicators. We expect a high variability between scenarios, as socio-economic developments affecting land use may either dampen (SSP1-RCP2.6) or strengthen (SSP2-RCP8.5) soil erosion by 2070 (Borrelli et al., 2020). Less increase in erosion is foreseen for high-income countries, generally located at temperate latitudes, whilst

low- and middle-income tropical and subtropical countries will be the most susceptible regions to high increase of erosion. This will translate into highly variable land productivity changes (likely positive for some countries) across regions and will accelerate the competitive shifts in comparative advantage on world agri-food markets.

2. The policy context

Refer to e.g. Montanarella and Panagos (2021)

3. Estimating future global soil erosion rates and land productivity losses

Long-term annual soil erosion rates are obtained from Borrelli et al. (2020), who use a combination of remote sensing, spatial analysis techniques and statistical data in the framework of the Revised Universal Soil Loss Equation (RUSLE) model. The model provides erosion rates at a $\sim 250 \times 250$ m cell bases for the land surface of 202 countries (around 2.89 billion cells; ~ 125 million km²), covering about 84.1% of the Earth's land area. The soil erosion (Mg ha⁻¹ yr⁻¹) resulting from interrill and rill erosion (Figure 1) processes is based on the following multiplicative equation:

$$A_g = R_g * K_g * LS_g * C_g * P_g \quad [\text{Eq. 1}]$$

where: A_g [Mg ha⁻¹ yr⁻¹] is the annual average soil loss, R_g [MJ mm h⁻¹ ha⁻¹ yr⁻¹] is the rainfall-runoff erosivity factor, K_g [Mg h MJ⁻¹ mm⁻¹] is the soil erodibility factor, LS_g [dimensionless] is the joined slope length and slope steepness factor, C_g [dimensionless] is the land cover and management factor, P_g [dimensionless] is the soil conservation or prevention practices factor.

According to equation 1, RUSLE consists of a multiplicative equation including five environmental parameters. The global rainfall erosivity factor (R_g) is computed according to Renard et al. (1997), using a combination of sub-hourly and hourly pluviometry data of 3,625 meteorological stations (collected across 63 nations) interpolated using the Gaussian Process Regression (GPR) (Panagos et al., 2017). The global soil erodibility factor K_g is measured based on the equation proposed by Wischmeier and Smith (1978) which relies on some intrinsic soil properties (e.g. texture, organic matter, structure and permeability) currently available at the ISRIC SoilGrids database at 1 km spatial resolution (Hengl et al., 2014). The topographic parameters, slope and upslope contributing area, needed to compute the LS_g factor are derived from the hole-filled SRTM 3 arc-seconds (ca. 90m) Digital Elevation Model (Reuter et al., 2007) for the land surface between 60° North

and 56° South and ASTER GDEM v2 data products for the extreme North latitudes (Robinson et al., 2014). The global land cover and management factor C_g is computed for the year 2001 and 2012, taking into consideration the individual land cover type, vegetation cover dynamics and farming systems of each cell. Two different approaches are undertaken to estimate the C_g factor values for agricultural and non-agricultural land. For agricultural land, data of 170 different crops (averaged over a period of twelve years) obtained from the FAOSTAT database (<http://www.fao.org/faostat/en/#data>) of the Food and Agriculture Organization's (FAO) are used (more detail in Borrelli et al., 2017). To assess the final modelling factor, i.e., P_g , the information about the proportion of cropland area under conservation agriculture provided by the countries to FAO are used. To evaluate whether the model outcomes comply with the regional findings of former studies, the global soil erosion maps of 2001 and 2012 are compared with a set of representative and highly advanced regional soil erosion assessments.

The study focuses on 14 million km², which is considered to be the global arable land area where crops are cultivated. This area corresponds to approximately 11% of the total modelled area of 125 million Km², which coincides with the statistics provided by the World Bank and FAO .

It should be recognised that the crop productivity loss due to erosion includes high uncertainty and depends on many factors such as erosion rate, crop type, crop yields, seasonality, etc. To estimate the associated land productivity losses by region (LPL_r) arising from soil erosion, this study follows the same approach as Panagos et al. (2018):

$$LPL_r = \frac{SEA_r}{TAA_r} * 0.08 \quad [Eq. 2]$$

Where SEAr is the area of severe erosion per region/country 'r' in hectares and TAAr is the agricultural area in each region/country 'r'. This study assumes a mean crop productivity loss of 8% in arable lands threatened by severe erosion (> 11 t ha⁻¹ yr⁻¹). This assumption is based on a thorough literature review (see Panagos et al., 2018 and Table S1 of the Supplementary material) taking into account experimental results on crop losses in cases of severe erosion in different areas all over the world (Panagos et al., 2018).

Land productivity losses by GTAP10 region and by scenario are reported in Table 1.

Table 1. Land productivity losses (% changes) at the year 2070 due to soil erosion by scenario. RUSLE model output.

	Land Productivity Loss		
	RCP 26	RCP 45	RCP 85
Albania	5.7	5.5	6.0
Argentina	0.3	0.5	0.5
Armenia	2.6	2.5	2.7
Australia	0.2	0.1	0.3
Austria	0.4	0.3	0.5
Azerbaijan	1.1	1.1	1.1
Bahrain	0.0	0.0	0.0
Bangladesh	3.7	3.8	4.4
Belarus	0.0	0.0	0.0
Belgium	0.0	0.0	0.0
Benin	5.0	5.2	5.3
Bolivia (Plurinational State of)	3.9	4.6	4.2
Botswana	0.2	0.1	0.1
Brazil	6.2	6.2	6.3
Brunei Darussalam	7.2	7.3	7.3
Bulgaria	0.9	0.8	1.1
Burkina Faso	2.3	1.3	2.6
Cambodia	4.6	4.7	4.4
Cameroon	4.7	5.1	6.3
Canada	0.0	0.0	0.0
Caribbean	6.0	5.3	5.3
Chile	2.0	2.1	1.9
China	2.5	3.0	3.2
Colombia	6.0	6.2	6.3
Costa Rica	5.7	5.6	5.6
Cote d'Ivoire	6.7	6.7	6.7
Croatia	0.7	0.7	0.8
Cyprus	0.3	0.3	0.2
Czech Republic	0.0	0.1	0.1
Denmark	0.0	0.0	0.0
Dominican Republic	3.9	4.4	4.1
Ecuador	4.6	4.8	5.2
Egypt	0.0	0.0	0.0
El Salvador	7.8	7.8	7.7
Estonia	0.0	0.0	0.0
Ethiopia	5.8	4.5	5.6
Finland	0.0	0.0	0.0
France	0.2	0.3	0.3
Georgia	2.0	2.7	2.3
Germany	0.0	0.0	0.1
Ghana	6.4	6.5	6.6
Greece	1.8	1.9	2.0

Guatemala	7.7	7.7	7.7
Guinea	5.5	5.5	5.5
Honduras	6.7	6.6	6.6
Hungary	0.0	0.1	0.1
India	2.2	2.5	2.8
Indonesia	6.7	6.6	6.6
Iran (Islamic Republic of)	1.5	1.2	1.2
Ireland	0.4	0.8	1.0
Israel	0.3	0.1	0.1
Italy	2.0	2.1	2.1
Jamaica	3.4	5.0	4.9
Japan	3.1	3.7	4.3
Jordan	1.6	0.7	0.5
Kazakhstan	0.1	0.1	0.1
Kenya	5.1	3.1	4.8
Kuwait	0.0	0.0	0.0
Kyrgyzstan	2.2	2.5	2.6
Lao People's Democratic Republic	6.8	6.8	6.6
Latvia	0.0	0.0	0.0
Lithuania	0.0	0.0	0.0
Luxembourg	0.1	0.2	0.4
Madagascar	4.8	4.9	5.0
Malawi	5.4	5.5	5.7
Malaysia	5.3	5.4	5.4
Malta	1.2	0.7	0.9
Mauritius	7.5	7.5	7.4
Mexico	3.3	3.6	3.7
Mongolia	1.1	0.4	1.5
Morocco	2.0	1.7	0.7
Mozambique	3.7	3.6	3.6
Namibia	1.0	0.7	0.4
Nepal	5.6	5.5	5.7
Netherlands	0.0	0.0	0.0
New Zealand	1.6	1.3	1.7
Nicaragua	7.9	7.8	7.8
Nigeria	3.9	4.1	4.5
Norway	2.2	3.4	2.5
Oman	0.9	0.7	1.0
Pakistan	1.4	1.6	1.5
Panama	7.0	7.2	7.1
Paraguay	4.7	4.9	5.5
Peru	5.8	5.8	6.0
Philippines	6.9	7.0	7.0
Poland	0.0	0.0	0.0
Portugal	0.5	0.5	0.6
Puerto Rico	5.8	3.1	5.1
Republic of Korea	5.2	5.7	5.7

Rest of Central America	6.1	5.7	3.4
Rest of East Asia	6.3	6.4	6.7
Rest of Eastern Africa	0.8	0.9	0.8
Rest of Eastern Europe	0.7	1.1	1.4
Rest of EFTA	1.7	1.5	1.7
Rest of Europe	2.3	2.6	2.7
Rest of Former Soviet Union	0.1	0.2	0.1
Rest of North Africa	1.0	1.2	0.6
Rest of Oceania	7.1	6.0	7.0
Rest of South African Customs Union	6.9	7.2	7.2
Rest of South America	1.3	2.3	1.5
Rest of South Asia	1.6	2.2	2.4
Rest of South Central Africa	5.6	5.5	5.7
Rest of Southeast Asia	5.2	5.5	6.2
Rest of Western Africa	1.3	1.2	1.7
Rest of Western Asia	1.4	1.3	1.4
Romania	0.4	0.6	0.8
Russian Federation	0.1	0.1	0.1
Rwanda	6.9	6.9	6.7
Saudi Arabia	2.4	2.2	2.1
Senegal	0.3	0.2	0.3
Singapore	7.1	7.1	7.1
Slovakia	0.1	0.1	0.2
Slovenia	2.0	1.7	2.1
South Africa	3.0	3.5	3.6
Spain	0.7	0.8	0.7
Sri Lanka	5.1	4.1	4.1
Sweden	0.0	0.0	0.0
Switzerland	1.3	1.3	1.4
Tajikistan	2.9	3.2	2.8
Thailand	4.7	5.1	4.8
Togo	6.6	6.7	6.9
Trinidad and Tobago	2.3	4.0	2.4
Tunisia	1.0	0.8	0.1
Turkey	1.4	1.4	1.7
Uganda	5.2	5.4	5.7
Ukraine	0.0	0.1	0.1
United Arab Emirates	0.1	0.3	0.3
United Kingdom	0.1	0.1	0.1
United Republic of Tanzania	3.4	3.7	3.5
United States	2.2	2.6	2.9
Uruguay	1.5	1.7	2.1
Venezuela (Bolivarian Republic of)	4.9	4.7	5.3
Viet Nam	7.0	7.1	7.0
Zambia	3.3	3.3	3.1
Zimbabwe	4.2	3.7	3.0

4. Measuring the economic consequences of soil erosion

The soil erosion rates estimated by RUSLE are long-term averages based on time-invariant environmental and topographic parameters, and crop management and land cover change, which change at a very slow pace over time. In the CGE model, the resulting equivalent regional land productivity change is typically modelled as an exogenous technical change parameter in the land demand function, detailing the ratio of output per unit of land input.

To assess these marginal impacts, an exogenous shock is applied to the land productivity parameters. The difference between this counterfactual and the benchmark data gives us a marginal estimate of the resulting market impacts.

Results will be presented aggregated for 19 macro-regions, detailed in Table 2.

Table 2. Regional aggregation.

Macro-Regions	MAGNET regions
Oceania	Australia, New Zealand, Rest of Oceania
China	China, Hong Kong, Taiwan
Indonesia	Indonesia
India	India
South East Asia	Japan, Republic of Korea, Mongolia, Cambodia, Laos, Malaysia, Philippines, Thailand, Vietnam, Bangladesh, Nepal, Sri Lanka, Pakistan, Rest of East Asia, Rest of South-East Asia, Rest of South Asia
USA&Canada	USA, Canada, Rest of North America
Brazil	Brazil
South America	Argentina, Bolivia, Chile, Colombia, Ecuador, Paraguay, Perú, Uruguay, Venezuela, Rest of South America
Central Amer. and the Caribbean (CAmer&Caribb)	Costa Rica, Dominican Republic, El Salvador, Guatemala, Honduras, Jamaica, Mexico, Nicaragua, Panama, Puerto Rico, Trinidad and Tobago, Caribbean, Rest of Central America,
EU 27	Austria, Belgium, Bulgaria, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Netherlands, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden,
Rest of Europe	UK, Switzerland, Norway, Albania, Belarus, Ukraine, Rest of EFTA, Rest of Eastern Europe, Rest of Europe
Russia	Russian Federation
Central Asia	Armenia, Azerbaijan, Georgia, Kazakhstan, Kyrgyzstan, Tajikistan, Rest of Former Soviet Union
Iran	Iran
West Asia	Bahrain, Iran, Israel, Jordan, Kuwait, Oman, Qatar, Saudi Arabia, UAE, Turkey
North Africa	Egypt, Morocco, Tunisia, Rest of North-Africa
West Africa	Benin, Burkina-Faso, Cameroon, Cote d'Ivoire, Ghana, Guinea, Nigeria, Senegal, Togo, Rest of Western Africa, Rest of South-Central Africa,

East Africa	Ethiopia, Kenya, Madagascar, Rwanda, Tanzania, Uganda, Rest of Eastern Africa
Central South Africa	Central Africa, South Central Africa, Malawi, Mozambique, Zambia, Zimbabwe, Botswana, Namibia, South Africa, Rest of South African Custom Union, Rest of the World

The sector aggregation in MAGNET includes all GTAP agricultural cropping activities, both rainfed and irrigated (i.e., rice, wheat, other cereals, horticulture, oilseeds, raw sugar, plant-based fibres and other crops) and non-arable and food processing activities.

5. Results

6. Policy implications and concluding remarks

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