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Analysis

Remaining Loyal to Our Soil: A Prospective Integrated Assessment of Soil Erosion on Global Food Security

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ABSTRACT

Soil loss by water erosion represents a key threat to land degradation worldwide. This study employs an integrated quantitative modelling approach to estimate its long-term global sustainability impacts. The global biophysical model estimates a mean increase of soil erosion rates of between 30 and 66% over the period 2015–2070 under alternative climate-economic scenarios, assuming different greenhouse gas concentration trajectories. In a subsequent step, projected soil erosion rates are converted into land productivity losses and inputted into an economic global simulation model to identify those regional hotspots where the greatest market tensions are expected to occur.

The headline result is that of a global economic contraction of up to 625 billion US$ by the year 2070. Moreover, soil erosion represents an acute challenge to food security in vulnerable regions (Africa and some tropical regions), where for certain crops (particularly oilseeds) the threat of shortages is potentially significant. Under the worst-case scenario, global primary agricultural production losses could amount to 352 million tonnes by 2070. Exploring different long-term socioeconomic-environmental pathways confirms the merits of sustainable management practises in coping with market and environmental stresses arising from soil erosion that limits the global increase of land used for food consumption to 115,000 km^2 above the long run baseline. Finally, free (and fair) trade is essential to allow less affected regions to expand (marginally) their production, thereby cushioning the market tensions that are expected to occur in more acutely affected areas of the world.

1. Introduction

The biophysical effects of land degradation processes are well-recognized (e.g., Borrelli et al., 2017; Poesen, 2018). For example, soil erosion by water causes the loss of topsoil and nutrients (Quinton et al., 2010; Alewell et al., 2020), reduces soil fertility (Ma et al., 2019; Qiu et al., 2021) and releases carbon dioxide (Lugato et al., 2018; Chappell et al., 2016), exacerbating global warming (Telles et al., 2011; Zhao et al., 2013). Less soil fertility, in turn, reduces land productivity and crop yields, affecting agricultural production, food security, international agri-food markets and the global economy.

Perhaps surprisingly, empirical evidence on the economic impacts of soil erosion is scarce, although all known studies paint a similar picture. Employing an economy-wide application to the European Union, Panagos et al. (2018) examined the socio-economic consequences of soil erosion by water. In their bio-physical model, the authors estimate an annual cost of crop productivity loss of € 1.25 billion. The cropland productivity reductions lead to an agricultural production loss of € 300 million and a resulting fall in real GDP of € 155 million in the macroeconomic model. In their study of soil erosion impacts at the global

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level, Sartori et al. (2019) follow a similar approach. They report an *annual* loss of eight billion US$ to the global economy, corresponding to 33.7 million tonnes of agricultural and food losses. The authors also show that international agri-food prices rise by between 0.4%–3.5%, depending on the food product category, with particular concerns highlighted for food security and affordability in the poorest parts of the world. A further economy-wide modelling study for Burkina Faso (Sawadogo, 2021) shows limited macroeconomic impacts but sizeable effects on food security of soil erosion, whilst a micro-econometric analysis for Malawi reveals significant reductions in production and GDP due to topsoil loss, disproportionately affecting least-productive households (Asfaw et al., 2020).

The above cited studies largely focus on specific regions, whilst a longer-term prospective analysis on the global market impacts of soil erosion remains conspicuously absent. Following the same interdisciplinary approach of Sartori et al. (2019), this study aims to fill that gap. Country-level long-term estimates of future soil erosion by water are taken from Borrelli et al. (2020), who employ a high spatial resolution Revised Universal Soil Loss Equation (RUSLE)-based semi-empirical modelling approach (GloSEM). They estimate future rates of global soil erosion by the year 2070, under alternative combinations of Shared Socioeconomic Pathway (SSP) and Representative Concentration Pathway (RCP) scenarios. Soil erosion rates are then converted into land productivity losses and inserted into a state-of-the-art computable general equilibrium (CGE) model called the Modular Applied GeNeral Equilibrium Tool (MAGNET) (Woltjer and Kuiper, 2014). The counterfactual thus captures the resulting marginal 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.

A further advance on Sartori et al. (2019) is that the current study also explores alternate pathways of climate-economic uncertainty (coherent combinations of Shared Socioeconomic Pathways (SSPs) and Representative Concentration Pathways (RCPs)) in a bid to assess the resilience of the world economy to soil erosion under different prospective futures. Furthermore, in addition to the typical market indicators reported in Sartori et al. (2019), the paper also presents relevant sustainability indicators, such as land demand, water and land footprints, along with a discussion on the implications for the EU soil strategy (EC, 2021).

The rest of this paper is structured as follows. Section 2 explains how future soil erosion rates and land productivity losses are obtained and describes the climate-economic scenarios used to estimate soil erosion rates. Section 3 explains how the economic impact of soil erosion is measured and how the scenarios considered in this study are designed, whilst the economic results and other indicators are presented in Section 4. Section 5 discusses the results in the context of ongoing global policy developments, and a final section presents some of the caveats and adds some concluding remarks.

2. Future Global Soil Erosion Rates and Land Productivity Losses

2.1. The Global Soil Erosion Platform and the RUSLE Model

The Global Soil Erosion Modelling (GloSEM) platform hosted in the European Soil Observatory has been updated to estimate future erosion scenarios that integrate both climate change and land use change scenarios (Borrelli et al., 2022). The Revised Universal Soil Loss Equation (RUSLE) model is used to quantitatively estimate long-term soil erosion rates combining inputs for rainfall intensification (Erosivity), soil resistance (Erodibility), cropping systems and land cover (Cover-Management), topographic conformation (slope length and slope steepness) of the fields and soil conservation practices (management) (Renard et al., 1997). The pedological and topographic conditions are assumed as stable through time; therefore, the soil erodibility factor and the topographic factor remain unchanged in future projections (Panagos et al., 2021). The other three factor inputs (i.e. climate, land cover and management) are mainly driven by anthropogenic activities and their possible change in both time and space are modelled. Compared to the Global Soil erosion baseline assessment (Borrelli et al., 2017), projections include the changes in rainfall erosivity, land use change and soil conservation.[1] A Full description of GloSEM, including the factors and the equations per factor are described in detail in Borrelli et al. (2022).

The RUSLE model is preferred to other process-based modelling options as the latter require inputs that are not currently available either at global scale or in future projections. To estimate the future global soil erosion for the period 2060–2080 (reference year: 2070), future projections of land use are obtained from the integrated model assessment of Global Land Use/cover and Future Change (Hurtt et al., 2020) and the 2070 rainfall erosivity projections for three scenarios based on 19 IPCC climatic models (Panagos et al., 2022). The combination of land use and climate change shows a potential substantial increase in average soil erosion totalling +30% (RCP2.6), +51% (RCP4.5), and + 66% (RCP8.5) (Borrelli et al., 2020). The wider confidence intervals are related to the variability of future climate projections of the 19 IPCC General Circulation Models. The GloSEM modelling simulations suggest that climate change is the major driver of the change in soil erosion compared to land use change. The dominant effect of climate change in future soil erosion projections has been confirmed also in the Mediterranean (Morán-Ordóñez et al., 2020), Northern Europe (Marcinkowski et al., 2022), China (Wang and Wang, 2019), Sri Lanka (De Silva et al., 2023), Africa (de Hipt et al., 2018) and South America (Riquetti et al., 2023). Regarding land use change, the substantial increases in agricultural areas (and deforestation) in Sub-Saharan Africa, Brazil, India, Myanmar, and some districts of China have the major effect. The outputs are presented at high spatial resolution (ca. 250x250m cell size at the equator).

2.2. Climate-Economic Scenarios in the RUSLE Model

The estimates of soil erosion rates computed by Borrelli et al. (2020) are available for some combinations of SSP and RCP scenarios. The SSPs include a narrative, which describes plausible alternative changes in aspects of society such as demographic, economic, technological, social, governance and environmental factors (Kriegler et al., 2012; Samir and Lutz, 2017; O'Neill et al., 2017). The RCPs describe possible greenhouse gas concentration trajectories, consistent with certain socio-economic assumptions, which determine the concentration of GHG emissions in the atmosphere (van Vuuren et al., 2011). In this study, we use the soil erosion rates estimated under three alternative RCP-SSP combinations, placed along a hypothetical GHG concentration/mitigation challenge line (Fig. 1). A stringent GHG concentration pathway and lesser socio-economic mitigation challenges characterise scenario RCP2.6-SSP1, termed "Sustainability". As a polar opposite, RCP8.5-SSP5 or "Fossil-fuelled development" is referred to as the worst-case climate change scenario, with a very high level of GHG emissions and strong fossil fuel-driven socio-economic development. Finally, a "Middle of the road" (RCP4.5-SSP2) scenario is characterised by social, economic and technological trends that do not significantly shift from historical patterns.

2.3. Estimating Land Productivity Losses

The loss of soil due to water erosion will decrease arable land productivity (Pacheco et al., 2018) as erosion removes organic matter and important nutrients necessary to sustain healthy crops. Soil erosion alters the biological, physical and chemical characteristics of soil leading to a drop of agricultural productivity (Lal, 2015).

[1] The reader may refer to Sartori et al. (2019) for a detailed description of the RUSLE model.

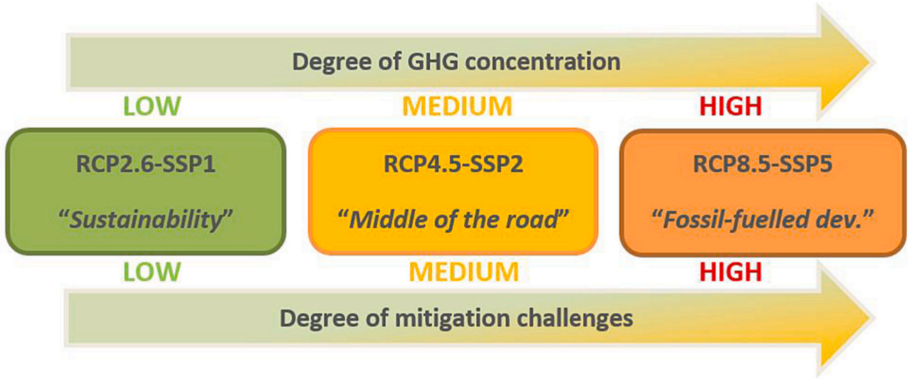

Fig. 1. Climate-economic scenarios considered in this study.

To compute the crop productivity losses due to water erosion, this study employs a literature review of 16 past studies (see Table S3 of the Supplementary material), which estimated the losses of crop productivity at around 8% where soil erosion rates are high (> 11 t ha^{-1} yr^{-1}, severe erosion area, Panagos et al., 2018). The literature review takes into account results of experimental sites of crop productivity losses because of erosion processes around the world; however, those estimates have high uncertainty. The land productivity losses per country are obtained multiplying the ratio "severe erosion area per region over the total agricultural area per region" by 8%. Sartori et al. (2019) provide a detailed explanation of how land productivity losses are obtained.

The future rates of soil erosion are predicted by modelling the change in potential of global soil erosion mainly driven by climate change by 2060–2080 (Panagos et al., 2022) using three alternative representative concentration pathways (RCP2.6, RCP4.5 and RCP8.5, Borrelli et al., 2020). The climate projections and global land cover dynamics indicate that global soil erosion may increase in the range of 30–66% by 2060–2080, substantially influenced by the climatic driver, which seems to suggest that the world is moving towards a more vigorous hydrological cycle over the coming decades. Lower rates of increase in erosion are 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 accelerated increases in soil erosion rates.

Areas with intense agricultural sectors in conjunction with intense rainfall are those under greater risk of productivity losses. Thus, higher productivity losses are estimated for Northern Latin America, the Caribbean, Central and Southeast Africa, China, Indonesia, Southeast Asia and other low-income tropical countries (Fig. 2).

To simulate the economic impact of soil erosion within a global market simulation model, country-level land productivity losses by scenario are aggregated into 17 countries and macro-regions (six 'large' agricultural producers -Brazil, China, India, Indonesia, Iran and Russia- plus 11 macro-regions grouping neighbouring countries), represented in Fig. 3. Macro-regions' land productivity losses are reported in Table 1. Indonesia, Brazil and Caribbean will be the most affected regions with productivity losses reaching 6% over the period 2015–2070, followed by China, India, Southeast Asia, South America and Central South Africa where productivity losses will range between 3 and 4%. All country-level estimates by scenario are reported in Table S1 of the Supplementary material.

3. Measuring the Long-Term Resource and Economic-Related Consequences of Soil Erosion

3.1. The MAGNET Model and the Database

To enumerate the economic and resource impacts of soil erosion, a state-of-the-art multi-region, multi-sector neoclassical computable general equilibrium (CGE) model, known as the Modular Applied GeNeral Equilibrium Tool (MAGNET) (Woltjer and Kuiper, 2014), is employed. At its core, MAGNET is based on the well-known Global Trade Analysis Project (GTAP) model (Corong et al., 2017). The key driving mechanisms of this class of market simulation model are represented in Fig. 4.

Convenient mathematical functions operationalise the theoretical economic tenets of neoclassical constrained optimisation, thereby governing the intermediate, final and investment behaviour of agents (i.e., producers, households, government, investors) across the global economy. Bilateral trade demand functions follow a two-stage Armington (1969) structure that exogenously differentiates between each domestic and imported composite commodity 'c' as well as between imported commodity 'c' by regions of origin. Following the convention of the GTAP model, lower-level substitution elasticities between imports by region of origin are twice the magnitude of those of the upper nest. The behavioural equations are supported by market clearing equations and accounting identity conventions to ensure a stable equilibrium within the closed system of the model.

These market-clearing and accounting equations are underpinned by national accounts monetary transactions data in the form of a social accounting matrix (SAM) for a 'benchmark' year. In common with the GTAP model, MAGNET employs version 10 of the GTAP database (Aguiar et al., 2019), with a benchmark of 2014 and coverage of up to 141 regions and countries, 65 tradable sectors and eight factors of production (including agricultural land). In addition, bilateral gross (i.e., two-way) trade flows data complete with information on trade taxes and transport costs interconnect each of the macroeconomic accounts between all partner countries.

The behavioural parameters of the model equations are 'calibrated' such that they faithfully replicate the initial equilibrium conditions inherent within the benchmark database. To solve the system of simultaneous equations for a set of equilibrium prices, the number of endogenous variables must be equal to the number of equations (closure). By shocking exogenous 'drivers' (i.e., typically technology change, border taxes, factor endowments), simultaneous price and quantity adjustments in 'N' markets are calculated to arrive at a new 'counterfactual' equilibrium characterised by matching demand and supply; equal income, output and expenditure flows, and a net zero balance of payments (i.e., sum of the current and capital accounts). Comparing the counterfactual with the benchmark gives an indication of the market impact of the shock on market indicators (e.g., prices, outputs, trade flows and real incomes).

For the current paper, a key advantage of MAGNET (vis-à-vis the standard GTAP model) is its advanced treatment of agricultural factor and product markets. More specifically, MAGNET explicitly characterises agricultural factor market rigidities, in terms of land transfer between heterogeneous agricultural activities; and labour and capital transfer between agricultural/non-agricultural uses to characterise

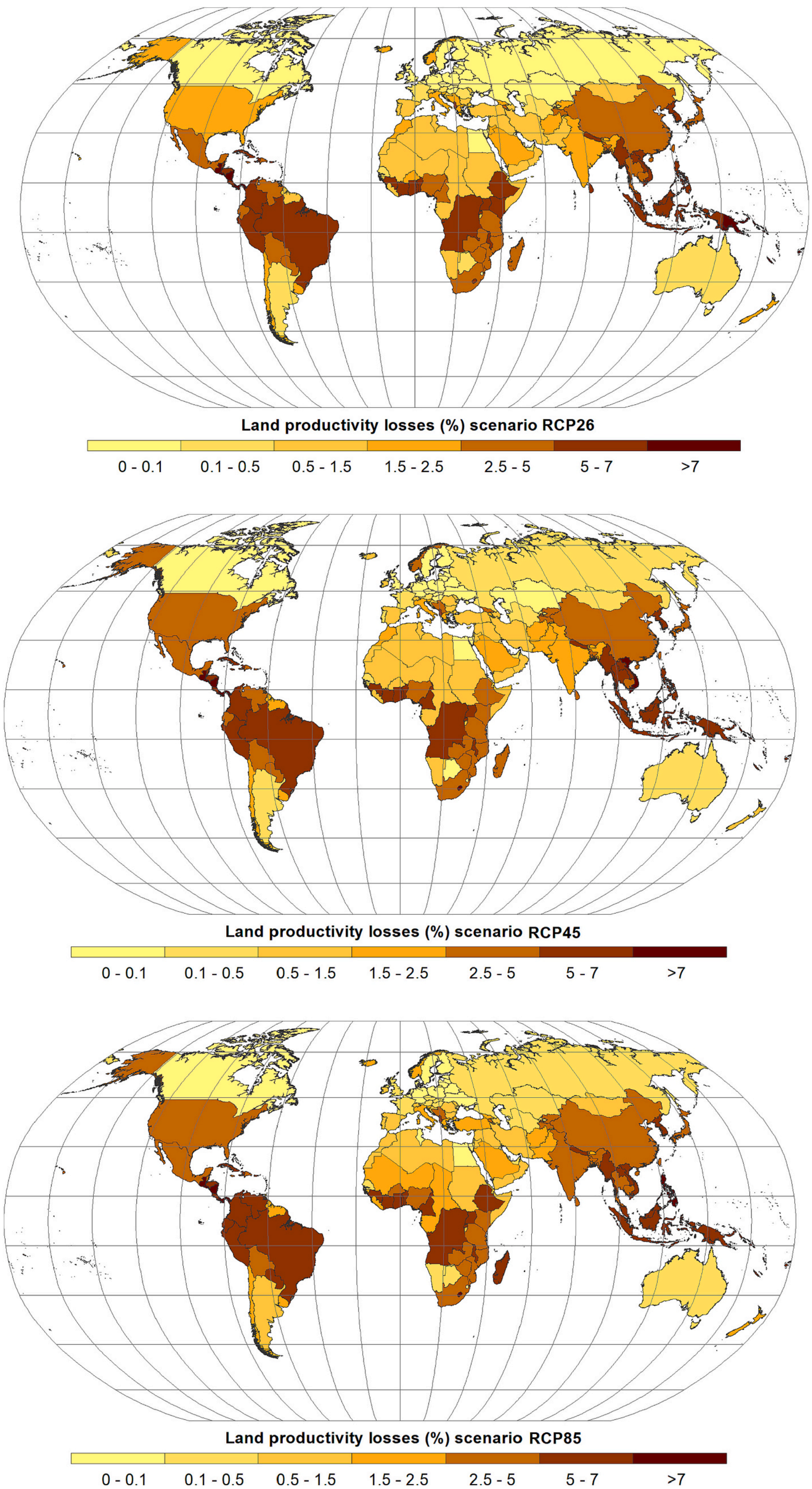

Fig. 2. Land productivity losses by RCP2.6-SSP1 (top panel), RCP4.5-SSP2 (central panel) and RCP8.5-SSP5 (bottom panel) scenario. Country-level estimates are available in Table S1 of the Supplementary material.

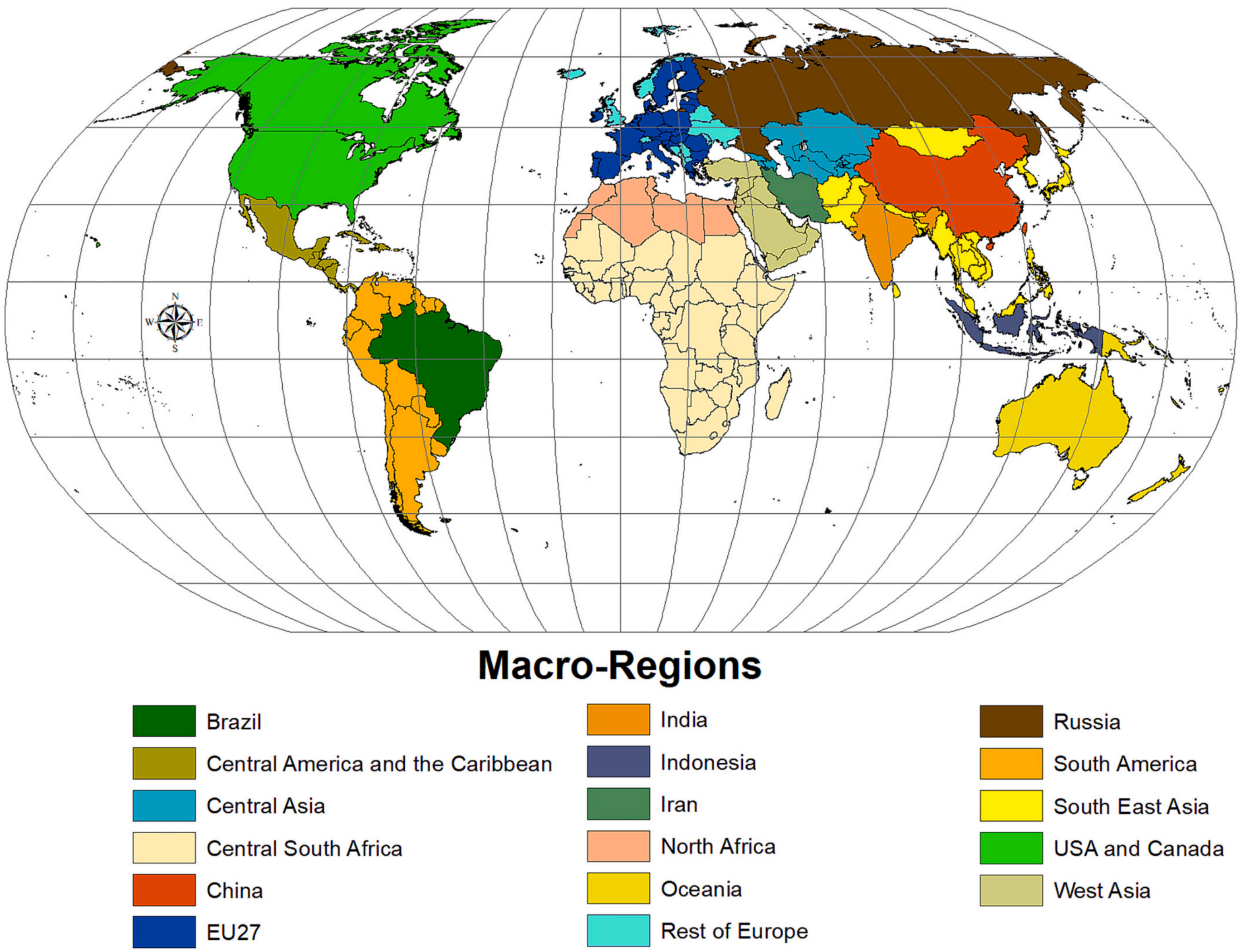

Fig. 3. Regional aggregation. The six disaggregated countries are among the biggest agricultural producers globally and are: Brazil, China, India, Indonesia, Iran and Russia. The rest of the world is grouped following a regional criterion. Neighbouring countries share similar geographical characteristics and exhibit comparable soil erosion rates (e.g., USA and Canada, North Africa, the EU27). Details on the content of each macro-region are reported in Table S2 of the Supplementary material.

Table 1
Regional land productivity losses by scenario (%) over the period 2015–2070.

Regions	*RCP26 - SSP1*	*RCP45 - SSP2*	*RCP85 - SSP5*	Regions	*RCP26 - SSP1*	*RCP45 - SSP2*	*RCP85 - SSP5*
Brazil	−6.1	−5.99	−6.21	*NorthAfr*	−1.22	−1.28	−0.54
CA_Carib	−4.01	−4.19	−4.26	*Oceania*	−0.56	−0.39	−0.59
CS_Africa	−3.39	−3.32	−3.56	*Rest_Eur*	−0.41	−0.79	−0.5
CentAsia	−0.26	−0.28	−0.3	*Russia*	−0.08	−0.11	−0.11
China	−2.51	−2.96	−3.19	*SE_Asia*	−3.26	−3.18	−3.62
EU27	−0.48	−0.83	−0.57	*SouthAm*	−3.04	−3.28	−3.3
India	−2.19	−2.46	−2.8	*USACan*	−1.87	−2.19	−2.49
Indonesia	−6.5	−6.44	−6.44	*WestAsia*	−2	−1.86	−1.91
Iran	−1.45	−1.2	−1.2	–	–	–	–

Source: Borrelli et al. (2020).

wage and rent differentials. As a result, agricultural sector supply responsiveness in MAGNET is relatively inelastic compared with GTAP. In addition, the assumption of fixed land supply in GTAP is relaxed, with the introduction of asymptotic land supply curves calibrated to biophysical data on available agricultural land areas (Eickhout et al., 2009). The potential for bringing additional land into agricultural production is limited to the maximum potentially available land, estimated by the IMAGE land management model (van Meijl et al., 2018; Doelman

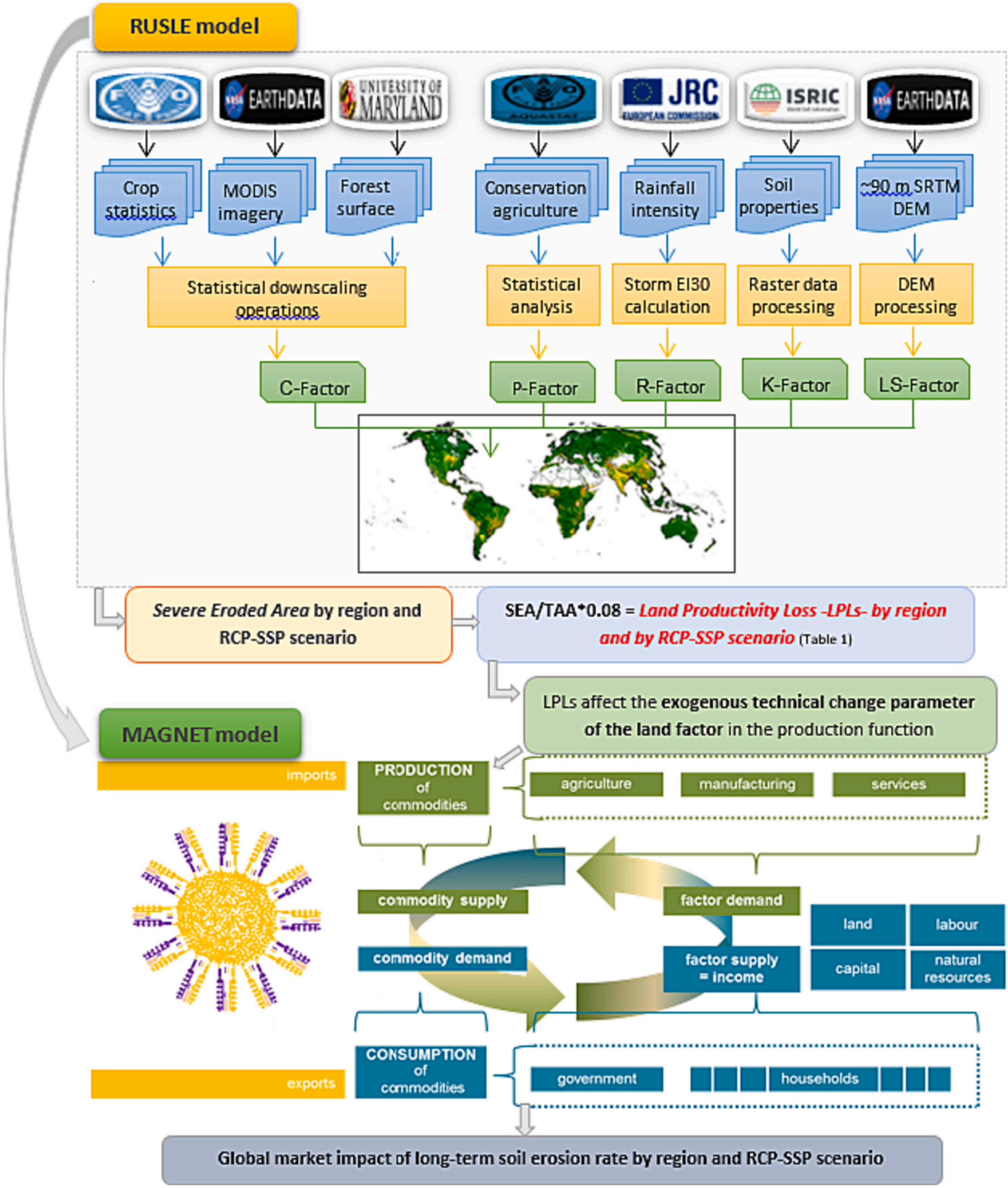

Fig. 4. A graphical representation of the integrated modelling.

et al., 2018).[2] The default IMAGE asymptote is defined as the total land available for agriculture, which excludes areas with prohibitively high land conversion costs (mainly ice, desert and wetlands), urban and non-productive protected areas (Woltjer and Kuiper, 2014). To improve the treatment of gradual structural economic change, and in contrast to Sartori et al. (2019), a long-run variant of MAGNET is employed, where the model rolls-over successive single time period solutions across chosen discrete time frames.

For this study, a 17 macro-region aggregation is employed (see Fig. 3). Taking advantage of MAGNET activity splits, the sector disaggregation includes irrigated and rainfed agricultural cropping activities (rice, wheat, other cereals, horticulture, oilseeds, raw sugar, plant-based fibres and other crops), all non-arable and food processing activities, fertilisers, energy and natural resources. Non-food manufacturing and non-food services are aggregated into three macro-sectors (see Table S4 of the Supplementary material).

3.2. Long-Term Economic Baselines and Scenarios

The assumptions of the climate-economic scenarios presented in Fig. 1 are used in the economic model to produce three socio-economic "baselines". In each baseline, the world economy is projected from the benchmark year of 2014 to 2070, where exogenous forecasts of socio-economic variables consistent with the narratives of the three SSPs (SSP1, SSP2 and SSP5) are assumed. These projections include population, Gross Domestic Product (GDP) and endowment (skilled and unskilled labour, capital stock and natural resources) growth rates, region specific technological change (Fricko et al., 2017) and improvements in land productivity (obtained from the IMAGE model, Doelman et al., 2018) over time (i.e., the projected crop yield). The labour force changes in proportion to population (i.e., fixed employment rates by skill type), whilst a long run fixed capital to output ratio is assumed as exogenous changes in capital are proportional to real GDP. In a pre-simulation run, these projections are inserted, where exogenous real GDP growth projections are targeted by an endogenous region-wide total factor productivity (TFP) variable. In the subsequent baseline, calibrated TFP changes are exogenously inserted with GDP adjusting endogenously to its target values.

To assess the marginal impact of soil erosion in each of these three baselines, the additional uniform negative land productivity shocks reported in Table 1 are applied to the parameter which determines the productivity level of the land factor in the production function of each agricultural activity, within a country and by RCP-SSP scenario. It results in three – RCP26-SSP1, RCP45-SSP2 and RCP85-SSP5 - counterfactual economic 'scenarios', vis-à-vis the 'baselines' upon which they are based.[3] The difference between this counterfactual scenario and the baseline data gives a marginal estimate of the resulting market impacts of soil erosion induced by water.

4. Results

The CGE model captures the direct "first-round" impacts from relative soil productivity changes across regions. Thus, whilst the sign of land productivity shocks provided by GloSEM is negative in all regions, the magnitude of this effect is regionally heterogeneous. In general, those regions with larger crop productivity deterioration will exhibit marginal relative deteriorations in competitiveness, resulting in a larger negative crop production trend. In MAGNET, the direct market implications of said regional land productivity losses fed from RUSLE also depend on the re-allocation of agricultural land between competing agricultural uses, the relative importance of domestic crop production and trade dependence, the importance of the supply chain between upstream agriculture and downstream food processing for domestic and foreign markets and the strength of domestic demand conditions for agricultural and food products. In addition, the model also accounts for 'second-round' economy-wide ripple effects. For example, the redistribution of labour and capital between agricultural and non-agricultural uses affects wages and rents, which impacts on household incomes, production and macroeconomic growth.

Unless otherwise stated, all the results presented in this section are expressed as deviations in the scenario, perturbed with the land productivity shocks, with respect to the baseline, for the year 2070. All marginal impacts are reported in either percentage terms, volumes or dollar values.

4.1. Macroeconomic Impacts

As expected, soil erosion by water is not beneficial to real GDP growth (Table 2). At the global level, the total loss comparing 2070 to 2014 will range from 216 (RCP26-SSP1) to 625 (RCP85-SSP5) billion dollars. In global GDP terms, this amounts to a loss of between 0.06% and 0.12%, whilst the average annual loss is approximately between four and 11 billion dollars. At the regional level, the most affected areas are Central-South Africa (CS_Africa) and India, followed by Indonesia and China. Central-South Africa and India together contribute to more than half of the global loss. Measured in percentage terms, Central-South Africa exhibits the largest GDP loss (0.37%), under the scenario RCP45-SSP2, due to the lower projected GDP growth in 2070 (see Fig. S1 of the Supplementary material). In the remaining regions the impacts are fairly muted, either because the land productivity shock is relatively low and/or because the agriculture sector only contributes a minor share to the total GDP.

The comparison of the three scenarios with their respective baselines suggests that there are no significant *qualitative* differences, although scenario SSP5 exhibits the largest losses, on average. RCP85-SSP5 exhibits the worst absolute impacts, mainly due to larger assumed GDP projections (Fig. S1 in the Supplementary material) and higher land productivity shocks (Table 1).

4.2. Impact on Production

Primary agricultural production losses arising from soil erosion range from approximately 102 million tonnes (RCP26-SSP1) to 352 million tonnes (RCP85-SSP5) of crops (Table 3). If we include the impacts on downstream food activities (i.e., livestock, dairy products and processed food), the two extremes amount to −113 and − 395 million tonnes, respectively (shown in Table S5 of the Supplementary material). Due to the reduced availability of agricultural goods on international markets and the consequent price increase (see Figs. 9 and 10), their total value increases moderately, by up to approximately 140 billion dollars under the RCP85-SSP5 scenario (Fig. S2).

The estimates reported in Table 3 reveal the marginal impacts on crop production by 2070. At the regional level, the general pattern is that crop production is expected to incur losses in most regions. Exceptions are predicted for the EU27, Rest of Europe and Russia because these regions are impacted by relatively lower land productivity losses (see Table 1), which place them in a relatively more competitive trade position, compared to the rest of the world. Drilling down into this

[2] It is worth noting that land supply is endogenously computed in the macroeconomic model, implying that it may not be (fully) consistent with the land use change projections used to calculate the land productivity losses caused by soil erosion.

[3] The global biophysical model employed cannot differentiate the land productivity loss per crop type for the following reasons. Firstly, in the global soil loss model geo-referenced data on crop cultivation are not available. Secondly, experimental observations on land productivity losses per crop type at the global level are limited (a review is available in Table S3 of the Supplementary material). Lastly, the impact of cover crops or less erosive crops (e.g. wheat) is already implicitly considered in the RUSLE component Cover management (C-factor), which is the most influential factor of the model while estimating soil erosion.

Table 2
Cumulative GDP impacts at the year 2070 (US$ millions 2014 prices) and % over total GDP in brackets. Deviations scenario vs baseline by year 2070.

Regions	*RCP26 - SSP1 (% GDP)*	*RCP45 - SSP2 (% GDP)*	*RCP85 - SSP5 (% GDP)*	*Regions*	*RCP26 - SSP1 (% GDP)*	*RCP45 - SSP2 (% GDP)*	*RCP85 - SSP5 (% GDP)*
Brazil	−1323 (−0.02)	−1073 (−0.02)	−8057 (−0.08)	*Oceania*	−122 (0.00)	29 (0.00)	−356 (−0.01)
CA_Carib	−1187 (−0.01)	−1891 (−0.03)	−3303 (−0.03)	*Rest_Eur*	−222 (0.00)	−189 (0.00)	−1486 (−0.01)
CS_Africa	−69,612 (−0.16)	−107,518 (−0.37)	−180,984 (−0.30)	*Russia*	−672 (−0.01)	−761 (−0.01)	−3362 (−0.03)
CentAsia	−646 (−0.02)	−585 (−0.02)	−1642 (−0.03)	*SE_Asia*	−5540 (−0.02)	−6682 (−0.03)	−19,272 (−0.05)
China	−22,544 (−0.03)	−18,288 (−0.03)	−88,616 (−0.08)	*SouthAm*	−2830 (−0.03)	−3969 (−0.05)	−11,410 (−0.10)
EU27	−542 (0.00)	−176 (0.00)	−1764 (−0.00)	*USACan*	−2512 (−0.01)	−566 (0.00)	−6136 (−0.01)
India	−86,344 (−0.12)	−93,300 (−0.17)	−212,432 (−0.21)	*WestAsia*	−2062 (−0.02)	−1916 (−0.02)	−7474 (−0.05)
Indonesia	−19,114 (−0.10)	−24,155 (−0.19)	−76,340 (−0.30)	*TOTAL*	*−216,641 (−0.06)*	*−262,237 (−0.09)*	***−625,751 (−0.12)***
Iran	−448 (−0.03)	−332 (−0.02)	−1305 (−0.05)	*Yearly impact*	*−3869*	*−4683*	***−11,174***
NorthAfr	−924 (−0.01)	−867 (−0.02)	−1812 (−0.02)	–	–	–	–

Table 3
Marginal changes in crop production (million tonnes). Deviations scenario vs baseline by year 2070. Crops include all irrigated and non-irrigated agricultural activities.

Regions	*RCP26 - SSP1*	*RCP45 - SSP2*	*RCP85 - SSP5*	Regions	*RCP26 - SSP1*	*RCP45 - SSP2*	*RCP85 - SSP5*
Brazil	−9.2	−5.4	−47.0	*Oceania*	−0.2	0.3	0.2
CA_Carib	−0.5	−4.9	−11.3	*Rest_Eur*	0.5	0.1	0.3
CS_Afr	−20.1	−37.4	−69.0	*Russia*	0.7	0.9	1.1
CentAsia	0.0	0.2	0.5	*SE_Asia*	−1.5	−11.3	−30.0
China	0.5	0.4	−39.1	*SouthAm*	−17.0	−18.2	−36.0
EU27	3.7	4.2	8.6	*USACan*	−19.3	−15.7	−25.5
India	−9.1	−16.3	−21.9	*WestAsia*	0.2	−0.2	−1.9
Indonesia	−30.9	−42.5	−80.4	*Total*	*−102.1*	*−145.6*	***−352.3***
Iran	0.0	0.1	0.4	*Yearly*	*−1.8*	*−2.6*	***−6.3***
NorthAfr	0.0	0.1	−1.3	–	–	–	–

result, one observes that although Russia shows the mildest land productivity loss, the EU27 is the winner region in terms of increases of agricultural production in all scenarios. This is because of the EU27's broader base of crop production and its relatively greater agricultural trade exposure, which enables it to take advantage of its relative competitive gains. Looking closer at the 2014–2070 evolution of the percentage share of agriculture in total GDP, in the three baselines (see Fig. S3 in the Supplementary material), one observes that it is relatively more stable in the EU27 compared with Russia, where the decline is stronger (a similar trend emerges for other developing countries).

Compared to projected total crop production in 2070 (Fig. 5), expected crop losses due to soil erosion will be significant in Indonesia (up to −5.9%), Central-South Africa (up to −2.8%), South America (up to −2.5%). Relevant losses will occur in the USA and Canada (up to −1.7%) and Brazil (up to −1.4%). At the global level, the range of crop deterioration is moderate, spreading from −0.81% (RCP26-SSP1) up to −1.8% (RCP85-SSP5). Negligible losses are expected in Central and West Asia in some scenarios, whilst South America, South Asia and Central-South Africa will suffer the largest crop production deterioration.

Fig. 6 shows the shares of the global loss in crop production arising from soil erosion in each of the scenarios. Thus, focusing on the eight agricultural activities considered in this study, the largest share of this reduction comes from the oilseeds sector, covering up to 70% of global crop production losses in the RCP2.6-SSP1 scenario. The reason for this general observation is because envisaged productivity falls from soil erosion hit hardest in those regions that are key players on global oilseeds markets, especially in Indonesia, South America and Brazil (see also Fig. S4 of the Supplementary material). Other notable drops are observed in horticulture, whose major contributor is Central South Africa, and other cereals activities. Detailed crop-specific impacts by region and by scenario are reported in Table S7 of the Supplementary material.

The largest drops incurring to the oilseed activities can also be

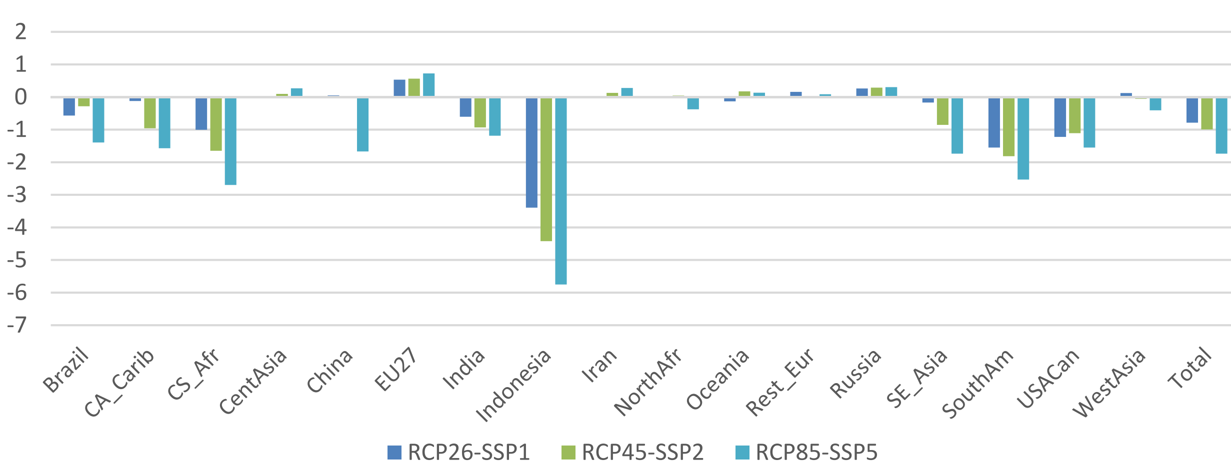

Fig. 5. Change in crop production as % of total projected crop production. Deviations scenario vs baseline by year 2070.

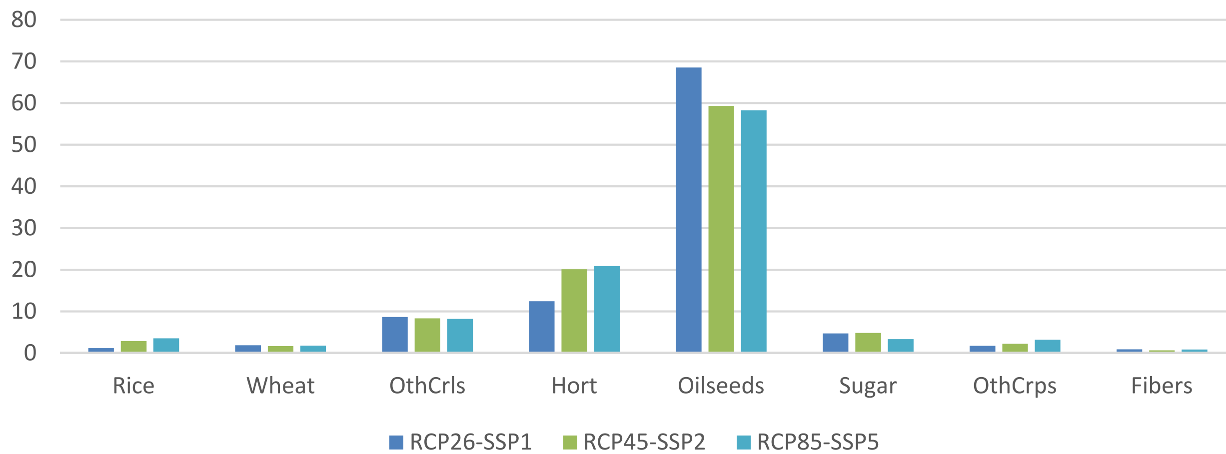

Fig. 6. The share (%) of the total loss in crop production, distributed by crop activities. Deviations scenario vs baseline by year 2070. Note: OthCrls refers to other cereals, Hort stands for horticulture, OthCrps refers to other crops and Fibres identifies plant-based fibres.

appreciated from Fig. 7, which shows the evolution of the marginal changes in millions of tonnes of lost crop production by scenario at three time interval steps. Whilst the short-term (2030) differences in production losses across scenarios are negligible, they get larger over time, especially for some activities (i.e., oilseeds, horticulture, and other cereals).

4.3. Impact on Land[4]

With declining land productivities, land use increases in all regions to meet the demand for food (Fig. 8 and Table S6 of the Supplementary material). Globally, agricultural land use is estimated to rise by between 10 (RCP85-SSP5) and 27 million hectares (RCP26-SSP1), depending on the scenario, which is equivalent to a 0.2% - 0.5% rise in global land use.

Different and sometimes opposing drivers lead to this outcome and disentangling these effects is not a straightforward task. Firstly, a priori, land demand is expected to rise to compensate for lower per hectare productivity. In regions, where soil erosion rates are relatively larger, the increase in land demand may be substantial (e.g., Brazil). Secondly, where the availability of unused agricultural land is relatively more abundant (i.e., higher land supply elasticities), like in Central South Africa and Latin American countries, the resulting rise may also be significant.

Another result presented in more detail is that regional and global land demand are larger in RCP26-SSP1 and RCP45-SSP2 scenarios than RCP85-SSP5. This result strongly depends on the assumptions of the economic model, particularly how the land market is modelled in MAGNET (see Supplementary material S.2 for a detailed explanation).[5] In short, there is a limited availability of land that can be converted into cropland, defined by an asymptote. The asymptote remains unchanged under the three SSPs. The conversion possibilities depend not only on biophysical suitability, but also on land prices. The economic projections show that the total amount of land demanded is lowest under RCP26-SSP1 and highest under RCP85-SSP5 (Fig. S5 of the Supplementary material). A clear implication is that, under RCP85-SSP5, there will be less available additional land to convert into cropland, because the equilibrium point -the quantity of land demanded at a certain price- is already closer to the asymptote in the RCP85-SSP5 baseline. Thus, under RCP85-SSP5 the marginal cost of land conversion, which rises as land demand approaches the asymptote, is higher, which dampens additional marginal demand for land.

Focusing on the activities contributing the most to the land demand increase, Fig. 8 shows that these are livestock, in particular beef, other cattle and milk, though they are not directly impacted by the land productivity shock. This is one of the many second-order effects to which the economic model gives insight: the market mechanism reallocates agricultural land from lower to relatively more productive competing uses, despite the share of the land factor over total value added in the livestock sectors compared to the other agricultural sectors is expected to steadily decrease by 2070 (Fig. S7 of the Supplementary material). The substantial decrease expected in oilseeds production (see Fig. 6) prevails instead over the loss of productivity, generating a significant decrease in the demand for land under RCP85-SSP5 scenario (Fig. 9, oilseeds).

4.4. Impact on Prices

The lower availability of agri-food production will inevitably push up the domestic prices of the agri-food commodities in all regions (Fig. 10) and consequently their global price (Figs. 11 and 12). The countries suffering the highest price increase are those facing the largest impact in terms of production loss, such as Central-South Africa, India and Indonesia. A noticeable consequence of the price increase is that food affordability further deteriorates, particularly in those regions where food security is already threatened. In developing regions, even marginal price changes could have important implications on the possibility to buy food for a large share of the population.

The results highlight the relevance of simulating different alternative futures and the uncertainty behind the scenarios (see also Fig. S6 in the Supplementary material). Under the RCP85-SSP5 scenario, the agricultural price index increases and their impact on food security is much more visible than under the other scenarios, with higher price rises in Central-South Africa, India and Indonesia under RCP85-SSP5.

Figs. 11 and 12 show that soil erosion inflates global crop prices, with substantial differences across scenarios. Once again, price increases are larger in the RCP85-SSP5 scenario, where the highest land productivity losses occur, compared to RCP26-SSP1 and RCP45-SSP2. Among most impacted commodities is paddy rice, a key staple for food security. Its world price rises by up to >4% in the worst scenario (RCP85-SSP5). This suggests that food affordability would be highly compromised under a

[4] Following an observation by one of the referees, it should be noted that in MAGNET, the mathematical function that governs the transfer of heterogeneous agricultural land between activities, tracks land values (rents) measured by 'effective' land units rather than tracking 'physical' land units. As a result, when translating changes in land use across sectors, there is a degree of bias in the actual physical quantity of land units employed. For a treatment of this problem, see Zhao et al. (2017). Despite this methodological misspecification in the current study, the overall qualitative message of the paper remains unchanged.

[5] According to SSPs assumptions, under the SSP1 scenario it is assumed that tropical deforestation rates are strongly reduced, and are lower than the SSP2 and SSP5 rates (O'Neill et al., 2017).

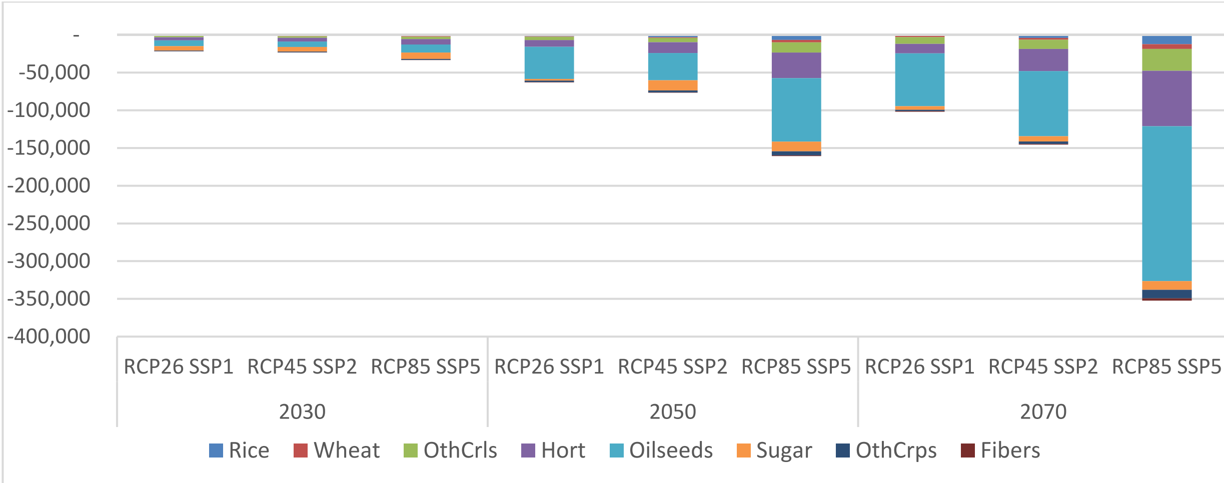

Fig. 7. Total loss in crop production (physical quantity, million tonnes), distributed by crop activities. Deviations scenario-baseline by year 2030, 2050, 2070. Note: OthCrls refers to other cereals, Hort stands for horticulture, OthCrps refers to other crops and Fibres identifies plant-based fibres.

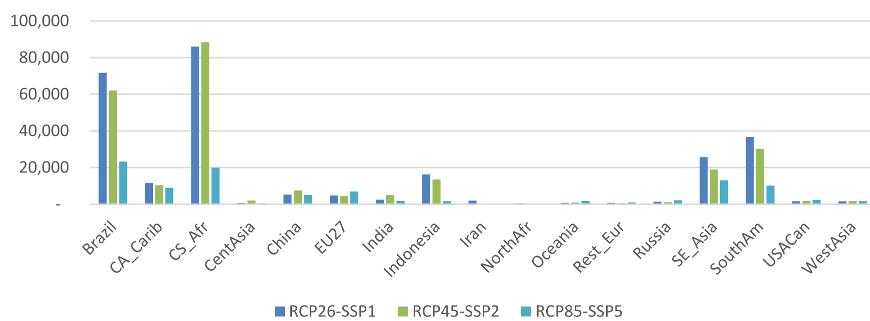

Fig. 8. Marginal change in land demand, due to soil erosion (km^2). Deviations scenario vs baseline by year 2070.

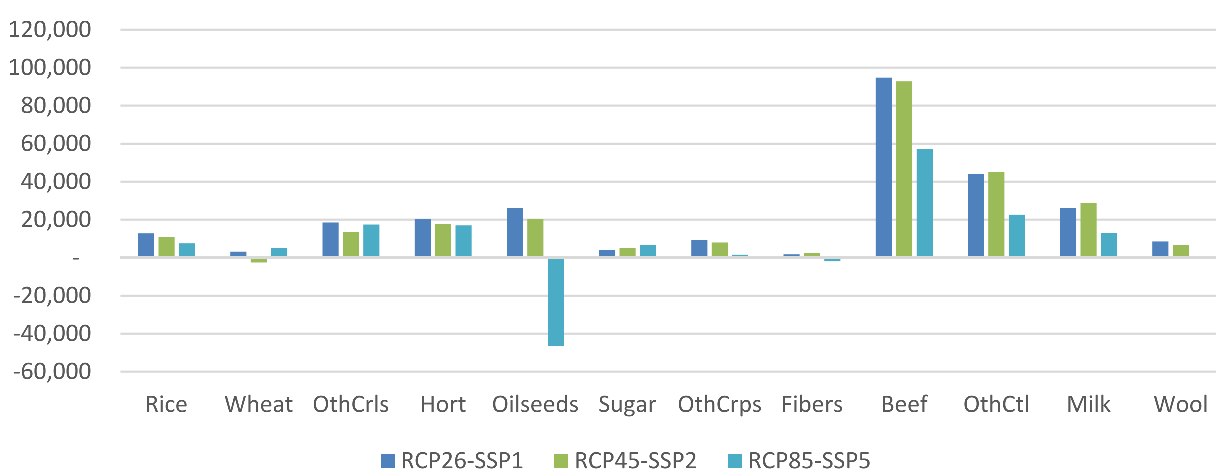

Fig. 9. Marginal change in global land demand by crop and animal activities, due to soil erosion (km^2). Deviations scenario vs baseline by year 2070. Note: Othcrls refers to other cereals, Hort stands for horticulture, OthCrps refers to other crops, Pbfibres identifies plant-based fibres and OthCtl is other cattles.

combination of fossil-fuelled development and soil erosion. A considerable world price increase is also expected in horticulture, oilseeds and plant-based fibres (up to 4.3%). The effect on world prices of the RCP26-SSP1 and RCP45-SSP2 scenarios is more muted, although may be significant for some crops (oilseeds and plant-based fibres activities, Fig. 12).

4.5. Virtual Flows and Footprints

This section examines the environmental impact of soil erosion through the lens of two per capita virtual flow intensity measures, the land use footprint and the water abstraction footprint. The methodology follows that of Philippidis et al. (2021).

Table 4 shows the absolute deviations of the three scenarios from their respective baselines in 2070 for the footprint of land use (m^2/capita/year) and water withdrawals (m^3/capita/year) associated with

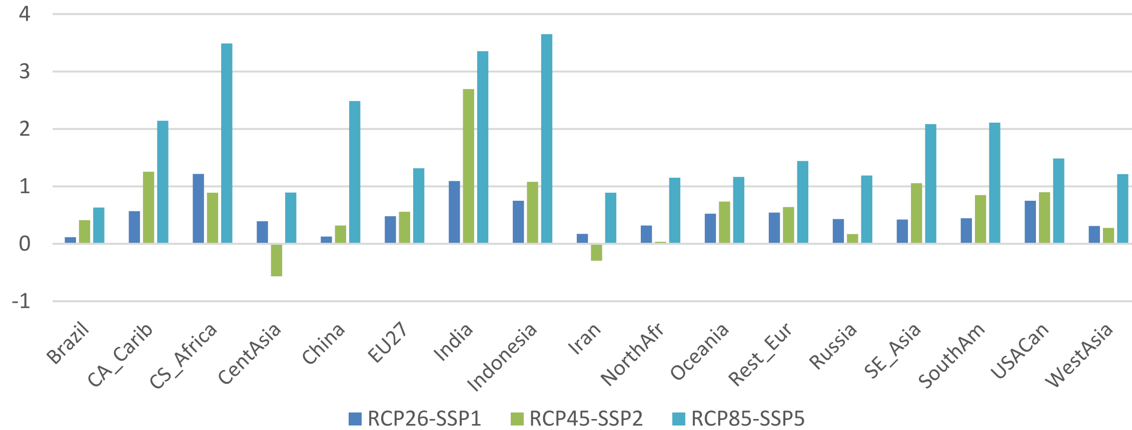

Fig. 10. Marginal % change in consumption price of agricultural commodities by region. Deviations scenario-baseline, year 2070. Note: the % change is the difference between the final value of the cumulative index (2014–2070) computed in the scenario vs the baseline.

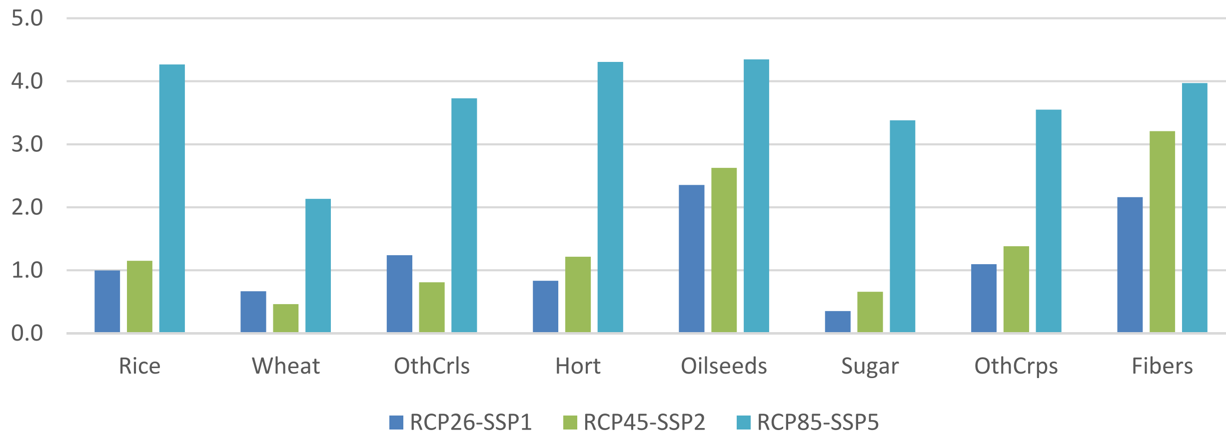

Fig. 11. Marginal % change in world price of crops by scenario. Deviations scenario vs baseline by year 2070. Note: the % change is the difference between the final value of the cumulative index (2014–2070) computed in the scenario vs the baseline. Note: OthCrls refers to other cereals, Hort stands for horticulture, OthCrps refers to other crops and Fibres identifies plant-based fibres.

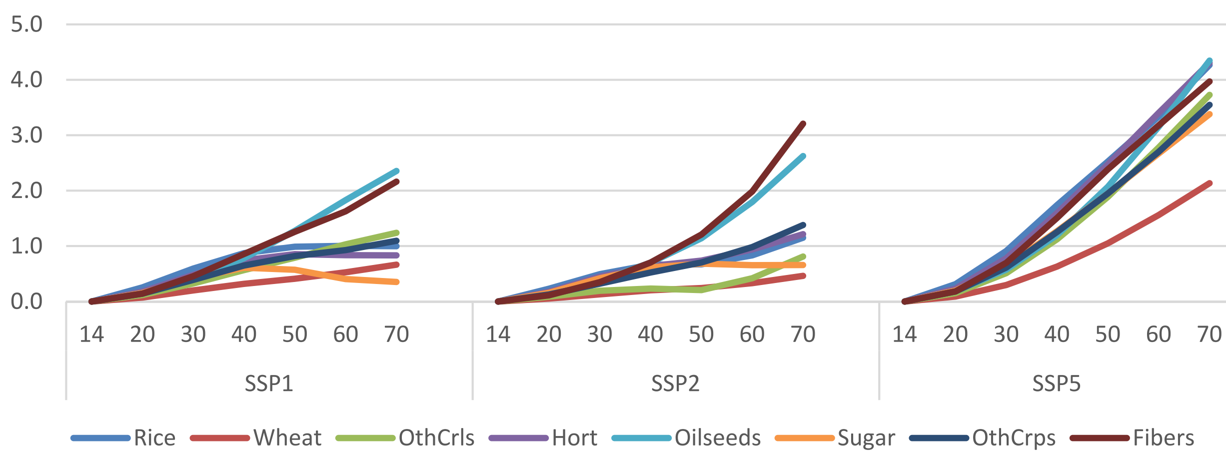

Fig. 12. Percentage change in world price of crops. Deviations scenario vs baseline. Note: 2014 = 100.

household food consumption. Falling land productivities due to soil erosion lead to increased aggregate land demand, as shown in Fig. 8, and as a result, the per capita footprint rises. However, the magnitude of this effect is driven by: (i) the land productivity losses reported in Table 1 that depresses per capita incomes and therefore (ceteris paribus) reduces food demands and footprints; (ii) the proximity of land use to land availability limits in each SSP-RCP baseline (without soil erosion) and the resulting implied land supply elasticity in each region; and (iii) the size of the negative productivity impact and the compensatory desired rises in land demand to maintain nutritive intake levels.

In general, the relative rise in the footprint is greatest in RCP2.6-SSP1. Indeed, when comparing RCP2.6-SSP1 (*with* soil erosion present) with RCP8.5-SSP5 (*with* soil erosion present), there is greater flexibility for land use increases relative to the corresponding RCP-SSP

Table 4
Final food demand land use and water abstraction footprints. Deviations of scenarios vs baselines by year 2070.

	LAND USE FOOTPRINTS (m^2/capita/year)			WATER ABSTRACTION FOOTPRINTS(m^3/capita/year)		
Region	RCP26-SSP1	RCP45-SSP2	RCP85-SSP5	RCP26-SSP1	RCP45-SSP2	RCP85-SSP5
Brazil	122	116	101	2.1	2.3	0.9
CA_Caribbean	33	32	37	1.1	0.7	0.6
CS_Africa	42	8	42	-0.2	-0.3	0.1
Cent_Asia	-1	-4	2	-0.4	-1.0	-0.6
China	2	3	2	0.7	0.9	1.0
EU27	-2	4	-10	0.1	0.3	-0.3
India	4	0	3	0.8	-1.2	0.7
Indonesia	28	26	23	9.6	8.9	8.1
Iran	7	-2	-3	2.7	1.8	-0.7
North_Africa	-8	-1	-16	0.7	-0.3	-2.2
Oceania	-25	-14	-56	0.0	0.1	-0.3
Rest_Europe	-1	3	-6	0.1	0.1	-0.2
Russia	-13	-11	-20	0.1	0.0	-0.2
SE_Asia	22	18	15	3.6	2.6	3.0
SouthAmerica	96	78	59	1.9	1.6	2.0
USA_Canada	13	16	2	0.5	0.3	0.5
West_Asia	-9	-2	-3	0.5	0.2	-1.1
WORLD	20	12	15	1.2	0.6	0.9

Note: The footprints shown in the table above measure land and water use in final household food consumption, expressed as m^2/capita/year for land and m^3/capita/year for water. Negative numbers represent a decrease in the footprint compared to the corresponding SSP-RCP baseline in 2070 and are highlighted in green, positive numbers represent an increase in the footprint compared to the baseline in 2070 and are highlighted in red. The deeper the colour, the greater the deviation from the baseline.

baseline without soil erosion (see also discussion on land in Section 4.3). Another factor is that the stronger negative macroeconomic impact for RCP8.5-SSP5 reported in Table 2 has a greater depressing effect on per capita incomes and, by extension, food demands. Comparing RCP4.5-SSP2 with RCP8.5-SSP5, the latter scenario has stronger per capita income reductions, but it also has stronger crop productivity losses, which pushes up per capita land requirements. The latter effect outweighs the former (particularly in Central and Sub-Saharan Africa), such that global land footprints in RCP8.5-SSP5 rise marginally more compared with RCP4.5-SSP2.[6]

When simulating the impact of soil erosion, it becomes apparent that this contributes to an increase in water abstraction to partially compensate for the reduced land productivity. The highest effect can be observed in Indonesia. Here, soil erosion leads to a 48%, 110% and 270% increase in water abstraction in scenario RCP26-SSP1, RCP45-SSP2 and RCP85-SSP5 compared to their respective baselines from 2020 to 2070. A further comparison at the global level across the scenarios reveals that the water abstraction footprint trend is the same as the global land footprint trends. Moreover, in those regions where soil erosion leads to a reduction in the land footprint, water abstraction also tends to decrease slightly. On a region-by-region basis, however, there are deviations from the land footprint trends, since the comparative pattern (e.g., by crop and region) of available irrigated water abstraction differs from the comparative pattern of utilized land areas.

5. Policy Developments

In this chapter we discuss the policy initiatives and how they are linked to the results presented here.

The UN Food Systems Summit in 2021 placed also soils in the centre of the transition to a more sustainable food system. The present study confirms the importance of combatting soil erosion to maintain or even increase agricultural productivity against the background of a 50% higher food demand in 2050.

Although the impacts of soil erosion in high income regions are smaller compared to most of the low-income countries, the pioneering policies and initiatives of the former contribute directly or indirectly and can catalyse global acknowledgement and action against soil erosion.

For instance, the EU has set up the vision that all soil ecosystems should be in healthy condition by 2050,[7] thus contributing to the overall goals of the European Green Deal, to existing EU medium- and long-term policy objectives for 2030 and 2050 (EC, 2021; Montanarella and Panagos, 2021). The Soil Strategy (EC, 2021, p. 1) states "land and soil continue to be subject to severe degradation processes such as erosion, compaction, organic matter decline, pollution, loss of biodiversity, salinisation and sealing." For 2023, a Soil Health Law is under preparation to ensure the same level of protection as water, air or the marine environment. While soil erosion is the main driver to land degradation, the Farm to Fork and Biodiversity Strategies (EC, 2018) stress the need for healthy soils to ensure ecosystem services and productivity in a less fossil-based agriculture.

[6] However, considering different land use futures in SSPs according to Popp et al. (2017), such as different land use regulations, changes in consumer diets, land-based mitigation strategies and levels of international cooperation would result in low mitigation and adaptation challenges in SSP1 due to highly regulated land use and strongly reduced deforestation rates, healthy diets with low meat content and high engagement in international cooperation; and high mitigation and low adaptation challenges in SSP5 due to incompletely regulated land use changes with slowly reduced deforestation rates, unhealthy diets with high meat content and delayed international cooperation. These developments would have an impact on land demand and limit the potential for land expansion in all scenarios, but with large differences in the magnitude and partly also in the direction of the impact. They are therefore expected to lead to a reduction in the land footprint compared to the figures presented in Table 4, with the largest reduction in land expansion and therefore in the land footprint expected in SSP1.

[7] The simulations in this study focus on the year 2070, which is beyond the EU's policy objectives of a healthy soil by 2050. Yet, the implementation of the scenarios does not allow a simple interpolation of the results in 2050. The reason is the dynamically growing world economy, which over-proportionally increases towards the end of the scenarios' time horizon. The physical effect of the soil erosion in 2050 is rather similar to 2070, so that at least qualitatively the results (trends) can be also interpreted in the context of the EU Soil Strategy for 2050. The soil loss by water erosion is projected to increase by 13–25% in the EU by 2050 (Panagos et al., 2021). This will accelerate the existing land degradation problems and further contribute to land productivity losses.

As shown in chapter 4, for the EU we observe gradually increasing land productivity losses induced by soil erosion in the different RCP-SSP scenarios. Soil erosion is in particular a problem for Southern European countries, amounting to land productivity losses between 0.5% in Spain to 2.0% in Italy and Greece (Panagos et al., 2018). It should be noted, that values are much higher in the Western Balkan countries and might require specific attention also in the context of the accession negotiations (Blinkov et al., 2013; Borrelli et al., 2017).[8]

As shown in earlier sections, general production decreases in non-European countries, hit much stronger by soil erosion, stand in contrast with slight increases of production in the EU due to market mechanism and comparative advantages. Oilseed production as a consequence of soil erosion is reduced mainly in South Asia (Indonesia), a key exporter of palm oil, and South America (Brazil), a key exporter of soybeans. The considerable increase of oilseeds production (and vegetable oils and fats) in the EU can compensate partly the reduced imports. Turning to sugar, the main market player, Brazil, reduces its production by about 35 million tonnes in RCP85-SSP5. The EU can only fill 10% of this gap with an increased production of approximately 3.5 million tonnes.

With soil erosion impacting considerably more on non-EU regions, the presented scenarios suggest that the impacts of this phenomenon for the EU are of a more indirect nature, which in turn become more prescient the longer the time frame under consideration. The increase of EU oilseed production is in line with EU‘s planned reduction of import dependency of protein crops (EC, 2018). In addition, the more muted rises in wheat and horticulture production are in line with either strategic objectives or comparative advantages. On the other hand, the strong increase of sugar production in the EU (3.5 million tonnes equivalent to an increase of almost 20%), may not be coherent with the sustainability objectives as outlined in the Farm to Fork strategy.

Turning to Africa, about 40% of the continent's soils are under degradation and soil erosion in Sub-Saharan Africa is one of the root causes of stagnating or declining agricultural productivity (FAO, 2016). The estimates of soil erosion rates employed in this study confirm a concerning picture for Africa, which will be one of the most affected continent of the world. Our results say that, on average, land productivity decreases by about 3% at the continental level, and future crop and GDP losses amount to about one fifth and one third respectively of total global losses. However, national policies regulating soil use are lacking in many countries. Where policies exist, funding is often not a priority and policy implementation can be ineffective due to a lack of political will or implementation capacity (FAO, 2016). At the international level, in 2015 the FAO launched a new programme in the context of the Global Soil Partnership, to reduce soil degradation for greater food and nutrition security in Africa.[9] A second important initiative put in place to combat land degradation, although restricted to the Sahel region only, is the Great Green Wall project.[10]

Under such conditions, a co-ordinated global mind-set and response is required. Agricultural production and food consumption are globally interconnected and, without a suitable soil regulation, free and fair trade could create producer reactions not necessarily in line with the overall direction towards a more sustainable food system. Similar to the challenge of greenhouse gas emissions, also for soil (erosion), which is on first sight a local phenomenon, a global and comprehensive approach needs to be taken.

[8] Albania, the Republic of North Macedonia, Montenegro, and Serbia are candidate countries. Bosnia and Herzegovina and Kosovo are potential candidates.

[9] African Soil Partnership, https://www.fao.org/global-soil-partnership/regional-partnerships/africa/en/).

[10] https://www.greatgreenwall.org/about-great-green-wall

6. Concluding Remarks

Under the spectre of climate change and population growth, global initiatives to reduce land degradation, such as the Great Green Wall program (UNCCD, 2020), are deemed essential. Indeed, the global agrifood markets situation in the year 2022, hit by disruptions of important global value chains and consecutive moratoria of environmentally friendly measures in the EU, illustrate such a situation. Responding to the research needs of the international community and following Sartori et al. (2019), this paper takes an integrated biophysical-economic approach to estimate the long-run economic impact of soil erosion at a global scale. As a departure from Sartori et al. (2019), the research takes a medium to long-term time horizon to 2070. A further innovation is that it recognises uncertainty through the implementation of different narratives of climate-economic progress combining the Shared Socioeconomic Pathway and Representative Concentration Pathway (SSP-RCP) “Sustainability” (RCP2.6-SSP1), “Middle of the road” (RCP4.5-SSP2), and “Fossil-fuelled development” (RCP8.5-SSP5). These climate-economic baselines have different hypotheses on emission concentration, mitigation challenges, GDP and population growth projections, and land productivity. Finally, compared with Sartori et al. (2019), the study broadens the economic assessment to also encompass sustainability indicators.

The Global Soil Erosion Modelling (GloSEM) platform with the Revised Universal Soil Loss Equation (RUSLE) model provides newly updated estimates of future erosion scenarios that integrate both climate change and land use change scenarios. The regional land productivity losses calculated by RUSLE vary only slightly by climate scenario, reaching 6% in Indonesia, Brazil and Caribbean, followed by China, India, South East Asia South America and Central Africa where productivity losses range between 3 and 4%. In a subsequent step, the soil erosion rates are converted into land productivity losses to input into the multi-region Modular Applied GeNeral Equilibrium Tool (MAGNET). To assess the marginal long-run market impacts of soil erosion, this paper employs the MAGNET macroeconomic simulation model. Three RCP-SSP baselines are simulated without and with soil erosion effects, modelled as negative land productivity shocks inputted from the RUSLE model.

The paper underlines the following messages. The results confirm the negative effects of soil erosion on the economy in all regions, however, with different orders of magnitude. The economic contraction on a global scale differs between the scenarios, ranging from 216 billion US$ (−0.06%) in RCP26-SSP1 to −625 billion US$ in RCP85-SSP5 (−0.12%) by the year 2070. Soil erosion presents a significant challenge to the supply of agricultural products in some of the world's most vulnerable regions. Depending on the scenario, crop production is most affected in Indonesia (up to 6% reduction), Central and Southern Africa (up to 3%), and South America (up to 3%). In particular the losses in oilseeds and horticulture with a share in the total loss (physical quantities) of 47 to 68% and 12 to 21% respectively, reflect the importance of those crops in areas with high soil erosion. The study shows how trade links allowing relatively more competitive regions to expand (marginally) their production, which can help to cushion global markets against the risk of global production falls and the threat of agricultural commodity price increases. Greater opening of these markets and unfettered trade would logically help to reduce such risks even further. Finally, the analysis of footprints of land and water clearly shows that the presence of soil erosion in all scenarios leads to an increase in the global land and water footprint associated with household food consumption. Due to the opposing forces of additional land availability under soil erosion (biophysical constraint) and depressed food demands from marginal macroeconomic contractions in real incomes under soil erosion (economic constraint), the relative footprint impacts across the scenarios are, a priori, difficult to predetermine. Notwithstanding, with the smallest relative macroeconomic contraction, and the greatest additional land availability to accommodate soil productivity losses, the largest possible global per capita land and water footprint rises to meet food demands are recorded at 20 m^2/cap/year and 1.2 m^3/cap/year in the RCP2.6-SSP1 scenario. This result depends on the land supply assumption in the macro-model, which allows for a greater flexibility for land use increases in the RCP2.6-SSP1 scenario. This is equivalent to a global increase of land and water of approximately 167,000 km^2 and 10 billion m^3, respectively.

Whilst this study represents a further step in understanding the global sustainability impacts of soil erosion, a number of considerations and caveats should be noted. Physical and economic models typically work at different temporal and spatial scales, which complicates model linkage. Most pertinently, the need to interface RUSLE with MAGNET implies that the site-specific soil erosion data must be adapted at the larger spatial scale of the CGE model. Additional uncertainty arises from the assumptions of the study. As discussed in Section 2, it is assumed that land productivity losses occur only on severely eroded land with average crop productivity losses assumed at 8%. Although based on a deep literature review, this average estimate masks considerable heterogeneity across regions. The study also employs the restrictive assumption that land productivity losses are assumed to be uniform for all cropping activities within the same country, whilst one must also be aware that soil erosion brings about not only a loss of land productivity, but also of the physical land stock (not considered in this study). As discussed in Section 4.5, this study does not take into account the differences in possible land use consistent with land management practises consistent within the SSPs, whilst a further modelling refinement would be to explore the importance of adaptation (e.g., including new crop varieties, cultivation techniques, soil erosion prevention measures) in curbing the negative effects of soil erosion. On a more general point, the study focuses exclusively on soil erosion rates by water, whilst a more complete picture would involve a more comprehensive consideration of other natural processes and human activities, which may exacerbate the impact on land productivity (i.e. wind, overcropping, deforestation, etc.). All these points constitute potential avenues for future research.

Disclaimer

The views expressed are purely those of the authors and may not in any circumstances be regarded as stating an official position of the European Commission.

CRediT authorship contribution statement

Martina Sartori: Conceptualization, Formal analysis, Investigation, Methodology, Project administration, Supervision, Visualization, Writing – original draft, Writing – review & editing. **Emanuele Ferrari:** Conceptualization, Investigation, Methodology, Writing – original draft, Writing – review & editing. **Robert M'Barek:** Investigation, Writing – original draft. **George Philippidis:** Conceptualization, Investigation, Methodology, Validation, Writing – original draft, Writing – review & editing. **Kirsten Boysen-Urban:** Writing – original draft. **Pasquale Borrelli:** Conceptualization, Data curation, Investigation, Visualization. **Luca Montanarella:** Conceptualization, Data curation. **Panos Panagos:** Conceptualization, Data curation, Investigation, Supervision, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors whose names are listed immediately below certify that they have NO affiliations with or involvement in any organization or entity with any financial interest (such as honoraria; educational grants; participation in speakers' bureaus; membership, employment, consultancies, stock ownership, or other equity interest; and expert testimony or patent-licensing arrangements), or non-financial interest (such as personal or professional relationships, affiliations, knowledge or beliefs) in the subject matter or materials discussed in this manuscript.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolecon.2023.108103.

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