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# A linkage between the biophysical and the economic: Assessing the global market impacts of soil erosion

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ABSTRACT

Employing a linkage between a biophysical and an economic model, this study estimates the economic impact of soil erosion by water on the world economy. The global biophysical model estimates soil erosion rates, which are converted into land productivity losses and subsequently inserted into a global market simulation model. The headline result is that soil erosion by water is estimated to incur a global annual cost of eight billion US dollars to global GDP. The concomitant impact on food security is to reduce global agri-food production by 33.7 million tonnes with accompanying rises in agri-food world prices of 0.4%–3.5%, depending on the food product category. Under pressure to use more marginal land, abstracted water volumes are driven upwards by an estimated 48 billion cubic meters. Finally, there is tentative evidence that soil erosion is accelerating the competitive shifts in comparative advantage on world agri-food markets.

## 1. Introduction

In a changing world of eight billion people facing the critical threats of climate change, water scarcity and depletion of soil fertility, the agricultural economy is faced with the challenge of maintaining food security whilst respecting environmental and ecological boundaries (Altieri and Nicholls, 2017). A key element for ensuring a sustainable system of food production is linked to effective soil management, which requires a reduction in soil erosion rates (Poesen, 2018). Among various land degradation processes, soil erosion is recognized as a major environmental problem causing a loss of topsoil and nutrients, reduced soil fertility (Zhao et al., 2013) and, as a consequence, reduced crop yields (Telles et al., 2011). Furthermore, soil erosion may unlock and thereby increase emissions of $CO_2$, exacerbating global warming (Lugato et al., 2018).

The main causes for soil erosion by water are geomorphological factors (heterogeneous surfaces, steep slopes) combined with climatic risk (rainfall erosivity, increased number of dry days combined with strong thunderstorms) and human activities (e.g. land use change, deforestation, overgrazing, agricultural intensification) (Panagos et al., 2016). Soil erosion is a major threat to agricultural soil productivity (losses in yields, nutrients and plantations) and may also generate off-site impacts such as sedimentation, flooding, damage to properties, landslides, and water eutrophication (Boardman and Poesen, 2006). The best techniques to prevent or reduce soil erosion rates are reduced tillage, contour farming, terraces, afforestation of slopes, plant residues, cover crops, grass margins and brush layers (Poesen, 2018; Panagos et al., 2016).

A recent estimation of land degradation costs shows that the global economic impact is highly uncertain, from 40 to 490 billion US$, and varies from country to country (Nkonya et al., 2016). More than two decades ago, Pimentel et al. (1995) estimated the on-site costs of water erosion in the United States of America to be about 16 billion US$ per year based on expert knowledge. Similarly, the agricultural

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productivity loss due to soil erosion in the European Union is estimated to be around 300 million € (Panagos et al., 2018) using a combination of the recent soil loss assessment and the well-known Global Trade Analysis Project (GTAP) computable general equilibrium (CGE) simulation model. A recent application to the African continent estimates the annual loss of crop yield to be about 280 million tonnes (Wolka et al., 2018), compared with a corresponding figure of only six million tonnes in the European Union (Panagos et al., 2018).

With one notable exception (Panagos et al., 2018), a typical feature of the aforementioned studies is that they carry out a 'first-order' cost evaluation exercise focusing on agricultural production losses (Martínez-Casasnovas and Ramos, 2006; Erkossa et al., 2015; Hein, 2007). More specifically, the economic value of land productivity loss is calculated by the direct loss in production of the affected crops (tonnes) multiplied by their respective average market prices ($/tonnes). Thus, the vast majority of these studies do not capture the resulting 'second-round' effects of structural economic change that arise owing to shifts in primary resources, particularly the land factor. Moreover, to the best of our knowledge, there is no study that fully captures these structural impacts from land productivity losses due to soil erosion at the *global* scale.

To close this gap in the literature, an approach akin to Panagos et al. (2018) is followed. Thus, a sequential modelling framework is employed, where national and regional soil erosion rates provided by the recent global soil erosion assessment (Borrelli et al., 2017) are first converted into land productivity losses, and then implemented into the Modular Applied GeNeral Equilibrium Tool (MAGNET) (Woltjer and Kuiper, 2014). At its core, MAGNET is essentially the GTAP model (Corong et al., 2017), although it is preferred largely because it contains a superior modelling treatment of agricultural factor markets. The counterfactual thus captures the resulting marginal market impacts in agricultural (and non-agricultural) activities, which arise in each region due to soil erosion.

The rest of this paper is structured as follows. Section two explains how soil erosion rates and land productivity losses are obtained. Section three shows how the economic impact of soil erosion is measured, whilst the results are presented in Section four. A final section discusses how these findings can benefit the formulation of relevant land use policy, presents some of the caveats and adds some concluding remarks.

## 2. Estimating global soil erosion rates and land productivity losses

Long-term annual soil erosion rates are obtained from Borrelli et al. (2017), 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 ˜250 × 250 m cell bases for the land surface of 202 countries (around 2.89 billion cells; ˜125 million km$^2$), covering about 84.1% of the Earth’s land area. The soil erosion (Mg ha$^{-1}$ yr$^{-1}$) resulting from interrill and rill erosion (Fig. 1) processes is based on the following multiplicative equation:

$$A_g = R_g * K_g * LS_g * C_g * P_g \quad (1)$$

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 Eq. (1), RUSLE consists of a multiplicative equation including five environmental parameters (Fig. 1). 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 3625 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. 90 m) 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. More detailed information on Eq. (1) is provided in Appendix A1.

The study focuses on 14 million km$^2$, 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 Km$^2$, which coincides with the statistics provided by the World Bank[1] and FAO[2] .

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): (2)$LPL_r = SEA_r/TAA_r$*0.08Where SEA$_r$ is the area of severe erosion per region/country 'r' in hectares and TAA$_r$ is the agricultural area in each region/country 'r'. This study assumes a mean crop productivity loss of 8% in arable lands threated 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).

## 3. Measuring the economic impact of soil erosion

### 3.1. Model framework and data

Neoclassical multi-region CGE models enumerate the theoretical economic tenets of constrained optimisation, to govern the behaviour of agents (i.e., households, producers, government, investors – see Fig. 1) across the global economy. 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 (Fig. 1).

To underpin the model framework, a ‘benchmark’ equilibrium year of data representing a balanced system of national economic accounts, gross bilateral trade flows and protection and international transport margins is required. To ensure the model replicates the equilibrium conditions of the benchmark year, the mathematical parameters of the behavioural equations are ‘calibrated’ to the database. Ensuring that the number of endogenous variables and model equations are equal (closure), powerful computer algorithms are employed to reach an

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[1] https://data.worldbank.org/indicator/ag.lnd.arbl.zs

[2] http://www.fao.org/docrep/005/y4252e/y4252e06.htm

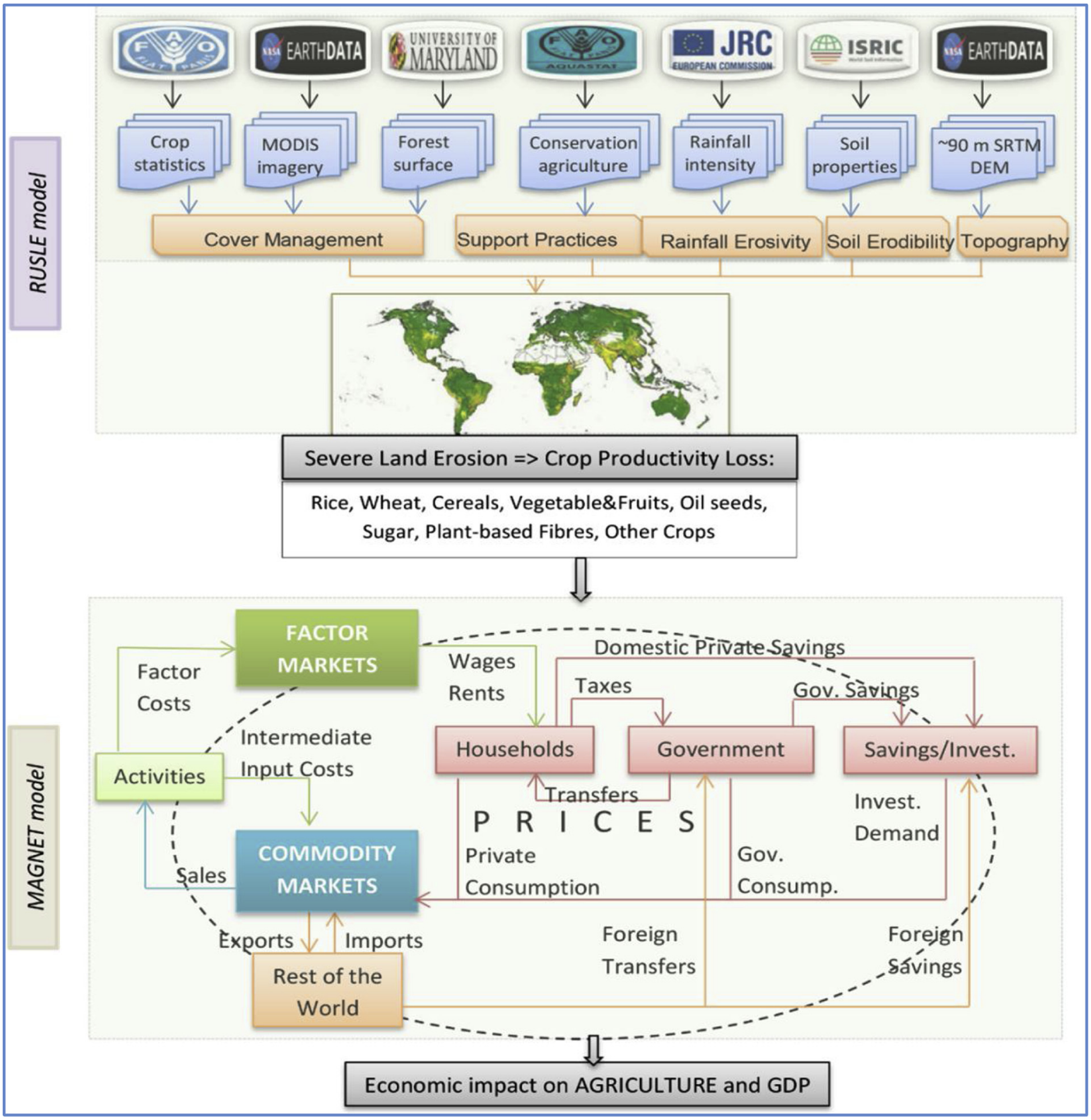

**Fig. 1.** Sequential modelling approach adopted in this study and model description.

‘equilibrium’ solution. More specifically, in response to a policy or structural shock, the economic system moves to a new ‘counterfactual’ solution characterised by a unique set of prices such that demand matches supply in ‘n’ markets; income, output and expenditure flows are equal, and the balance of payments between the current and capital accounts nets to zero. Comparing the counterfactual with the benchmark gives an indication of the marginal impact of the shock on market indicators (i.e., typically in terms of prices, outputs, trade flows and real incomes).

In this study, a state-of-the-art recursive dynamic, multi-region, multi-sector neoclassical CGE model, known as the Modular Applied GeNeral Equilibrium Tool (MAGNET) (Woltjer and Kuiper, 2014), is used. A key advantage of MAGNET is its modular structure that allows the user to easily switch on/off non-standard modelling extensions which are pertinent to the research question at hand. Given this flexibility, the model has been used in numerous contexts including land-use change (e.g., Schmitz et al., 2014); EU domestic support (e.g., Boulanger and Philippidis, 2015); biofuels and bioeconomy (e.g., Smeets et al., 2014; Philippidis et al., 2018a); food security (Rutten et al., 2013), climate change (van Meijl et al., 2018) and international trade (Philippidis et al., 2018b 2018b). In common with GTAP, MAGNET is calibrated to the GTAP database (Aguiar et al., 2016), which in this study employs version 9 with a benchmark year of 2011. The GTAP data encompasses 141 regions and countries, 57 tradable sectors and eight factors of production (including agricultural land).

An important modelling advance over the standard GTAP model is that MAGNET explicitly characterises the rigidity in agricultural factor markets, both in terms of land transfer between different agricultural activities; and in the labour and capital markets to characterise the wage and rent differentials that exist between agricultural and non-agricultural labour and capital markets.[3] As a result, agricultural sector supply responsiveness in MAGNET is relatively inelastic compared with GTAP. In addition, in contrast with the assumption of fixed agricultural

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[3] See Appendix A2 for further discussion.

land supply in GTAP, the sustainability of land availability is measured more precisely in MAGNET through the use of biophysical data on available agricultural land areas. More specifically, a region specific asymptotic endogenous agricultural land supply function signals available land areas corresponding to changes in the real rental rate of land (Eickhout et al., 2009).[4] 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., 2006; Doelman et al., 2018). 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).[5]

### 3.2. Model integration

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 (Fig. 1), 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.

It is assumed that the productivity impacts of soil erosion rate reported for 2010 by the RUSLE model are already embedded within the 2011 GTAP benchmark data equilibrium. Thus, to assess these marginal impacts, an exogenous reverse (positive) shock is applied to the land productivity parameters to capture the soil erosion event that led up to the 2011 benchmark year. The difference between this counterfactual and the benchmark data gives us a marginal estimate of the resulting market impacts.

## 4. Simulation results

### 4.1. Land productivity losses due to soil erosion

Fig. 2 shows that the highest productivity losses are observed where the highest erosion rates (mean erosion in arable lands $> 11\ \text{t ha}^{-1}\ \text{yr}^{-1}$) occur in countries with high share of agricultural land. In the majority of Caribbean countries (Nicaragua, Guatemala, Haiti, El Salvador, Honduras, Panama), Brazil, Central African countries (Congo, Liberia, Democratic Republic of Congo, Ivory Coast, Malawi and Ethiopia) and some parts of South-East Asia (Vietnam, Philippines, Indonesia, Laos, South Korea) more than 70% of the arable land is experiencing severe erosion ($> 11\ \text{t ha}^{-1}\ \text{yr}^{-1}$). On the contrary, Australia, Canada, Saharan countries, the Russian Federation, Kazakhstan, Uzbekistan, Ukraine and most of the European Union have less than 3% of their arable land under severe erosion. On average, more than 3.4 million km$^2$ of arable land worldwide (24%) is suffering from severe erosion.

To maximise the richness of available regional land productivity estimates generated by the RUSLE model as input for the MAGNET model, outputs are aggregated to 115 countries (see Table S3 of the Supplementary material), the results of which are presented as 18 macro-regions (8′large' countries plus 7 macro-regions grouping neighbouring countries and the rest of the world, Table 1)[6] .

The sector aggregation in MAGNET includes the seven main GTAP agricultural cropping activities (i.e., rice, wheat, other cereals, horticulture, oilseeds, raw sugar, and a residual 'other cropping' activity) and seven non-arable and food processing activities (i.e., livestock, meat, dairy, processed sugar, processed rice, vegetable oils and fats, other food). Fertilizers, non-food manufacturing, services and energy and natural resources activities are aggregated into four sectors (see Table S4 of the Supplementary material).

### 4.2. Macroeconomic impact

The CGE model captures the 'first-round' impacts from *relative* soil productivity changes across regions. Thus, whilst the magnitude of the reverse productivity shocks provided by RUSLE is consistent in sign across all regions, the strength of this effect is highly heterogeneous. Those regions with larger (smaller) crop productivity deterioration will exhibit marginal relative deteriorations (improvements) in competitiveness, resulting in a marginal negative (positive) crop production trend. In addition, the model also accounts for 'second-round' economy-wide ripple effects which are both 'local' and 'broader' in nature. The former are felt through the re-allocation of agricultural land between competing uses and the vertical transmission from upstream agriculture to downstream food activities (i.e., supply of inputs). The latter reflects the impacts on the returns to labour and capital (i.e., wages and rents) from their redistribution from agricultural to non-agricultural uses, and the resulting economy-wide repercussions on household incomes, production and macroeconomic growth. Results show that global losses in crop production are clearly overestimated by a direct-impact computation.[7] Unless otherwise stated, all marginal impacts reported are either in percentage terms, volumes or dollar values.

As expected, the macro impacts are fairly muted, given that the annual land productivity shock is relatively moderate and concentrated in the agriculture sector. The general pattern is that soil erosion is not beneficial to real gross domestic product (GDP) growth (Fig. 3 and Table S5 of the Supplementary material): the declining productivity in agriculture arising from the deterioration of the land factor has an almost unambiguous negative economic impact. In monetary terms, this amounts to a loss of approximately 8 billion US dollars of GDP.

In all regions, a decrease in the production possibilities with the same input availability should bestow negative macroeconomic impacts to the region under consideration. This is particularly the case where estimated regional land productivity deteriorations due to soil erosion are larger (i.e., Indonesia, 'Central America and the Caribbean'). Equally, regions which have a larger agricultural base and a relatively larger share of value added accruing from the land factor (i.e., India) also show greater relative decreases in their GDP, despite more moderate changes in land productivity. In relative terms, the biggest losers due to soil erosion are Indonesia and India, with recorded losses approximating 0.1% of GDP, whilst in Nigeria and 'Central America and the Caribbean', the reported loss is closer to 0.04% of GDP.

In other regions (i.e., Europe, USA and Canada, Oceania, MENA) agriculture's share of GDP is relatively small, in some cases heavily subsidized, and land productivity losses are less pronounced. As a result, macroeconomic losses are negative and in some cases (USA and Canada, Oceania) even marginal gains are observed as these regions find themselves in a relatively more favourable production and trade position (Tables 2A, 2Band Fig. 7).

### 4.3. Agriculture and food security

#### 4.3.1. Production

As a measure of global food security, Tables 2A, 2B show that food production has decreased by approximately 33.7 million tonnes[8]

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[4] See Appendix A3 for further discussion.

[5] For further details see Woltjer and Kuiper (2014), pp. 71-77.

[6] Results are also available for all 115 aggregated regions in the Supplementary material document.

[7] Table S11 of the Supplementary material compares the marginal absolute change in crop production by country as obtained from the CGE analysis and from a back-on-the-envelope direct-impact estimation. Additional comments are provided in the Supplementary material.

[8] Physical quantities are updated as ex-post calculations using endogenous

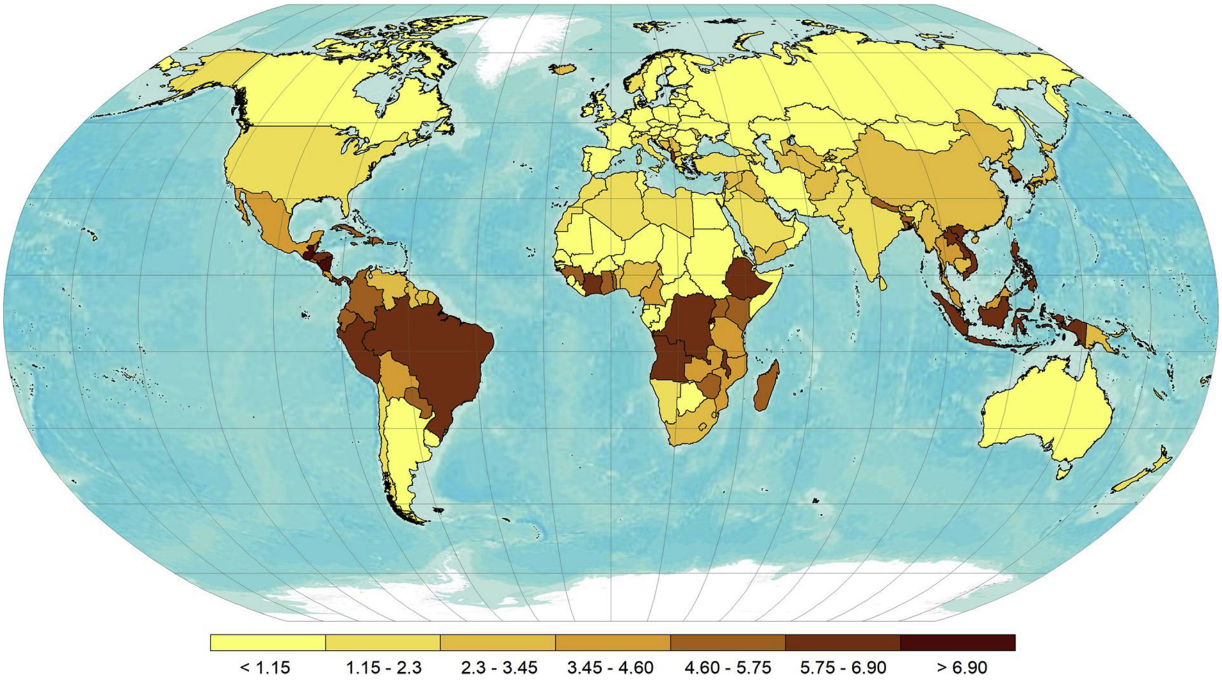

**Fig. 2.** Estimated annual absolute land productivity losses (%) from the Global RUSLE model. Country values are reported in Table S2 of the Supplementary material.

**Table 1**
. Regional aggregation for result visualization. In 2011, the ten largest producers of agricultural goods were: China, Brazil, India, USA, Indonesia, Russia, Thailand, Nigeria, Argentina and France. We have kept disaggregated the first five countries and the only African country of the list. USA and Canada are aggregated together as Canada's geographical characteristics a land productivity shock are more similar to those of the USA than Mexico's.

| Macro-Regions | MAGNET regions | Arable land (million ha) |
|---|---|---|
| Brazil | Brazil | 71 |
| China | China | 112 |
| India | India | 160 |
| Indonesia | Indonesia | 20 |
| Nigeria | Nigeria | 34 |
| Russia | Russian Federation | 122 |
| USA&Canada | USA and Canada | 196 |
| Central Amer. and the Caribbean (CAmer& Caribb) | Costa Rica, Guatemala, Honduras, Nicaragua, Panama, Caribbean | 5 |
| Central Asia | Armenia, Azerbaijan, Georgia, Kazakhstan, Kyrgyzstan, Tajikistan | 33 |
| West, Central, East and South Africa (WCES Africa) | Benin, Burkina-Faso, Cameroon, Cote d'Ivoire, Ghana, Guinea, Senegal, Togo, Rest of West-Central Africa, Rest of South-Central Africa, Ethiopia, Kenya, Madagascar, Malawi, Mozambique, Rwanda, Tanzania, Uganda, Zambia, Zimbabwe, Rest of East Africa, Botswana, Namibia, South Africa | 160 |
| Europe | Austria, Belgium, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Netherlands, Poland, Portugal, Slovakia, Slovenia, Spain, Sweden, UK, Switzerland, Norway, Albania, Bulgaria, Belarus, Croatia, Romania, Ukraine, Turkey | 171 |
| Middle East-North Africa (MENA) | Bahrain, Iran, Israel, Jordan, Kuwait, Oman, Qatar, Saudi Arabia, UAE, Egypt, Morocco, Tunisia, Rest of North-Africa | 60 |
| Mexico | Mexico (Rest of North America) | 24 |
| Oceania | Australia, New Zealand | 48 |
| South America | Argentina, Bolivia, Chile, Colombia, Ecuador, Paraguay, Perú, Uruguay, Venezuela | 62 |
| South-East Asia (SE Asia) | Japan, Republic of Korea, Mongolia, Cambodia, Laos, Malaysia, Philippines, Thailand, Vietnam, Bangladesh, Nepal, Sri Lanka, Pakistan | 80 |
| Rest of the World | Rest of the World (ROW) | 48 |

(Table 2A), of which 22.5 million tonnes are crops (Table 2B), due to severe erosion. This is equivalent to 0.41% (0.27% for crops only) of global agricultural production. Results are also illustrated in Fig. 4 (absolute variation in agri-food production in million tonnes) for all available countries (corresponding numbers are reported in Table S6.1 and S6.2 of the Supplementary material). Due to the lower amount of agri-food products available in the international markets and the consequent price increase, the total value of these goods has increased by 24.9 billion US$.

Given the description of the 'first-round' model driver discussed above, the contribution to the total impact on crop output varies substantially across macro-regions. According to the output of the RUSLE model, the areas of China and South-East Asia have larger land productivity losses reflecting the larger soil erosion effects. As a result, these regions are major drivers in the global crop output deterioration.

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*(footnote continued)*
changes in sector specific agricultural production volumes from the model over each period based on Ramankutty (2005). The original data source is FAOSTAT data on harvested areas and yields to derive the production quantities which are provided as a satellite account for MAGNET.

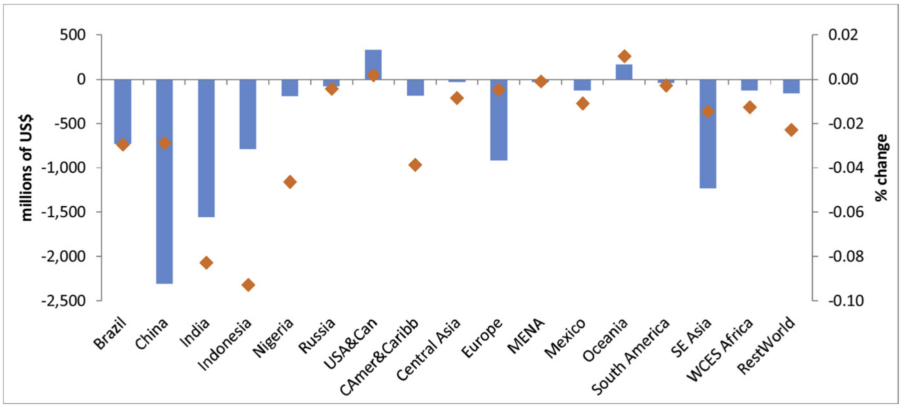

**Fig. 3.** Marginal % and absolute change in GDP (US $, 2011 prices) due to severe soil erosion.

**Table 2A**
Marginal absolute change in selected crop activities due to severe soil erosion ('000 tonnes). Negative (positive) numbers mean output losses (gain).

| | Rice | Wheat | OthCereals | Horticulture | OilSeeds | Sugar | *TOT Crops* |
|---|---|---|---|---|---|---|---|
| Brazil | −15 | −279 | 175 | −974 | −1,030 | −4,071 | *−6,330* |
| China | −522 | 1390 | −53 | −3,227 | −716 | −700 | *−3,865* |
| India | −888 | −748 | −143 | −2,522 | −510 | −2,599 | *−7,739* |
| Indonesia | −770 | 0 | −201 | −695 | −1,675 | −334 | *−4,102* |
| Nigeria | −3 | 1 | −20 | −255 | −10 | 0 | *−283* |
| Russia | 9 | 395 | 96 | 84 | 100 | 45 | *729* |
| USA&Can | 126 | −95 | 627 | 431 | 758 | −58 | *1,856* |
| CAmer&Caribb | −22 | 0 | −34 | −245 | −47 | −304 | *−690* |
| Central Asia | 2 | 221 | 10 | 38 | 85 | −1 | *473* |
| WCES Africa | 4 | 17 | 57 | −93 | 81 | 49 | *230* |
| Europe | 32 | 467 | 755 | 533 | 447 | 1,005 | *3,320* |
| MENA | 8 | 156 | 39 | 437 | 7 | 118 | *797* |
| Mexico | −2 | −99 | −165 | −259 | −32 | −69 | *−654* |
| Oceania | 9 | 148 | 162 | 110 | 34 | 129 | *657* |
| South America | 48 | 115 | 178 | −108 | 481 | 23 | *750* |
| SE Asia | −1,798 | −270 | −191 | −2,450 | −1,595 | −226 | *−7,136* |
| RestWorld | −195 | −89 | −33 | −305 | −43 | −7 | *−700* |
| *Tot World* | *−3,976* | *1,343* | *1,278* | *−9,381* | *−3,662* | *−6,991* | *−22,526* |

**Table 2B**
Marginal absolute change in livestock and food activities due to severe soil erosion ('000 tonnes). Negative (positive) numbers mean output losses (gain).

| | Livestock | Meat | ProcSugar | ProcRice | VegOilFat | Dairy | *TOT Agri-Food (2A + 2.2)* |
|---|---|---|---|---|---|---|---|
| Brazil | −385 | −182 | −1,089 | 19 | −62 | −9 | *−8,170* |
| China | −786 | −498 | −250 | −418 | −502 | −22 | *−6,737* |
| India | −1,114 | −207 | −760 | −451 | −490 | −268 | *−11,259* |
| Indonesia | −49 | −5 | −106 | −512 | −247 | 0 | *−5,031* |
| Nigeria | 0 | 0 | 2 | 81 | −7 | 6 | *−228* |
| Russia | 3 | 14 | 17 | 4 | 35 | 11 | *817* |
| USA&Can | −112 | −39 | −55 | 93 | 84 | −110 | *1,660* |
| CAmer&Caribb | −69 | −17 | −106 | −13 | −3 | −11 | *−924* |
| Central Asia | −18 | 4 | 1 | 3 | 35 | −4 | *495* |
| WCES Africa | 32 | 6 | 64 | 71 | 94 | 1 | *482* |
| Europe | 42 | −3 | 602 | 27 | 250 | 35 | *4,232* |
| MENA | −28 | 35 | 66 | 18 | 44 | −15 | *903* |
| Mexico | −98 | −30 | −18 | 0 | −30 | −1 | *−848* |
| Oceania | 72 | 19 | 61 | 7 | 23 | −52 | *786* |
| South America | −128 | −49 | 9 | −11 | 144 | −19 | *667* |
| SE Asia | −518 | −256 | −42 | −1,106 | −511 | −43 | *−9,839* |
| RestWorld | −94 | −56 | 5 | −69 | 44 | −28 | *−921* |
| *Tot World* | *−3,242* | *−1,258* | *−1,594* | *−2,257* | *−1,097* | *−527* | *−33,725* |

More specifically, Indonesia, China, India and the rest of South East Asia's crop production has decreased by approximately 4.1, 3.9, 7.7 and 7.1 million tonnes, respectively (Table 2A). A similar observation can be made for Brazil, where the result is a decrease in crop output of 6.3 million tonnes.

In contrast, for the 'USA and Canada' region and Europe, which had smaller crop productivity impacts from the RUSLE model (Fig. 2), both regions exhibit the largest crop output increases. More specifically, these two regions show crop production rises of 3.3 million tonnes and 1.9 million tonnes, respectively.

Despite the negative impacts on crop production in Nigeria and other big countries of Central-South Africa (e.g., Kenya, Ghana, Ethiopia, see Table S6.1 and S6.2), overall African crop production rises slightly as a result of severe soil erosion (around 375 thousand tonnes),

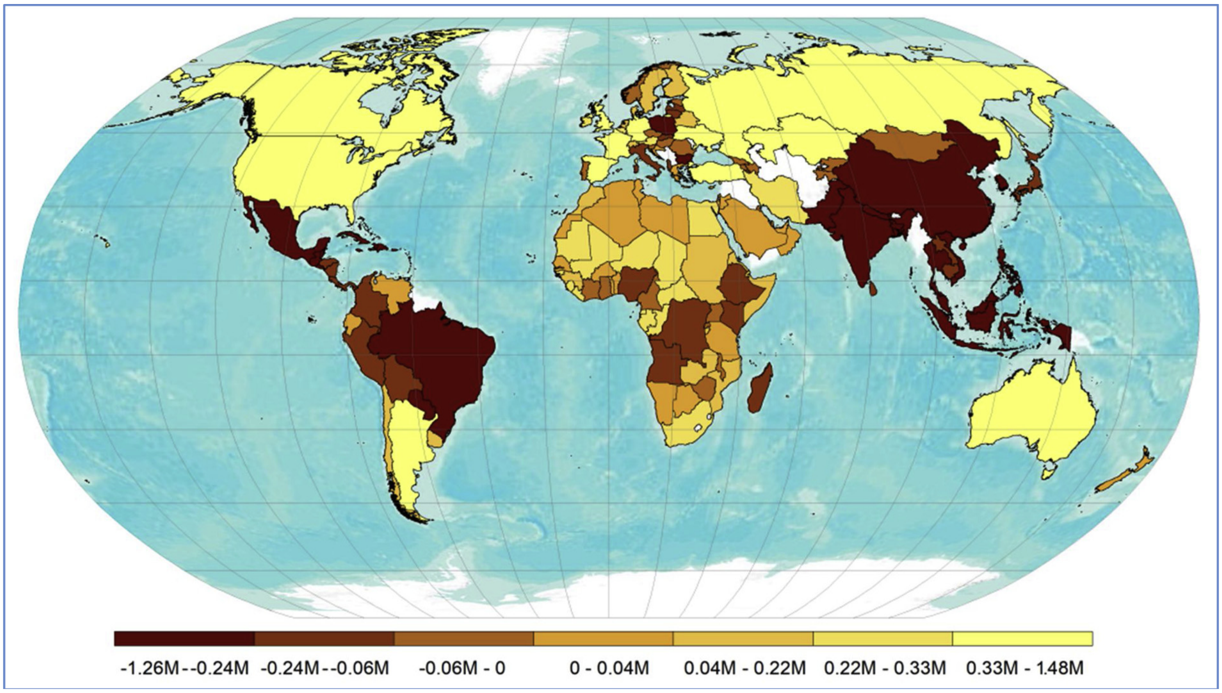

**Fig. 4.** Marginal absolute change in agri-food production (million -M- tonnes) due to severe soil erosion. Results are illustrated for 109 single countries, five macro-regions and one residual region, the latter for clarity reasons is not shown in the map. Macro-regions and the residual region are illustrated in Figure S1 of the Supplementary material.

in large part driven by the production gains recorded in South Africa and Northern African countries (i.e., Egypt)[9] . This result is due to two main factors. Firstly, whilst the demand for more marginal land increases in all regions (Table S7 and Fig. 5) to compensate for the lower land productivity, the availability of unused agricultural land is estimated to be relatively more abundant in the African continent (approximately 4 million against 2.3 million km$^2$ of China, Brazil and India). In this region, land demand expands by about 58,250 km$^2$ (26% of global rise), whilst in China, Brazil and India the increase is smaller, although significant (approximately 17,000, 29,500 and 7,400 km$^2$ respectively). Secondly, the countries located in the North and in the South of the African continent account for a big share of the agricultural production in Africa and compensate the substantial productivity losses occurred in the Central region. As a result, Africa as a continent experiences a slight improvement in its comparative advantage and positive production trends. The same result holds for other regions (e.g. 'USA and Canada', Europe and Oceania), where one or the other reason mentioned above may prevail in driving the positive production output.

Globally, land demand increases by approximately 223,000 km$^2$, equivalent to a 0.5% increase in global land use in agriculture. The largest contributions arise from cereals (27%), driven by the positive change in production, horticulture (19%) and oil seeds (19%) activities (Table 3).

Decomposing the result on production further (Supplementary material), it emerges that the positive result is driven by cereals and horticulture production increases in South Africa and in north African countries, while some West (Cameroon, Cote d'Ivoire, Ghana) and East African countries (Ethiopia, Kenya, Madagascar and Rwanda) suffer in terms of horticulture production loss, which are typically high value added cash crops for these countries.

Importantly, it should be noted that whilst land productivity losses are assumed to be uniform for all cropping activities within the same country, the market impacts on crop activities within a region is heterogeneous. This observation occurs due to the combination of regional patterns of soil erosion across the regions reported by RUSLE and the relative trade competitiveness of individual crops across regions, captured in the MAGNET model. For example, rice production is found to be acutely affected by the pattern of soil erosion. The average productivity shock hitting the top 75% of world rice producers (principally in South East Asia and China) is 3.7%, compared with 2.1% for the remaining countries (not shown). As a result, examining the collective impact on paddy- and processed rice activities (Tables 2A, 2B), this single supply chain accounts for 19% of the global agri-food volume decrease. Similarly, horticultural products account for 28% of the agri-food volume decrease, which is also driven by South-East Asia and China. Given Brazil's comparative advantage in soybean and sugar cane, the same observation can be made for these two crops. More precisely, oilseed makes up 11% of the overall agri-food production decrease, whilst the entire sugar production chain makes up 26% of the total.

In the case of wheat and other cereals, global production increases by 2.6 million tonnes (which in relative terms is 0.1% for both, see Fig. 6), and reflects the fact that calculated region wide land productivity impacts from erosion effects for the key producers of these crops, are relatively lower. For example, the largest wheat producers (e.g., Canada and Russia) are hit by an average productivity shock of 1.3%, compared with 3% for the remaining countries.

In livestock and food processing activities, the local 'second-round' model drivers discussed at the beginning of this section come to the fore. With decreased global production in many cropping activities, feed costs are also higher because of soil erosion impacts. As a result, livestock, meat and dairy production is also lower (3.2 million tonnes, 1.3 million tonnes and 527 thousand tonnes, see Table 2B). Similarly, the upstream-downstream links between crops and food processing sectors show the implications of the net decrease in crop output on food processing sectors.

### 4.3.2. *Trade*

The results in Fig. 7 show the marginal impacts on the agri-food

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[9] This result cannot be directly observed from Table 2A as the North-Africa region is aggregated with the countries of the Middle East.

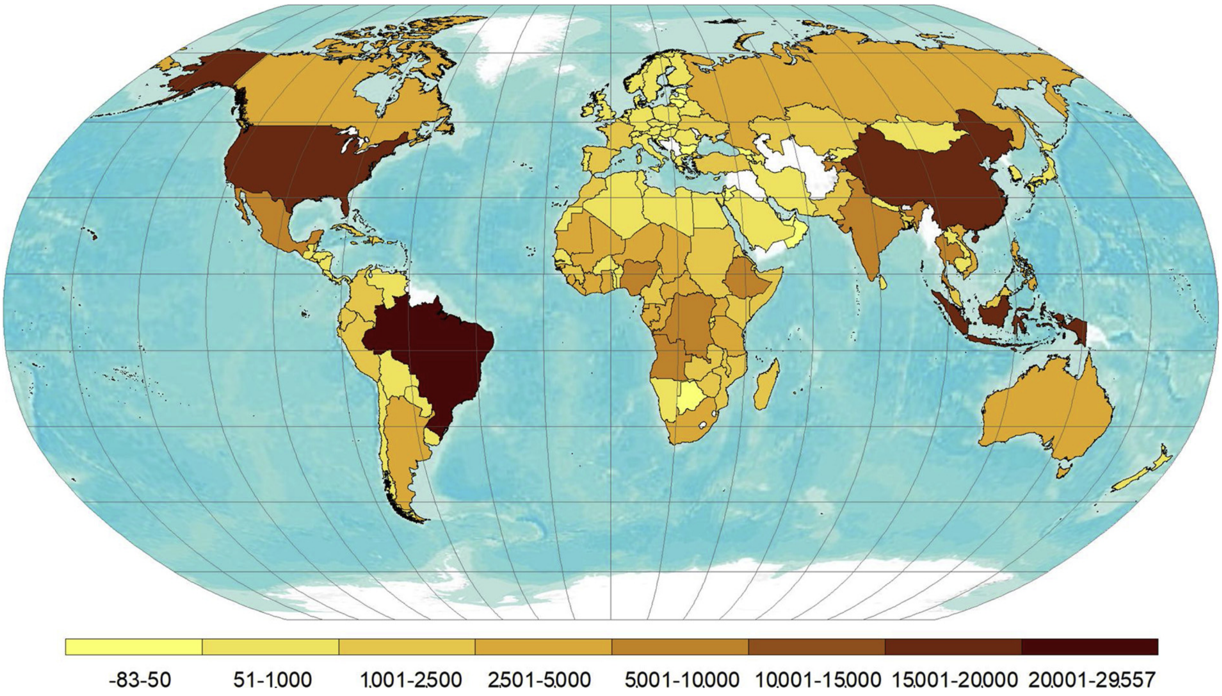

**Fig. 5.** Marginal absolute change in land demand by country (km$^2$) due to severe soil erosion. Results are illustrated for 109 single countries, five macro-regions and one residual region, the latter for clarity reasons is not shown in the map. Macro-regions and the residual region are illustrated in Figure S1 of the Supplementary material.

**Table 3**

. Marginal absolute change in land demand (km$^2$) due to severe soil erosion. Percentage value in the last column indicate the percentage change relative to the amount of land used in agriculture in 2011.

| | Rice | Wheat | OthCereals | Hortic. | OilSeeds | Sugar | OthCrops | *Total* | *% of Tot* |
|---|---|---|---|---|---|---|---|---|---|
| Brazil | 1,393 | 41 | 8,747 | 3,786 | 9,660 | 4,020 | 1,909 | *29,556* | *1.1%* |
| China | 2,599 | 4,821 | 4,136 | 3,764 | 702 | 152 | 893 | *17,067* | *0.3%* |
| India | 2,024 | 1,151 | 1,980 | 972 | 277 | 203 | 797 | *7,404* | *0.5%* |
| Indonesia | 6,099 | 0 | 1,805 | 2,048 | 3,198 | 194 | 4,237 | *17,581* | *3.1%* |
| Nigeria | 312 | 20 | 1,774 | 2,406 | 976 | 6 | 344 | *5,838* | *0.8%* |
| Russia | 25 | 2,789 | 474 | 43 | 1,199 | −1 | 12 | *4,541* | *0.2%* |
| USA&Can | 379 | 2,401 | 7,814 | 1,085 | 8,820 | 119 | 811 | *21,429* | *0.5%* |
| CAmer&Caribb | 357 | 2 | 1,247 | 1,495 | 175 | 657 | 670 | *4,603* | *1.7%* |
| Central Asia | 7 | 1,534 | 171 | 132 | 503 | 3 | 435 | *2,785* | *0.1%* |
| WCES Africa | 2,096 | 1,266 | 17,809 | 15,459 | 6,581 | 488 | 5,885 | *49,584* | *0.5%* |
| Europe | 48 | 2,365 | 3,236 | 1,529 | 2,611 | 206 | 272 | *10,267* | *0.4%* |
| MENA | 46 | 2,157 | 1,192 | 1,717 | 62 | 36 | 120 | *5,330* | *0.1%* |
| Mexico | 12 | 77 | 3,475 | 1,164 | 61 | 358 | 435 | *5,582* | *0.5%* |
| Oceania | 14 | 1,227 | 1,397 | 325 | 330 | 26 | 186 | *3,505* | *0.1%* |
| South America | 786 | 784 | 2,159 | 2,049 | 3,808 | 361 | 1,174 | *11,121* | *0.4%* |
| SE Asia | 10,338 | 217 | 2,114 | 2,871 | 1,547 | 788 | 2,714 | *20,589* | *1.0%* |
| RestWorld | 1,450 | 590 | 1,196 | 1,512 | 835 | 141 | 391 | *6,115* | *1.1%* |
| *Tot WORLD* | *27,992* | *21,540* | *60,820* | *42,571* | *41,358* | *7,765* | *21,292* | *223,338* | *0.5%* |

trade balance (i.e., exports minus imports) measured in millions of US dollars. On the one hand, the 'production effect' determines the internal market balance and consequently available exports from each country/region. On the other hand, with increases in real growth, rising real incomes drive additional demand for agri-food products. In developing countries typified by lower per capita incomes, the marginal demand increases are expected to be larger given the higher income elasticity of demand. Examining the net impact of these drivers on the trade balances, large agri-food importers such as China and the rest of South East Asia have further increased their trade deficits. In contrast, the 'USA and Canada', Europe and the 'rest of South America', all of which are net exporters of agri-food commodities, gain a further relative competitive edge from soil erosion, resulting in improvements in their agri-food trade balances.

Examining the impacts on total agri-food trade, of the 450 billion $US in primary agricultural (crops and livestock) trade, soil erosion is found to reduce this by approximately 8.5 billion $US. Similarly, of the total food trade of 900 billion $US, the corresponding soil erosion impact is recorded as 3.5 $US billion.

### 4.3.3. *Food prices*

Examining the affordability of food, Fig. 8 clearly shows soil erosion has inflated food prices due to the productivity effects on producer prices in all countries. The most impacted commodity is paddy rice, whose world price has risen by 3.5%, followed by world prices in wheat, other cereals and other relevant staple foods (around 1.5% larger)[10] . The effects on primary agriculture are then transmitted to

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[10] The productivity driven effect drives a world price increase also in

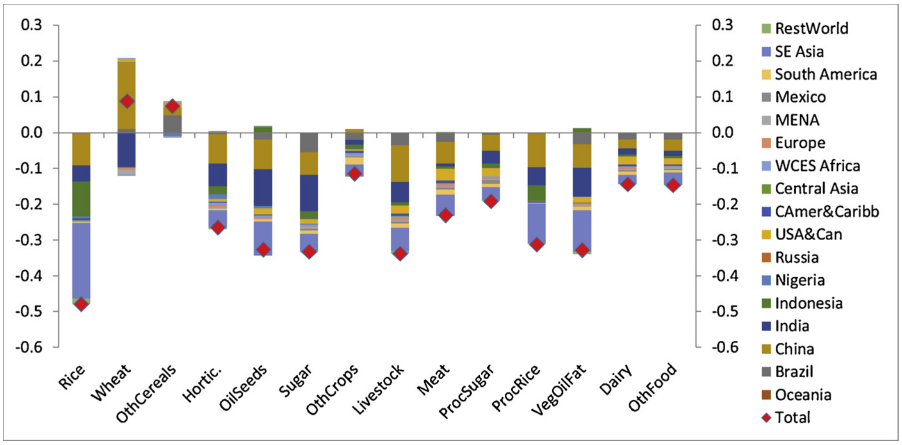

**Fig. 6.** Marginal percentage change in global agri-food production due to severe soil erosion by country shocks.

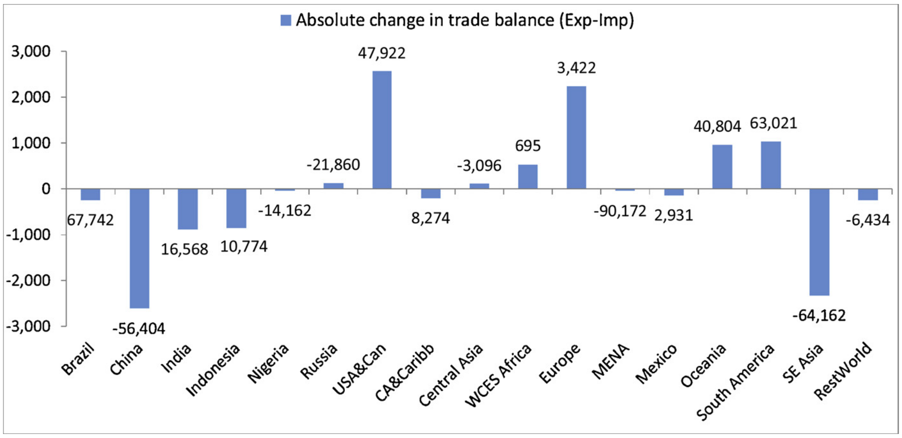

**Fig. 7.** Marginal change in trade balance (exports minus imports, millions of US$, 2011 prices) of agri-food commodities. Initial trade balance values (in millions of US$) are reported as bar labels. Negative (positive) values indicate that the region is a net importer (exporter) of agricultural products, while negative (positive) bars indicate that the region deteriorates (improves) its initial trade balance.

processed commodities.

The effects of world prices are again mainly driven by shocks in Asian countries, e.g. 37%, 25% and 15% of the change is due to the land productivity losses in South Asia, China and Indonesia, respectively. The same holds for processed rice as well. In terms of global price changes, it is interesting to note that China has the largest impact on most agri-food commodity prices, driving on average one-third of the global price changes (Fig. 8).

Fig. 9 shows the degree to which the affordability of food in each region has changed due to higher food prices. With food price index increases of over two per cent, Indonesia and India are the countries whose food prices are negatively affected the most. Despite the muted impacts on the food price index, for the more vulnerable members of the population whose food budget shares are particularly high, even marginal price changes could have important implications on the family food bill.

Decomposing the food price index changes, Fig. 9 also shows the extent to which the food price index within each region is mainly affected by land productivity shocks from within that same region vis-à-vis relative cost changes from imports from trading partners. For example, although it is a large agricultural producer, India is only on a par with self-sufficiency in most agricultural commodity categories. As a result, India's food price index is almost dominated by the changing cost structure in its domestic market. On the other hand, outliers are the

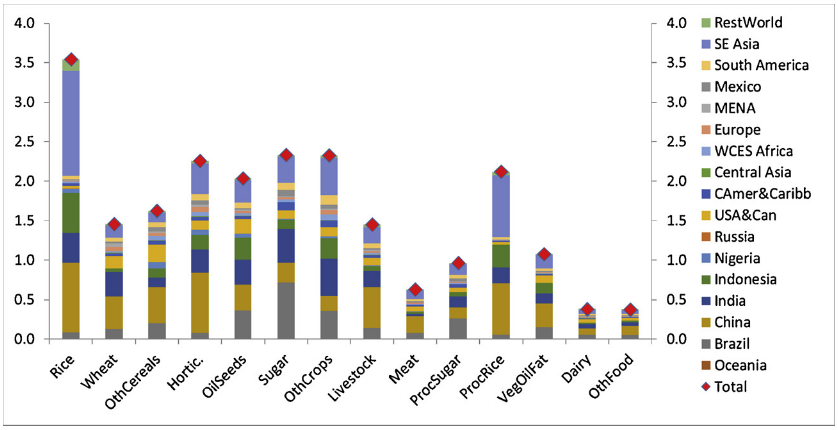

**Fig. 8.** Regional land productivity drivers of the marginal percentage change in world prices by commodity.

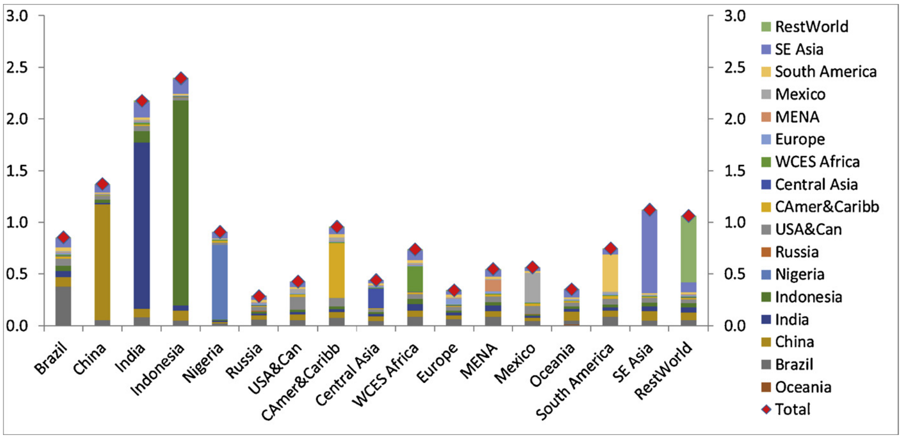

**Fig. 9.** Marginal percentage change in agri-food national price index due to severe soil erosion by country shocks.

Middle East-North Africa (MENA) and Central and South-African (CSA) regions, where self-sufficiency levels are well below unity and heavy trade dependence is more characteristic of their domestic markets. Thus, non-MENA and non-CSA region land productivity shocks make up respectively 80% and 66% respectively of the impact on the food price index in each region.

### 4.4. Water [11]

The land productivity loss due to severe soil erosion requires additional marginal land in production (see Fig. 5). Following the MAGNET model assumption that the share of irrigated land in each crop activity is exogenously fixed, an increase in land use increases water abstraction (Table 4 and Fig. 10). Globally, soil erosion has brought about a 1.6% increase of the water withdrawn for agricultural purposes (which is equal to more than 48 billion cubic meters). In absolute terms, China, Indonesia and South-East Asia represent approximately 14%, 12% and 23% of the global increase, due to the irrigation intensive system of rice production. In proportional terms, Brazil, the 'USA and Canada' region and South America witness water abstraction increases of up to 5%.

On a commodity basis, just under half of the water abstraction increase is due to the impacts of soil erosion in the paddy rice sector. As expected, this figure is almost exclusively driven by the regions of Asia, due to importance of this staple product in the diet (see also Table S8). To compensate for the lower productivity of land, in these countries land demand for rice production increases by about 21,000 km$^2$, corresponding to 75% of global increase in land demand for this crop (Table S7).

## 5. Discussion and concluding remarks

Employing an interdisciplinary approach that links a global biophysical model to a global economic model, this study takes a forward step in understanding the global economic costs of soil erosion. In the context of the broader debate, it provides a direct input into recent strategies such as the Economics of Land Degradation initiative (ELD Initiative, 2015; Nkonya et al., 2016) and the Global Land Outlook (GLO) currently proposed by United Nations Convention to Combat Desertification (UNCCD, 2017).

As a headline figure, the results show that soil erosion is unambiguously detrimental to global food production, resulting in a non-trivial decline in agricultural and food production of 33.7 million tonnes. Even under the (strong) assumption of existing compounded rates of soil erosion over time, coupled with projected rising rates of population, the implications for food security, natural resource management practises (i.e., land, water) and stable societies, particularly in the poorest parts of the world, are concerning. This reinforces the need for greater engagement by stakeholders to raise awareness regarding the central function of soil preservation in our society (Keesstra et al., 2016).

However, a further look at the results reveals that, compared with previous 'first-order' estimates of soil erosion costs, these findings draw markedly different conclusions. For example, in contrast to 'first order' estimates from Wolka et al. (2018), who measure a soil erosion driven production loss of 280 million tonnes in Africa, our study reveals a surprisingly diverse picture. Crop production in the African continent *increases* marginally by 0.35 million tonnes (due to the positive production changes in South Africa and North African countries), since marginal land productivity losses for this continent as a whole are estimated to be lower than in other regions (e.g., China, Brazil, Indonesia). Nonetheless, within the Sub-Saharan African region, the prospects for a number of African countries are more concerning. For example, some West African (Cameroon, Cote d'Ivoire, Ghana and Nigeria) and East African countries (Ethiopia, Kenya, Madagascar and Rwanda) suffer losses in horticultural and cereals production, which are typically high value added cash crops for these countries. In recognition of soil degradation, a number of soil conservation measures are already implemented at regional scale and in many countries[12] . For example, in Kenya small scale conservation tillage and terraces are used to improve water storage capacity and crop land productivity. In Ethiopia, degraded land areas have been enclosed from human and animal use and enhanced by additional vegetative and structural conservation measures, to permit natural rehabilitation (WOCAT, 2007; Giger et al., 2018).

Furthermore, comparing with the CGE study of Panagos et al. (2018), these results present a markedly different picture for the EU since, unlike their study which only examines erosion in the EU, the current scenario design models simultaneous erosion effects throughout the globe. With its relatively milder erosion rates, the EU now is in a relatively more favourable production and trade position, which contrasts sharply with the negative EU production impacts reported in Panagos et al. (2018).

Drilling down into the results, one also observes that even with an erosion shock corresponding to a single year, there are noticeable

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*(footnote continued)*
commodities whose global production is increasing, like wheat and cereals, as domestic price are rising globally.

[11] For further discussion of the water computation in MAGNET, see Appendix A4.

[12] See for example the African Soil Partnership (http://www.fao.org/global-soil-partnership/regional-partnerships/africa) or the Africa Soil Information Service (http://africasoils.net/).

**Table 4**
.Marginal change in water abstraction due to severe soil erosion (million m$^3$). Percentage values in the last column indicate the percentage change relative to the amount of water abstraction in 2011.

| | Rice | Wheat | OthCereals | Hort. | OilSeeds | Sugar | OthCrops | *Total* | *Marg. % chg over tot withdr.* |
|---|---|---|---|---|---|---|---|---|---|
| Brazil | 974 | 0 | 40 | 191 | 31 | 494 | 68 | 1,799 | *3.9* |
| China | 1,870 | 2,248 | 1,682 | 475 | 118 | 25 | 282 | 6,699 | *1.6* |
| India | 1,329 | 1,057 | 177 | 281 | 50 | 391 | 464 | 3,748 | *0.5* |
| Indonesia | 4731 | 0 | 376 | 32 | 703 | 55 | 11 | 5,908 | *4.0* |
| Nigeria | 6 | 5 | 1 | 16 | 7 | 66 | 5 | 105 | *1.5* |
| Russia | 8 | 15 | 4 | 1 | 1 | 0 | 45 | 73 | *0.5* |
| USA&Can | 248 | 44 | 462 | 198 | 218 | 19 | 1,166 | 2,355 | *1.3* |
| CAmer&Caribb | 149 | 0 | 12 | 177 | 19 | 262 | 9 | 628 | *4.0* |
| Central Asia | 5 | 20 | 34 | 36 | 7 | 1 | 198 | 301 | *0.8* |
| WCES Africa | 916 | 114 | 164 | 333 | 133 | 278 | 402 | 2,339 | *2.6* |
| Europe | 56 | 34 | 144 | 217 | 306 | 45 | 427 | 1,230 | *1.3* |
| MENA | 48 | 177 | 63 | 1,090 | 111 | 44 | 657 | 2,189 | *0.9* |
| Mexico | 2 | 63 | 133 | 426 | 6 | 93 | 313 | 1,036 | *1.8* |
| Oceania | 0 | 0 | 2 | 1 | 0 | 0 | 188 | 192 | *1.8* |
| South America | 665 | 45 | 264 | 871 | 83 | 309 | 372 | 2,609 | *2.6* |
| SE Asia | 9,460 | 266 | 245 | 257 | 13 | 892 | 280 | 11,412 | *2.2* |
| RestWorld | 1,551 | 687 | 561 | 1129 | 258 | 81 | 1,842 | 6,110 | *2.2* |
| *TOTAL* | *22,018* | *4776* | *4,363* | *5,730* | *2,064* | *3,056* | *6,725* | *48,733* | *1.6* |

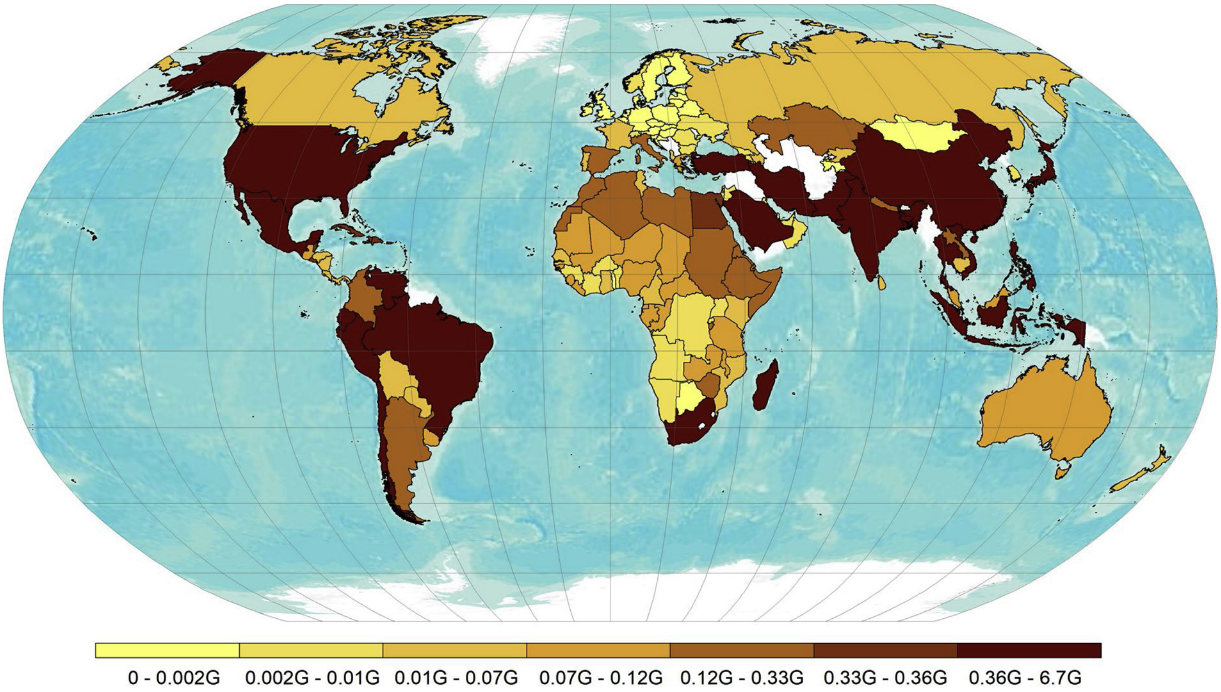

**Fig. 10.** Marginal change in water abstraction due to severe soil erosion (billion -G- m$^3$). Results are illustrated for 109 single countries, five macro-regions and one residual region, the latter for clarity reasons is not shown in the map. Macro-regions and the residual region are illustrated in Figure S1 of the Supplementary material.

global shifts in agricultural production in China, India and Brazil. These changes are particularly prevalent in the production of rice (and oilseeds on a lesser degree), which decreases by almost 0.5% globally. Indeed, our study reveals that falling land productivity, particularly for rice production, is a major driver of increased water abstraction in Asia. From a trade perspective, the heterogeneous rates of erosion across the planet give rise to accelerating current trends where net agri-food exporters such as USA, Canada, Europe and Oceanian countries continue to improve their net trade balances at the cost of net food importers such as China and South East Asian countries.

These effects call for the prioritization of soil governance and conservation strategy in all countries and international policy agenda. In this regard, the European Commission launched the Seventh Environment Action Programme, which requires that by 2020 land is managed sustainably and soil is adequately protected (Paleari, 2017). Focusing on agricultural land, the EU's Common Agricultural Policy (CAP) links support directly to the need to maintain agricultural land in good condition, whilst the post-2020 CAP includes as one of its main objectives, efficient soil management linked to actions to reduce soil erosion and increase soil organic carbon (Panagos and Katsoyiannis, 2019). In the USA, the Farm Bill extends soil conservation compliance requirements in order to qualify for the crop insurance subsidy (Islam and Reeder, 2014). At global scale, the FAO and its Global Soil Partnership launched in June 2018 a new programme to reduce soil degradation for greater food and nutrition security in Africa. Other countries are implementing local measures (WOCAT, 2007; Giger et al., 2018), yet a global multilateral environmental agreement on soil protection is missing (Montanarella and Alva, 2015).

Measures aimed at reinforcing ecosystem services, *ad hoc* regulation of human interventions and active farmers' participation contribute to minimize soil erosion. To this aim, protection and restoration of diverse plant communities on slopes are essential, as trees and diversified vegetation increase soil resistance to rain erosivity (Berendse et al., 2015). Other measures such as reduced tillage, buffer strips, agroforestry, plant residues and cover crops enhance soil fertility and control water runoff (Fageria et al., 2005; Triplett and Dick, 2008).

As in all modelling endeavours, there are caveats to the study. Firstly, as discussed in Section 2, there is uncertainty surrounding the soil erosion estimates from the global biophysical model and the assumption that land productivity losses occur only in severely eroded land. Secondly, the assumption of average crop productivity losses due to soil erosion is based on a literature review but in the real world it can vary from region to region. Further, physical and economic models typically work at different temporal and spatial scales. The need to interface RUSLE with MAGNET implies that the site-specific soil erosion data have to be adapted at the larger (national) spatial scale of the CGE model. Finally, whilst the economic framework provides some insights on the biophysical implications of soil erosion (e.g., land usage, water abstraction), a fuller treatment of the off-site costs (paid by the society) such as destruction of infrastructures, sedimentation, flooding, biodiversity and soil carbon losses, landslides, and water eutrophication, whilst requiring further research, are beyond the scope of this paper.

Connected to this last point, future analysis could therefore seek to broaden the list of indicators beyond recognised metrics such as prices, production, trade and GDP, where the latter has been criticised as a misleading measure of success or failure (Robert et al., 2014). Indeed, in the context of soil erosion, a broader set of indicators is very much inspired by the realisation of the Sustainable Development Goals (SDGs), particularly SDG 15, which targets indicators relating to land degradation and protection of ecosystems (i.e. sedimentation, flooding, landslides, water eutrophication, biodiversity loss, land abandonment, destruction of infrastructures). The extension of soil erosion to encapsulate these cost concepts may likely reveal even greater costs than the loss of crop productivity (Telles et al., 2011). 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.

## Appendix

### Appendix A1 Estimation of the global soil erosion equation

The evaluation of the long-term annual soil loss is carried out using the RUSLE model in a Geographical Information Systems (GIS) environment. RUSLE belongs to the class of detachment-limited models. Accordingly, the flow can theoretically transport an infinite quantity of sediment, but the amount of sediment actually available to be transported is limited by the soil detachment capacity given by the rainfall erosivity factor of the model. The soil loss in megagrams per hectare and year due to inter-rill and rill erosion processes are calculated according to Renard et al. (1997) by the following multiplicative equation:

$$\mathrm{A_g = R_g{*}K_g{*}LS_g{*}C_g{*}P_g} \qquad ((1))$$

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 erosivity factor, $K_g$[Mg h MJ-1 mm-1] is the soil erodibility factor, $LS_g$ [dimensionless] is the slope length-slope steepness factor, $C_g$ [dimensionless] is the land cover and management factor,$P_g$ [dimensionless] is the soil conservation or prevention practices factor. The subscript $g$ stands for global.

According to Eq. (1), RUSLE consists of a multiplicative equation including six environmental parameters:

- Rainfall Erosivity: The rainfall erosivity factor R, or rainfall erosivity index (EI30), is a numerical descriptor of the rainfall's ability to erode soil (Wischmeier, 1958). It expresses the kinetic energy of raindrop's impact and the rate of associated runoff.
- Soil Erodibility: The soil erodibility K-factor [Mg ha MJ-1 mm-1] is an empirical parameter based on the measurements of specific soil erodibility (Wischmeier and Smith, 1978). This parameter is generally measured based on some intrinsic soil properties such as texture, organic matter, structure and permeability of the topsoil profile.
- Slope Length and Steepness Factor: The LS-factor, also called the topographic parameter, in the RUSLE model represents the influence of the terrain topography on the sediment transport capacity of the overland flow (Wischmeier and Smith, 1978). To incorporate the impact of flow convergence in the estimation of the slope-length factor (LS), the RUSLE equation proposed by Renard et al. (1997) replaced by the ones proposed by Desmet and Govers (1996).
- Land Cover and Management Factor: The C-factor describes the land cover and management factor that measures the combined effect of all the interrelated cover and management variables (Wischmeier and Smith, 1978). It may range from 0 to 1 depending on the ground cover. Generally, values close to zero are typical of forested areas where the ground cover can reach up to 100%, whereas values close to one are typical of bare land.
- Support Practice Factor: The conversation support practice factor, P, is the ratio of soil loss with a conservation support practice like contouring, strip cropping, terracing and subsurface drainage (Wischmeier and Smith, 1978). Values for the support practice P-factor are generally the most uncertain and the most difficult to assess above the field-scale. Often, these are not taken into account in the vast majority of basin- and regional-scale assessments.

### Appendix A2 Labour and capital transfer in MAGNET

In the standard GTAP model, capital and labour are treated as perfectly mobile across different industrial uses. This implies that the return to capital (i.e., rent) and labour (i.e., wage) is equal for each industry 'i'. MAGNET follows the work on the agricultural variant of the GTAP model ('GTAP-AGR') by Keeney and Hertel (2015). Thus, labour and capital transfer between the primary agricultural and non-primary agricultural sub-

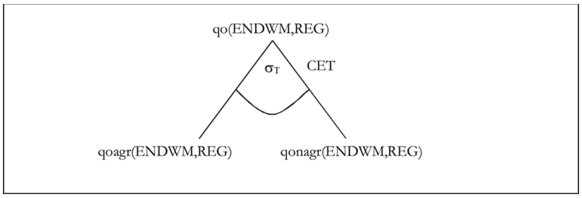

**Fig. A1.** The CET Labour/Capital Allocation between agricultural and non-agricultural sub sectors.

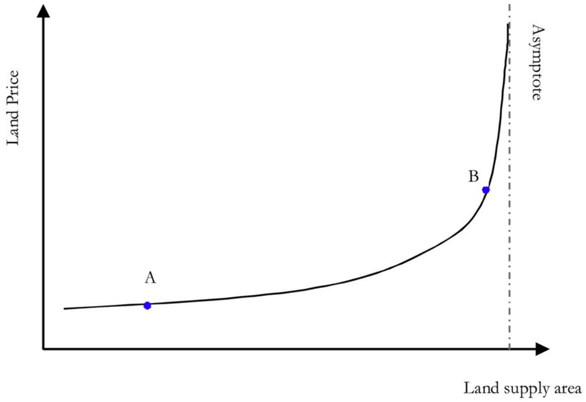

**Fig. A2.** Theoretical agricultural land supply curve.

sectors is made 'sluggish' via the usage of a Constant Elasticity of Transformation (CET) function (see Fig. A1). The policy implication is that in the real world, there are observed differences in the return to capital and labour between the two sub-sectors. For both labour and capital, the elasticity of transformation in each nest is the same as that employed in the GTAP-AGR model, and takes a value of 1.

Appendix A3 Agricultural land supply in MAGNET

In the standard CGE model treatments, land supply is exogenous in each region. However, in reality, agricultural land supply can adjust due to the idling of agricultural land or the conversion of land to agricultural uses. The supply of agricultural land depends on its biophysical suitability, institutional factors (agricultural, urban and nature protection policies) and land price (Tabeau et al., 2006, p.3). Biophysical suitability refers to climate, soil and water conditions that make a plot of land suitable for cultivation. Accordingly, biophysical parameters will define the maximum potentially available land surface that can be used for agricultural purposes (the asymptote in Fig. A2). At the outset, the most productive land is used first. With increases in land usage, farmers must employ less productive land implying that the marginal cost of conversion rises, which is reflected in a higher land price. This relationship between land usage and prices gives an upward sloping supply curve (see Fig. A2).

Any point along the supply curve is feasible from an agronomic point of view, however, every country/region will be positioned on a specific point, representing the current relative use of land in the agricultural sector. When the region is currently using a low proportion of all the potentially available land, any increase in demand for agricultural land will lead to conversion towards agricultural uses at a modest increase in price (e.g. point A in Fig. A2). In this zone of the supply curve, the supply elasticity is relatively higher, and the marginal cost of converting non-agricultural land into agricultural land is relatively lower. However, when a region is currently cultivating most of the available land (e.g. point B in Fig. A2), any increase in demand that requires the conversion of the scarce non-used land to agriculture, will lead to the conversion of the least productive land and at a relatively higher marginal cost (land supply elasticity is low).

The assumed land supply function for each of the regions in the MAGNET model is:

$$L = A - \frac{B}{P} \tag{A1}$$

where L is land supply, P is the real rental value of land, A is the maximum available agricultural land area (the land asymptote), and B is a positive parameter. The resulting land supply elasticity $E_s$ in respect of land price is defined as:

$$E_s = \frac{A}{L} - 1 \tag{A2}$$

In Tabeau et al. (2017), a full list of the land supply elasticities used in MAGNET can be consulted.

A4 Water abstraction in MAGNET

The MAGNET model includes a water module based on satellite data (Haqiqi et al., 2016) for irrigated and rainfed land areas and irrigated water withdrawals (in cubic meters) for the 140 regions of the MAGNET model for the year 2011. The modelling is *tops-down*, where changes in water withdrawals, calculated as an ex-post computation, are driven by proportional endogenous changes in irrigated land usage. Irrigated land use changes are calculated by assuming that the share of irrigated land in all crop activities in the one-year period contemplated within this study remains exogenously fixed. By linking the water withdrawals directly to land use instead of crop production implies that intensifying non-land inputs (e.g. capital, labour and fertilizer) can increase crop production without leading to more water withdrawals.

References

Desmet, P. J. J., Govers, G. 1996. A GIS procedure for automatically calculating the USLE LS factor on topographically complex landscape units. *Journal of soil and water conservation* 51, 427–433.

Renard, G., Foster, G.R., Weesies, G.A., Porter, J.P. 1991. RUSLE-Revised universal soil loss equation. *Journal of Soil and Water Conservation* 46, 30–33.

Wischmeier, W.H. 1958. A rainfall erosion index for a universal soil-loss equation. *Soil* Science *Society of America, Proceedings* 23, 246–249.

Wischmeier, W.H., Smith, D.D., 1978. Predicting rainfall erosion losses. Agriculture Handbook, n. 5.

## References

Aguiar, A., Narayanan, B., McDougall, R., 2016. An overview of the GTAP 9 data base. J. Glob. Econ. Anal. 1 (1), 181–208. https://doi.org/10.21642/JGEA.010103AF.

Altieri, M.A., Nicholls, C.I., 2017. The adaptation and mitigation potential of traditional agriculture in a changing climate. Clim. Change 140 (1), 33–45. https://doi.org/10.1007/s10584-013-0909-y.

Berendse, F., van Ruijven, J., Jongejans, E., Keesstra, S., 2015. Loss of plants pecies diversity reduces soil erosion resistance. Ecosystems 18, 881–888. https://doi.org/10.1007/s10021-015-9869-6.

Boardman, J., Poesen, J., 2006. Soil Erosion in Europe: Major Processes, Causes and Consequences. Soil Erosion in Europe. John Wiley & Sons, pp. 477–487 ISBN-13 978

0-470-85910-0.

Borrelli, P., Robinson, D.A., Fleischer, L.R., Lugato, E., Ballabio, C., Alewell, C., Meusburger, K., Modugno, S., Schütt, B., Ferro, V., 2017. An assessment of the global impact of 21st century land use change on soil erosion. Nat. Commun. 8, 2013. https://doi.org/10.1038/s41467-017-02142-7.

Boulanger, P., Philippidis, G., 2015. The EU budget battle: assessing the trade and welfare impacts of CAP budgetary reform. Food Policy 51, 119–130. https://doi.org/10.1016/j.foodpol.2015.01.004.

Corong, E., Hertel, T.W., McDougall, R.A., Tsigas, M.E., van der Mensbrugghe, D., 2017. The standard GTAP model, version 7. J. Glob. Econ. Anal. 2 (1), 1–119. https://doi.org/10.21642/JGEA.020101AF.

Doelman, J.C., Stehfest, E., Tabeau, A., van Meijl, H., Lassaletta, L., Gernaat, D.E.H.J., Hermans, K., Harmsen, M., Vassilis, D., Biemans, H., van der Sluis, S., van Vuuren, D.P., 2018. Exploring SSP land-use dynamics using the IMAGE model: regional and gridded scenarios of land-use change and land based climate change mitigation. Glob. Environ. Chang. Part A 48, 119–135. https://doi.org/10.1016/j.gloenvcha.2017.11.014.

Eickhout, B., Van Meijl, H., Tabeau, A., Stehfest, E., 2009. The impact of environmental and climate constraints on global food supply. In: Hertel, T., Rose, S., Tol, R. (Eds.), Economic Analysis of Land Use in Global Climate Change Policy. Routledge.

ELD Initiative, 2015. Report for Policy and Decision Makers: Reaping Economic and Environmental Benefits From Sustainable Land Management. Available from www.eld-initiative.org at the web address:. . http://www.eld-initiative.org/fileadmin/pdf/ELD-pm-report_05_web_300dpi.pdf.

Erkossa, T., Wudneh, A., Desalegn, B., Taye, G., 2015. Linking soil erosion to on-site financial cost: lessons from watersheds in the Blue Nile basin. Solid Earth 6 (2), 765–774. https://doi.org/10.5194/se-6-765-2015.

Fageria, N.K., Baligar, V.C., Bailey, B.A., 2005. Role of cover crops in improving soil and row crop productivity. Commun. Soil Sci. Plant Anal. 36, 2733–2757. https://doi.org/10.1080/00103620500303939.

Giger, M., Liniger, H., Sauter, C., Schwilch, G., 2018. Economic benefits and costs of sustainable land management technologies: an analysis of WOCAT's global data. Land Degrad. Dev. 29 (4), 962–974.

Haqiqi, I., Taheripour, F., Liu, J., van der Mensbrugghe, D., 2016. Introducing irrigation water into GTAP data base version 9. J. Glob. Econ. Anal. 1 (2), 116–155. data can be downloaded from. https://www.gtap.agecon.purdue.edu/resources/res_display.asp?RecordID=5168.

Hein, L., 2007. Assessing the costs of land degradation: a case study for the Puentes catchment, southeast Spain. Land Degrad. Dev. 18 (6), 631–642. https://doi.org/10.1002/ldr.802.

Hengl, T., Mendes de Jesus, J., MacMillan, R.A., Batjes, N., Heuvelink, G.B.M., Ribeiro, E., Samuel-Rosa, A., Kempen, B., Leenaars, J.G.B., Walsh, M.G., Gonzalex, 2014. SoilGrids1km — global soil information based on automated mapping. PLoS One 9https://doi.org/10.1371/journal.pone.0105992. e105992.

Islam, R., Reeder, R., 2014. No-till and conservation agriculture in the United States: an example from the David Brandt farm, Carroll, Ohio. Int. Soil Water Conserv. Res. 2 (1), 97–107.

Keeney, R., Hertel, T., 2015. GTAP-AGR: A Framework for Assessing the Implications of Multilateral Changes in Agricultural Policies, GTAP Technical Paper N. 24. https://www.gtap.agecon.purdue.edu/resources/res_display.asp?RecordID=1869.

Keesstra, S.D., Bouma, J., Wallinga, J., Tittonell, P., Smith, P., Cerdà, A., Montanarella, L., Quinton, J.N., Pachepsky, Y., van der Putten, W.H., Bardgett, R.D., Moolenaar, S., Mol, G., Jansen, B., Fresco, L.O., 2016. The significance of soils and soil science towards realization of the United Nations Sustainable Development Goals. Soil 2, 111–128. https://doi.org/10.5194/soil-2-111-2016.

Lugato, E., Smith, P., Borrelli, P., Panagos, P., Ballabio, C., Orgiazzi, A., Fernandez-Ugalde, O., Montanarella, L., Jones, A., 2018. Soil erosion is unlikely to drive a future carbon sink in Europe. 201.). Sci. Adv. 4 (11). https://doi.org/10.1126/sciadv.aau3523. art. no. eaau3523.

Martínez-Casasnovas, J.A., Ramos, M.C., 2006. The cost of soil erosion in vineyard fields in the Penedès–Anoia Region (NE Spain). Catena 68 (2-3), 194–199. https://doi.org/10.1016/j.catena.2006.04.007.

Montanarella, L., Lobos Alva, I., 2015. Putting soils on the agenda: the three Rio Conventions and the post-2015 development agenda. Curr. Opin. Environ. Sustain. 15, 41–48. https://doi.org/10.1016/j.cosust.2015.07.008.

Nkonya, E., Anderson, W., Kato, E., Koo, J., Mirzabaev, A., von Braun, J., Meyer, S., 2016. Global cost of Land degradation. In: Nkonya, E., Mirzabaev, A., von Braun, J. (Eds.), Economics of Land Degradation and Improvement – A Global Assessment for Sustainable Development. Springer International Publishing, Cham, pp. 117–165.

Paleari, S., 2017. Is the European Union protecting soil? A critical analysis of Community environmental policy and law. Land Use Policy 64, 163–173.

Panagos, P., Katsoyiannis, A., 2019. Soil erosion modelling: the new challenges as the result of policy developments in Europe. Environ. Res. 172, 470–474.

Panagos, P., Imeson, A., Meusburger, K., Borrelli, P., Poesen, J., Alewell, C., 2016. Soil conservation in Europe: wish or reality? Land Degrad. Dev. 27 (6), 1547–1551.

Panagos, P., Borrelli, P., Meusburger, K., Yu, B., Klik, A., Jae Lim, K., Yang, J.E., Ni, J., Miao, C., Chattopadhyay, N., Sadeghi, Seyed H., Hazbavi, Z., Zabihi, M., Larionov, G.A., Krasnov, S.F., Gorobets, Av., Levi, Y., Erpul, G., Birkel, C., Hoyos, N., Naipal, V., Oliveira, P.T.S., Bonilla, C.A., Meddi, M., Nel, W., Al Dashti, H., Boni, M., Diodato, N., Van Oost, K., Nearing, M., Ballabio, C., 2017. Global rainfall erosivity assessment based on high-temporal resolution rainfall records. Sci. Rep. 7, 4175. https://doi.org/10.1038/s41598-017-04282-8.

Panagos, P., Standardi, G., Borrelli, P., Lugato, E., Montanarella, L., Bosello, F., 2018. Cost of agricultural productivity loss due to soil erosion in the European Union: from direct cost evaluation approaches to the use of macroeconomic models. Land Degrad. Dev. 29, 471–484. https://doi.org/10.1002/ldr.2879.

Philippidis, G., Bartelings, H., Smeets, E., 2018a. Sailing into unchartered waters: plotting a course for EU bio-based sectors. Ecol. Econ. 147, 410–421. https://doi.org/10.1016/j.ecolecon.2018.01.026.

Philippidis, G., Sanjuán, A., Tabeau, A., van Berkum, S., Verma, M., 2018b. A Foresight Study of European East-West Agrifood Trade Options. German J. Agric. Econ. 67 (3), 160–175.

Pimentel, D., Harvey, C., Resosudarmo, P., Sinclair, K., Kurz, D., McNair, M., Crist, S., Shpritz, L., Fitton, L., Saffouri, R., 1995. Environmental and economic costs of soil erosion and conservation benefits. Science 267, 1117–1123. https://doi.org/10.1126/science.267.5201.1117.

Poesen, J., 2018. Soil erosion in the Anthropocene: research needs. Earth Surf. Process. Landf. 43, 64–84. https://doi.org/10.1002/esp.4250.

Ramankutty, N., 2005. Global Land Use Data for Integrated Assessment Modelling. Report Prepared for the U.S. Department of Energy: Award N. DE-FG02-01ER63215. . https://digital.library.unt.edu/ark:/67531/metadc794101/m2/1/high_res_d/861318.pdf.

Renard, K., Foster, G., Weesies, G., McCool, D., Yoder, D., 1997. Predicting Soil Erosion by Water: a Guide to Conservation Planning With the Revised Universal Soil Loss Equation (RUSLE). Agricultural Handbook. pp. 703.

Reuter, H.I., Nelson, A., Jarvis, A., 2007. An evaluation of void-filling interpolation methods for SRTM data. Int. J. Geogr. Inf. Sci. 21, 983–1008. https://doi.org/10.1080/13658810601169899.

Robinson, N., Regetz, J., Guralnick, R.P., 2014. EarthEnv-DEM90: a nearly-global, void-free, multi-scale smoothed, 90m digital elevation model from fused ASTER and SRTM data. ISPRS J. Photogramm. Remote Sens. 87, 57–67. https://doi.org/10.1016/j.isprsjprs.2013.11.002.

Rutten, M., Shutes, L., Meijerink, G., 2013. Sit down at the ball game: how trade barriers make the world less food secure. Food Policy 38, 1–10. https://doi.org/10.1016/j.foodpol.2012.09.002.

Schmitz, C., van Meijl, H., Kyle, P., Nelson, G.C., Fujimori, S., Gurgel, A., Havlik, P., Heyhoe, E., Mason d'Croz, D., Popp, A., Sands, R., Tabeau, A., van der Mensbrugghe, D., von Lampe, M., Wise, M., Blanc, E., Hasegawa, T., Kavallari, A., Valin, H., 2014. Land-use change trajectories up to 2050: insights from a global agro-economic model comparison. Agric. Econ. 45, 69–84. https://doi.org/10.1111/agec.12090.

Smeets, E., Tabeau, A., van Berkum, S., van Meijl, H., Woltjer, G., Moorad, J., 2014. The impact of the rebound effect of first generation biofuels on greenhouse gas emissions in the EU. Sustainable and Renewable Energy Reviews 38, 393–403. https://doi.org/10.1016/j.rser.2014.05.035.

Tabeau, A., Eickhout, B., van Meijl, H., 2006. Endogenous agricultural land supply: estimation and implementation in the GTAP model. Paper Presented at the 9th Annual Conference on Global Economic Analysis. https://www.gtap.agecon.purdue.edu/resources/download/2731.pdf.

Tabeau, A., Helming, J., Philippidis, G., 2017. Land Supply Elasticities: Overview of Available Estimates and Recommended Values for MAGNET. ISBN 978-92-79-69102-7, doi:10.2760/852141, JRC106592. EUR 28626 EN, Publications Office of the European Union, Luxembourg. http://publications.jrc.ec.europa.eu/repository/bitstream/JRC106592/kj-na-28626-en-n_.pdf.

Telles, T.S., Guimarães, M.D.F., Dechen, S.C.F., 2011. The costs of soil erosion. Revista Brasileira de Ciência do Solo 35 (2), 287–298.

Triplett Jr, G.B., Dick, W.A., 2008. No-tillage crop production: a revolution in agriculture!. Agron. J. 100, S153–S165. https://doi.org/10.2134/agronj2007.0005c.

UNCCD, 2017. Global Land Outlook. Available at:. . https://knowledge.unccd.int/sites/default/files/2018-06/GLO%20English_Full_Report_rev1.pdf.

van Meijl, H., van Rheenen, T., Tabeau, Eickhout,B., 2006. The impact of different policy environments on agricultural land use in Europe. Agric. Ecosyst. Environ. 114 (1), 21–38. https://doi.org/10.1016/j.agee.2005.11.006.

van Meijl, H., Havlik, P., Lotze-Campen, H., Stehfest, E., Witzke, P., Pérez Domínguez, I., Bodirsky, B., van Dijk, M., Doelman, J., Fellmann, T., Humpenoeder, F., Levin-Koopman, J., Mueller, C., Popp, A., Tabeau, A., Valin, H., van Zeist, W.J., 2018. Challenges of global agriculture in the climate change context by 2050. Environ. Res. Lett. 13 (2018), 064021.

Wischmeier, W., Smith, D., 1978. Predicting rainfall erosion losses: a guide to conservation planning. U.S. Dep. Agric. Handb. 537, 1–69.

WOCAT, 2007. In: Hanspeter, L., Critchley, W. (Eds.), Where the Land Is Greener – Case Studies and Analysis of Soil and Water Conservation Initiatives Worldwide, ISBN 978-92-9081-339-2.

Wolka, K., Mulder, J., Biazin, B., 2018. Effects of soil and water conservation techniques on crop yield, runoff and soil loss in Sub-Saharan Africa: a review. Agric. Water Manag. 207, 67–79. https://doi.org/10.1016/j.agwat.2018.05.016.

Woltjer, G.B., Kuiper, M.H., 2014. The MAGNET Model: Module Description. LEI Wageningen UR (University & Research centre), LEI Report 14-057, Wageningen.

Zhao, G., Mu, X., Wen, Z., Wang, F., Gao, P., 2013. Soil erosion, conservation, and eco-environment changes in the Loess Plateau of China. Land Degrad. Dev. 24, 499–510. https://doi.org/10.1002/ldr.2246.