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Cost of agricultural productivity loss due to soil erosion in the European Union: From direct cost evaluation approaches to the use of macroeconomic models

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Abstract

Much research has been carried out on modelling soil erosion rates under different climatic and land use conditions. Although some studies have addressed the issue of reduced crop productivity due to soil erosion, few have focused on the economic loss in terms of agricultural production and gross domestic product (GDP). In this study, soil erosion modellers and economists come together to carry out an economic evaluation of soil erosion in the European Union (EU). The study combines biophysical and macroeconomic models to estimate the cost of agricultural productivity loss due to soil erosion by water in the EU. The soil erosion rates, derived from the RUSLE2015 model, are used to estimate the loss in crop productivity (physical change in the production of plants) and to model their impact on the agricultural sector per country. A computable general equilibrium model is then used to estimate the impact of crop productivity change on agricultural production and GDP. The 12 million hectares of agricultural areas in the EU that suffer from severe erosion are estimated to lose around 0.43% of their crop productivity annually. The annual cost of this loss in agricultural productivity is estimated at around €1.25 billion. The computable general equilibrium model estimates the cost in the agricultural sector to be close to €300 million and the loss in GDP to be about €155 million. Italy emerges as the country that suffers the highest economic impact, whereas the agricultural sector in most Northern and Central European countries is only marginally affected by soil erosion losses.

KEYWORDS

agricultural productivity, computable general equilibrium, crop productivity loss, food security, system of environmental–economic accounting

1 | INTRODUCTION

Soil is subject to a series of degradation processes and threats. The main threats to soil, as identified in the European Union (EU) Soil Thematic Strategy (European Commission [EC], 2006), include erosion, decline in organic matter, local and diffuse contamination, sealing, compaction, decline in biodiversity, salinisation, floods, and landslides. The loss of soil due to water erosion degrades the arable land and eventually renders it unproductive (Pimentel et al., 1995). Soil erosion is the biggest threat to soil fertility and productivity, as it removes organic matter and important nutrients and prevents vegetation growth, which negatively affects overall biodiversity (Scherr, 2000). In particular, soil erosion changes the physical, chemical, and biological characteristics of soil, which leads to a drop in potential agricultural productivity and gives rise to concerns about food security, especially in the context of a growing world population (Food and Agriculture Organization [FAO], 2015a; Graves et al., 2015; Pimentel, 2006).

Soil degradation causes decline in soil quality and productivity. Among the soil degradative processes (decline in soil structure, compaction, salinisation, decline of soil biodiversity, acidification, etc.), soil erosion is the most well-known form of soil degradation (Lal, 2001). In this manuscript, we consider the impact of soil erosion by water in loss of agricultural productivity recognising that there also other forms of soil erosion (gully erosion, wind erosion, harvest erosion, etc.).

Soil erosion generates on-site costs that directly affect farming land. These costs are paid by farmers, through loss of fertile land. The on-site costs are mainly the value of future lost production due to the decline in soil resources (Colombo, Hanley, & Calatrava-Requena, 2005). These include losses in production, yields, and nutrients, damage to plantations, and reduction of the available planting area (Telles, de Fátima, & Dechen, 2011). Soil erosion also generates off-site costs as a consequence of sedimentation, flooding, landslides, and water eutrophication. These costs are generally incurred away from the farm and are paid by society. The off-site effects of soil erosion include the siltation of reservoirs, sediment impacts on fisheries, the loss of wildlife habitat and biodiversity, increased risk of flooding, damage of recreational activities, land abandonment, and destruction of infrastructure such as roads, railways, and other public assets (Colombo et al., 2005; Telles et al., 2011; Telles, Dechen, de Souza, & Guimarães, 2013).

A simple Google Scholar search for the term "soil erosion" yields around 1,070,000 results (December 18, 2017), whereas 3,820 publications are found with the term "costs of soil erosion" (0.4% of the publications relevant to soil erosion). This very small percentage shows that the focus is more on the physical rather than the economic aspects of this phenomenon. García-Ruiz, Beguería, Lana-Renault, Nadal-Romero, and Cerdà (2017) recognised that it is still difficult to evaluate the economic consequences of on-site effects. Moreover, a cost evaluation of losses in agricultural production and gross domestic product (GDP) due to soil erosion at the continental scale has not been addressed adequately in the literature.

The consequences of soil erosion for society could be severe. The EU Soil Thematic Strategy alerts policymakers to the need to protect soil, proposes measures to mitigate soil degradation, and includes soil erosion as a key priority for action (Kibblewhite, Miko, & Montanarella, 2012). The recognition of the importance of impact assessment has significantly increased in recent decades in the context of EU agricultural and environmental policies (Manos, Bournaris, Moulogianni, & Arampatzis, 2013). The impact assessment included in the proposal for an EU Soil Thematic Strategy (EC, 2006) estimated the cost of soil degradation due to soil erosion at €0.7 to €14.0 billion, on the basis of estimations made of 13 largest EU Member States (MSs) where erosion is most prevalent. The impact assessment also estimated the annual costs of the on-site effects of soil erosion to be around €40–860 million. No data were available for the other 15 EU MSs. The reason for the broad range in the estimated cost of soil erosion is due to uncertainties regarding its long-term impact on agricultural ecosystems.

After a literature review, we present the main methodologies used for estimating costs of agricultural productivity loss due to soil erosion (Table 1). The first two simple cost estimation methodologies consider the erosion control measures and the soil market price (Table 1). Kuhlman, Reinhard, and Gaaff (2010) used the cost (€296/ha) of erosion control in areas of severe erosion (>10 t ha^{-1} $year^{-1}$) and estimated a significant cost of around €3,571 million annually. This method estimates the cost of the application of measures such as the conversion of arable land into forest/pasture, terracing, buffer strips, residue management, cover crops, and conservation tillage. In the UK, Posthumus, Deeks, Rickson, and Quinton (2015) made a cost/benefit analysis of control measures against erosion and found that buffer strips, contour ploughing, and mulching are the most cost-effective ones. The second methodology applied by Robinson et al. (2014) focused on the commercial market price and reviewed the cost of fertile soil in the United States and the UK. The market price of soil for direct use was estimated at around US$20/t (Robinson et al., 2014). According to Robinson et al. (2014) and Panagos, Borrelli, and Robinson (2015), the market price of soil lost due to water erosion in Europe can be estimated at about US$20 billion per year. The main limitation of this methodology is the misrepresentation of market prices, which do not always reflect the actual value of soil (Adhikari & Nadella, 2011).

In addition to the two simple methodologies for estimating on-site cost of soil erosion (market price of soil and cost–benefit analysis), the most well-known methodologies are the replacement cost method (Dixon, Scura, Carpenter, & Sherman, 1994) and the productivity loss method (Gunatilake & Vieth, 2000) (Table 1). The cost of additional

TABLE 1 Methodologies for estimating costs of agricultural productivity loss due to soil erosion

Methodology	Valuing costs	Studies relevant to estimate of soil erosion cost
Cost–benefit analysis	Cost of soil erosion control measures (conversion arable into forest/pasture, terracing, buffer strips, residue management, cover crops, and conservation tillage)	Kuhlman et al. (2010), Posthumus et al. (2015), and Bizoza and de Graaff (2012)
Market price of soil	Commercial price of soil	Robinson et al. (2014) and Panagos, Borrelli, and Robinson (2015)
Crop productivity loss	Decreased crop production due to soil erosion	Gunatilake and Vieth (2000), Evans (1996), Enters (1998), Möller and Ranke (2006), this study, and 16 studies in Table 2
Replacement cost	Cost of fertilizers (N and P) to replace nutrient loss due to soil erosion	Martínez-Casasnovas and Ramos (2006), Möller and Ranke (2006), Hein (2007), Graves et al. (2015), Dixon et al. (1994), Enters (1998), and Bojo (1996)
Macroeconomic models (computable general equilibrium)	Estimate the cost represented by soil erosion loss in the agricultural sector	This study

nutrients to soil (nitrogen and phosphorus) to mitigate soil erosion is an example of replacement cost method. Recent studies (Hein, 2007; Martínez-Casasnovas & Ramos, 2006) have addressed this topic at local/regional scale. The productivity loss method estimates the losses of crop yields due to erosion and quantifies the economic loss by taking into account prices of crops. Evans (1996) estimated the cost of reduced yields due to erosion in the UK at £11.3 million.

At international policy level, soil erosion is also perceived as being among the main processes contributing to land degradation according to United Nations Convention to Combat Desertification (2017) Article 1. In this vein, a recent study carried out by Nkonya (2015) highlighted the need to estimate the costs of land degradation at the global scale. They promoted the Economics of Land Degradation initiative, which aims to develop a scientific basis for assessing the costs of land degradation. The United Nations' System of Environmental and Economic Accounting (SEEA, 2016) is a broadscale interdisciplinary environmental and socio-economic monitoring tool. The SEEA was introduced in 2014 and is gaining global momentum. It integrates environmental data with economic measures such as national income, stock markets, and GDP. In a letter to *Nature*, Obst (2015) pointed out that integrating information on soil resources with other measures of natural capital and economic activity remains one of the least developed areas of the SEEA.

Against this background, the main objective of this study is to propose an estimate of the cost of soil erosion in the EU, using direct cost evaluation approaches and macroeconomic models. The direct cost evaluation approach focuses on the cost of crop productivity loss (lost tonnes of crop commodities). In the literature, the crop productivity loss method is more reliable compared to replacement cost method (Bojo, 1996; Enters, 1998; Gunatilake & Vieth, 2000). In the macroeconomic approach (Table 1), the computable general equilibrium (CGE) model is used to quantify the impact of soil erosion on the overall economic activity of the agricultural sector and on the GDP of European MSs.

2 | STUDY AREA AND INPUT DATA

The study area is the European Union (EU-28) which, according to CORINE Land Cover (2014) statistics, has 167 million hectares of agricultural area (arable land, permanent crops, and heterogeneous agricultural areas).

The European Commission has established a number of indicators for monitoring the implementation and evaluation of the Common Agricultural Policy (CAP) during the period 2014–2020 (EC, 2014). The importance of agricultural practices for soil conservation has been discussed extensively in the literature (Panagos, Imeson, et al., 2016). Soil erosion is among the CAP context indicators that assess the impact of agro-environmental measures on sustainable development. The soil erosion indicator assesses rates of soil loss by water erosion processes (rain splash, sheet wash, and rills) and defines the areas affected by severe erosion (>11 t ha^{-1} year^{-1}; threshold set by the Organisation for Economic Co-operation and Development).

3 | METHODS

A brief description of biophysical model for estimating soil erosion (RUSLE2015) is given below. Next, we present the cost estimation methodologies (direct cost evaluation and effect on crop productivity and complex application of macroeconomic models), which are used to quantify the economic impact of soil erosion on land productivity.

3.1 | Estimating soil erosion rates at European scale

Soil erosion in the EU was estimated using the latest state-of-the-art soil erosion model, RUSLE2015 (Panagos, Borrelli, Poesen, et al., 2015). This model is based on a well-known and extensively used erosion model named RUSLE, which has been validated with more than 10,000 plot-years of experiments, and its input factors have been developed and weighted according to large number of field experiments (Renard et al., 1997). RUSLE2015 takes as input the five main factors (rainfall erosivity, soil erodibility, cover management, topography, and support practices), which are modelled using the most recently available pan-European datasets (Figure 1). Those input factors were modelled with homogeneous, updated, pan-European datasets such as LUCAS topsoil survey (20,000 points), Rainfall Erosivity Database at European Scale, CORINE Land Cover, Copernicus Remote Sensing datasets, Eurostat statistical data (crops, tillage, plant residues, and cover crops), 270,000 Land Use/Land Cover earth observations, Good Agriculture and Environmental Conditions database, and Digital Elevation Model (European Environment Agency). In the Supporting Information, we provide a comprehensive description of the RUSLE2015 erosion model.

The output of the RUSLE2015 model is a high-resolution dataset of soil loss by water erosion for the reference year 2010. The model estimates potential rates (t ha^{-1} year^{-1}) of soil erosion. This is a harmonised product designed to improve our knowledge of soil erosion at the EU level and does not challenge any regional modelling results (Panagos, Imeson, et al., 2016). The spatial patterns of erosion rates are mostly influenced by land cover, topography, and rainfall intensity. The agricultural lands, which is the focus in our study, have higher erosion rates compared to forests, grasslands, and shrublands. The RUSLE2015 dataset is further processed to estimate areas potentially affected by severe erosion in the EU, which are used as input in the agronomic analysis for estimating losses in crop productivity, agricultural sector production, and GDP (Figure 1).

RUSLE2015 results are available for our study area (EU-28). Other modelling results such as Pan-European Soil Erosion Risk Assessment model (Kirkby, Irvine, Jones, et al., 2008) or data collections such as EIONET dataset (Panagos et al., 2014) do not cover the whole study area. The RUSLE2015 model has been extensively presented in the literature (Panagos et al., 2016a; Panagos, Borrelli, Poesen, et al., 2015; Panagos, Imeson, et al., 2016) with its potentials and limitations. RUSLE2015 model also triggered controversial discussions within the soil science community regarding the applicability of models to assess soil erosion risks on large scale (Evans & Boardman, 2016; Fiener & Auerswald, 2016; Panagos et al., 2016a; Panagos et al., 2016b).

3.2 | Direct cost evaluation: Effect on crop productivity (lost tonnes of crop commodities)

The crop productivity loss methodology estimates crop yields expressed as tonnes per hectare for 10 commodity crops, predicts

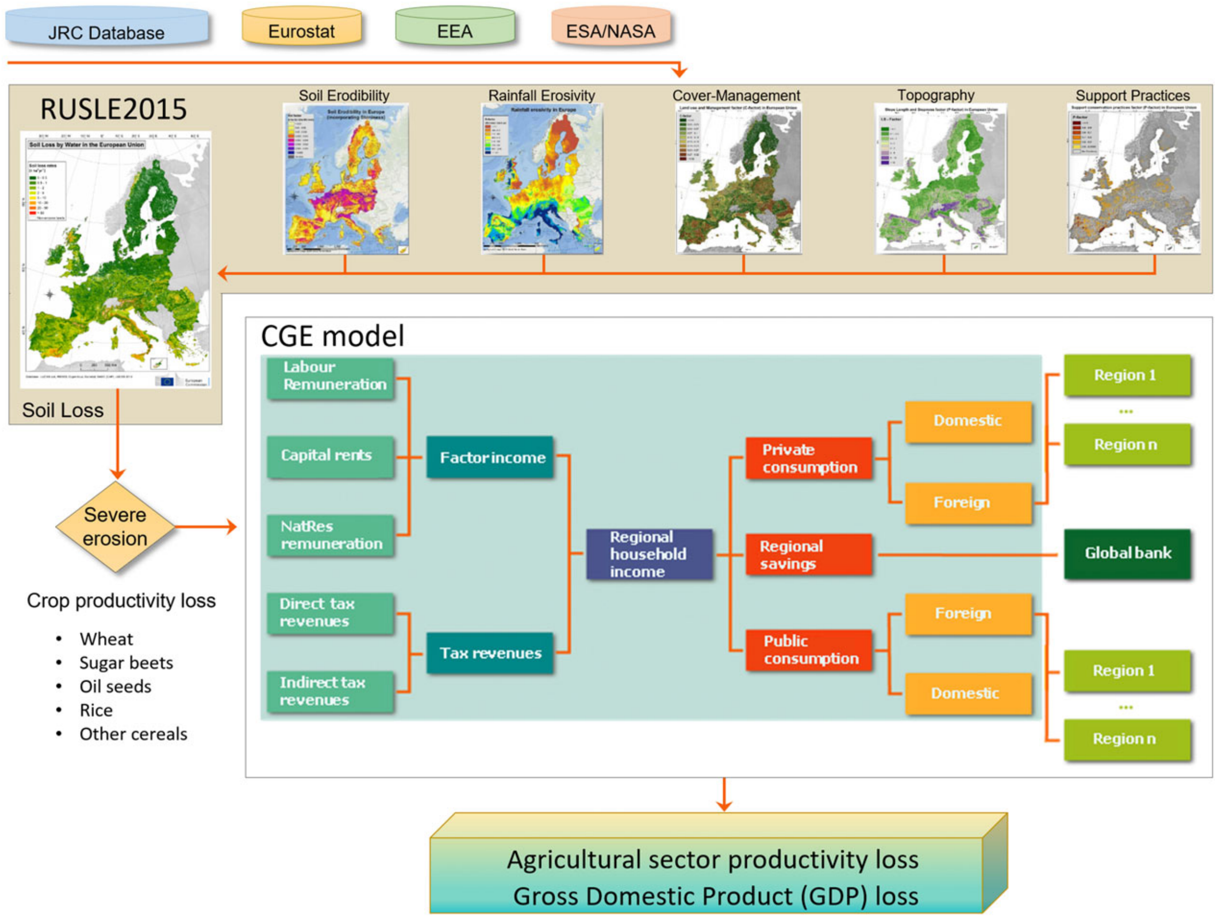

FIGURE 1 Workflow of soil erosion (RUSLE2015) and macroeconomic (computable general equilibrium [CGE]) integration for the cost evaluation of agricultural productivity losses. EEA = European Environment Agency; ESA = European Space Agency; JRC = Joint Research Centre; NASA = National Aeronautics and Space Administration [Colour figure can be viewed at wileyonlinelibrary.com]

areas where severe erosion will occur, and estimates the likely loss in crop productivity. An economic value of crop productivity loss per year was derived by multiplying the loss in production by the average market price of the 10 crops.

The crop productivity statistics, taken from Eurostat (2016), refer to the 2012–2014 period. We used the following two figures: (a) hectares of cultivated area (and harvested production) per country and (b) crop yield as tonnes per hectare for each country. The 10 crops considered are maize (including grain maize and green maize), barley (including winter and spring barley), rape (including rape and turnip rape) and soya, sunflower seeds, potatoes, sugar beets, rye, rice (including Japonica and Indica), pulses (including fresh, dry, and protein crops), and wheat. The area covered by those 10 crops is about 89% of the EU cultivated land. Due to the broad scale of the study (>167 million hectares of agricultural land) and the high diversification of crops in the EU, we have assigned the remaining 11% of EU cultivated land as wheat (the most common crop in the EU).

The market value for each crop is the producer's price (taken from the Food and Agriculture Organization of the United Nations Statistics, 2016) as an average price of period 2012–2014 using the exchange rate of November 20, 2016 (€1 = US$1.06). The loss of nutrients and organic carbon due to soil erosion and the subsequent agricultural productivity is also (partially) compensated by the extensive use of chemical fertilisers (Kuhlman et al., 2010), especially in our study area.

On the basis of relevant literature findings (Table 2), this study assumes that a crop productivity loss of 8% occurs in agricultural fields that have been intensively cultivated during the past 25–30 years, where erosion rates are high (>11 t ha^{-1} $year^{-1}$). The literature review of 16 studies (Table 2) takes into account the experimental results of crop productivity loss due to erosion, and it is well distributed in the world (United States, Canada, Europe, Spain, Africa, Indonesia, etc.). Due to the intense use of fertilisers in Europe and their ability to compensate moderate productivity losses, we do not consider any productivity loss in agricultural fields that have low and moderate erosion rates (<11 t ha^{-1} $year^{-1}$). According to Montgomery (2007), the United States Department of Agriculture also considers soil loss rates of less than 12 t ha^{-1} $year^{-1}$ (equivalent to 1 mm of erosion per year, assuming a bulk density of 1,200 kg/m^3) to be tolerable for maintaining crop productivity.

With the abovementioned data, the rate of loss in land productivity for each of the 28 MSs of the European Union was estimated as follows:

$$LPL_r = \frac{SEA_r}{TAA_r} * 0.08, \quad (1)$$

where *LPL* is the land productivity loss per MS (*r* represents the country index) expressed as %, *SEA* is the area of severe erosion per MS (ha), and *TAA* is the total agricultural areas of the MS (ha).

This assumes that the productivity loss is equally distributed across all crop types within MSs and that the variability between them

TABLE 2 Literature review of studies estimating the agricultural productivity loss due to soil erosion by water

Reference	Estimation of crop yield loss due to soil erosion	Comments on estimation method
Lyles (1975)	Productivity loss ~6% per 2.5 cm of soil loss	Experiments in the United States
Pierce, Larson, Dowdy, and Graham (1983)	2–4% productivity loss in case of severe erosion (>25 t ha^{-1} $year^{-1}$)	U.S. croplands; NRI survey
Battiston, Miller, and Shelton (1987)	8% productivity loss due to soil erosion	Corn yield experiments in Ontario
Magrath and Arens (1989)	0–12% annual productivity loss in case of severe erosion	Analysis of three comparable studies in Java, Indonesia
Schumacher, Lindstrom, Mokma, and Nelson (1994)	8% yield reduction in cornfields with severe erosion	North Central United States experiments
Pimentel et al. (1995)	Severe soil erosion by water (rates of higher than 17 t ha^{-1} $year^{-1}$) can cause a crop productivity loss of 8% annually.	Review article
Crosson (1995)	Productivity loss to only 0.4% per year (8% productivity loss after 20 years).	Review study based on Pimentel et al. (1995) article
Lal (1995)	Yield reductions due to severe erosion may range from 2% to 40%, with a mean of 8.2% for the continent.	A review of available data in African plots
Oyedele and Aina (1998)	Maize yield reduction of 10–17% on severely eroded	Plot experiments in Africa
Van den Born, de Haan, Pearce, and Howarth (2000)	9% productivity loss for maize and other grains under high erosion risk	European Union 15 countries based on ICONA 1991
De La Rosa, Moreno, Mayol, and Bonsón (2000)	12% reduction on crop productivity will be reached in 2100 with erosion rates of 16 t ha^{-1} $year^{-1}$.	Based on results in Andalusia region (Spain)
Bakker, Govers, and Rounsevell (2004)	2.7% yield decrease per decade according to findings in de-surfacing experiments; yield reductions due to soil erosion are around 4.3% per 10 cm of soil lost.	Based on data analysis (field data collection) in Europe
den Biggelaar, Lal, Wiebe, and Breneman (2001)	Crop productivity based on past plot studies for different crops in all continents, showing negligible effects for erosion rates <2 t ha^{-1} $year^{-1}$.	Analysis of soil erosion–productivity experiments
Bakker, Govers, Jones, and Rounsevell (2007)	4.9% yield loss in case of 10 cm soil erosion	Based on available water capacity analysis
Montgomery (2007)	Soil loss rates less than 12 t ha^{-1} $year^{-1}$ as tolerable for maintain the crop productivity	Based on the U.S. Department of Agriculture values
Larney, Janzen, Olson, and Olson (2009)	Grain yields may fall by 2.1% annually per cm of soil removal	Experiments in Alberta, Canada

Note. NRI = National Resources Inventory.

is due to different percentages of severely eroded land and total agricultural area. This hypothesis is made due to a lack of georeferenced crop areas per MS. Once the land productivity loss has been computed using (1), crop productivity loss per crop and MS is calculated as

$$CPL_{i,r} = LPL_r{*}CA_{i,r}{*}CP_{i,r}, \tag{2}$$

where *CPL* is the crop productivity loss per MS and crop, expressed in tonnes, LPL is the land productivity loss estimated using Equation 1, CA is the crop area (ha), and CP is the crop productivity (t/ha). The variables *i* and *r* represent the crop (Table 4: 10 crops in agronomical analysis) and the country indices, respectively.

Finally, the crop productivity loss is multiplied by the market price of each crop, to calculate the overall monetary loss. The results are aggregated per crop type and per MS.

3.3 | Higher order costs: Using a computable general equilibrium model

The land productivity losses estimated in the direct cost evaluation are key inputs for evaluating the macroeconomic impact of soil erosion on the agricultural sector and GDP (Figure 1). The macroeconomic effects of soil erosion can be further evaluated using economic models. This implies going beyond the direct cost represented by the loss in production and quantifying its impacts on the economic activity of the agricultural sector and of the overall capacity of a country to produce goods and services, namely, its GDP. Among the different economic modelling approaches that can provide an aggregated and systemic representation of the economic activity, CGE models are widely used and consolidated both within the academic and the policy environments (Böhringer & Löschel, 2006). It is worth noting that the macroeconomic effects captured by the CGE models originate from the decisions of representative consumers, firms, and the public sector, which are driven by changes in market prices. All these agents interact in the national and international economies.

Originally developed at the end of 1960s to assess the economic consequences of international and public sector policies, CGE models have been increasingly applied since the end of the 1990s to economically assess environmental impacts, particularly those associated with climate change. CGE models have been applied to various sectors such as agriculture (Tsigas, Frisvold, & Kuhn, 1997), tourism (Berrittella, Bigano, Roson, & Tol, 2006), and climate change effects such as sea-level rise (Bosello, Nicholls, Richards, Roson, & Tol, 2012; Darwin & Tol, 2001; Deke, Hooss, Kasten, Klepper, & Springer, 2001). More recently, CGE studies offer an estimation of a joint set of climate change impacts on growth and GDP: Eboli, Parrado, and Roson (2010), Ciscar et al. (2011), Ciscar et al. (2014), and Organisation for Economic Co-operation and Development (2015).

CGE models provide a multi-country, multi-sector description of the economic system in which representative firms and households demand and supply factors of production, goods, and services in order to maximise profits or utility. Demand and supply chains generate domestic and international trade flows, whereas prices adjust to guarantee their perfect matching. CGE models are calibrated; this means that their initial database and behavioural parameters replicate the economic transactions observed in a given year. Starting from the observed behaviour of "agents", CGE models calculate macroeconomic variables such as sectoral production, country GDP, and international trade flows. In principle, a CGE model can also economically quantify any "perturbation" of its initial market equilibrium (e.g., a tax, a subsidy, a technological shock, and a natural event) once this is appropriately translated into changes in demand or supply of factors, goods, and services represented in the model.

For the purpose of this study, we use the Intertemporal Computable Equilibrium System (ICES; Eboli et al., 2010), a recursive–dynamic CGE model based on the Global Trade Analysis Project 8 database (Narayanan, Aguiar, & McDougall, 2012). ICES is a dynamic, multiregional CGE model of the global economy, where growth is driven by endogenous capital accumulation processes and exogenous changes in the stock and productivity of primary resources (labour, land, and natural resources).

The overall idea of the simulation is to relate soil erosion to crop productivity losses and to use the CGE model to compute how these crop productivity losses affects the agricultural sector and the overall GDP of the countries being studied (Figure 1). Changes on crop yields are expected to affect agricultural production and prices, which have an impact on the demand and supply of agricultural commodities and all the other economic sectors that more or less directly trade with agriculture. This will finally affect GDP and import–export flows, as agricultural commodities are traded internationally. The results of the simulation stem from a comparative static experiment. This means that the macroeconomic effects of a change in land productivity are isolated ceteris paribus. However, they have to be considered as annual economic effects that occur in an economic system where markets are perfectly competitive, resources are fully employed, and capital and labour are perfectly mobile between all sectors. All of these conditions are rarely satisfied in reality, but this represents an ideal benchmark. In this model application, we use ICES in its static version (Fondazione Eni Enrico Mattei, 2017). The country and sectoral detail of the model used in this study are reported in Table 3.

The starting inputs to the CGE model are land productivity losses associated with soil erosion, computed using Equation 1. This input is then directly translated into productivity changes of the land production factor in the CGE model. In the CGE model, land is a primary production factor, which is used by the representative farmer in each country and crop industry together with labour, capital, and a set of intermediate factors to produce agricultural commodities. Table 4 shows the relationship between the crops considered in the agronomic analysis (crop productivity loss) described in previous section and the crops represented in the CGE model.

TABLE 3 Country and sectoral detail of the ICES model

Country	Sectors
Austria Belgium Czech Republic Denmark	Rice
Finland France Germany Greece	Wheat and remaining crops
Hungary Ireland Italy The Netherlands	Other cereals
Poland Portugal Spain Sweden	Oil seeds and oleaginous fruits
United Kingdom Cyprus Estonia Latvia	Sugar beets
Lithuania Luxembourg Malta Slovakia	Livestock
Slovenia Bulgaria Croatia Romania	Industry and extraction of natural resources
Rest of the world	Services

Note. ICES = Intertemporal Computable Equilibrium System.

TABLE 4 Correspondence between crops across the agronomic analysis and the CGE model

Crops in the agronomic analysis	Crops in the CGE model
Rice	Rice
Barley Maize Rye	Other cereals
Rape, turnip rape, and soya Sunflower seed	Oil seeds and oleaginous fruits
Sugar beets	Sugar beets
Potatoes Pulses Wheat and remaining crops	Wheat and remaining crops

Note. CGE = computable general equilibrium.

In the CGE model, land productivity loss is represented as $\tau_{i,r}$(equation 4), where i and r represent the crop and the country indices, respectively. The land productivity loss is derived from Equation 1 and is equal for all crops within the country. The land productivity loss is then used inside the (upper level of the) crop production functions. These take the form of a constant elasticity of substitution function, which depends on land, capital, and labour:

$$VA_{i,r} = \left(\alpha_{i,r} La_{i,r}^{\frac{\sigma_i-1}{\sigma_i}} + \beta_{i,r} K_{i,r}^{\frac{\sigma_i-1}{\sigma_i}} + \gamma_{i,r} L_{i,r}^{\frac{\sigma_i-1}{\sigma_i}}\right)^{\frac{\sigma_i}{\sigma_i-1}}; \sigma_i>0, \quad (3)$$

where VA is the value added and La, K, and L are the values of land, capital, and labour, respectively. The elasticity of substitution function is 1-

degree homogenous in the primary factors (land, capital, and labour) and allows for their substitution depending on σ_i (the higher the value, the higher the substitution). The variables α, β, and γ are the associated productivity factors. The $\alpha_{i,r}$ parameter is exogenous. It is modified in the simulation according to the influence of the loss in land productivity ($\tau_{i,r}$):

$$\alpha_{i,r}^{\mathrm{New}} = \left(1-\tau_{i,r}\right)\cdot\alpha_{i,r}. \quad (4)$$

4 | RESULTS AND DISCUSSION

Below, we present the cost of soil erosion due to the loss in productivity of crop commodities (per crop and country). The evaluation of the loss in crop productivity in terms of changes in GDP is described in the second subsection, on the basis of the application of the more complex CGE model. A final subsection presents the uncertainties of this study.

4.1 | Cost of productivity loss of commodity crops

The costs of losses in productivity are presented both per crop type (Table 5) and grouped at country level (Table 6). More than 12 million hectares of agricultural land in the EU (about 7.2% of the total) are potentially severely eroded every year (reference period: 2010). Almost 3 million tonnes of wheat and 0.6 million tonnes of maize are estimated to be lost annually due to severe erosion (Table 5). The highest productivity loss (as a percentage) is found for rice and wheat because they are the most dominant crops in the most erosive areas of Mediterranean countries (Italy, Spain, and Greece). On the other hand, rye has the lowest loss in productivity (0.18%), as it is mostly cultivated in countries with relatively low erosion rates (Germany and Poland).

The total economic loss in agricultural productivity due to severe erosion in the EU is around €1,257 million (reference year: 2010), which is about 0.43% of the EU's total agriculture sector contribution to GDP (estimated at €292,320 million). In 2001, the European Commission's Directorate-General for Agriculture obtained similar results (using a similar methodology to the one employed in this paper), estimating the mean on-site effects of soil erosion (cost) to be 0.42% of gross agricultural value in 13 countries (Görlach et al., 2004). Most (59%) of this cost is incurred by wheat, which is the most dominant crop in the EU. However, the total economic loss may be slightly higher, as the loss of high value crops (vineyards, fruit trees, orchards, etc.) is replaced by the lower cost of wheat.

Compared to the overall agricultural productivity loss of €1,257 million in EU, soil erosion by water has the highest impact in Italy, with a cost of around €619 million per annum (Table 6). Spain, France, Germany, Poland, and Italy are the countries with the highest absolute agricultural area (>15 million hectares), but Italy has a high proportion of land subject to severe erosion (33%). Slovenia also has a high percentage of agricultural area that is subject to severe erosion, but it is a relatively small country. The Nordic countries, the Baltic States, Denmark, the Netherlands, Belgium, and Ireland and the smaller states, Luxembourg, Malta, and Cyprus have minor economic losses because their area under severe erosion is relatively small (Table 6).

Soil erosion removes the upper fertile part of soils that contains nutrients. Other direct costs include the fertilisation applied by farmers to mitigate this fertility loss. Below, we provide some examples of replacement cost for mitigating soil erosion. For instance, Lugato, Paustian, Panagos, Jones, and Borrelli (2016) estimated a soil organic carbon displacement by water erosion in EU agricultural soils of about 9–14 Mt of carbon per year. Considering an average soil carbon/nitrogen (C/N) ratio of 9, the amount of displaced organic nitrogen is in the order of 0.9–1.5 Mt/year. Only a small amount of this organic nitrogen is available for crops after mineralisation, but assuming a conservative 2% annual mineralisation rate, its substitution with urea (with an average price of €350/t; FAO, 2015b) would cost €14–23 million per year. A consistent amount of phosphorous (P) is also displaced with sediments (by water erosion) from the topsoil, where it is preferentially accumulated due to fertilisations and its low mobility. Considering the average content of available P from the LUCAS dataset (Orgiazzi, Ballabio, Panagos, Jones, & Fernández-Ugalde, 2018), the erosion rates from RUSLE2015 and the price of P fertiliser (€440 as di-ammonium phosphate; FAO, 2015b), its substitution would cost €3–17 million per year. This wide range is related to the uncertain relation between plant uptake and available P from soil analysis; therefore, we

TABLE 5 Estimated annual productivity loss per crop using direct cost evaluation (year 2010)

Crop	Total area (1,000 ha)	Actual productivity (1,000 t)	Area severely eroded (1,000 ha)	Crop productivity loss in affected areas (1,000 t)	% of tonnes lost	Price (€/t)	Crop productivity loss (million €)
Maize	15,703.0	111,586	1,124.0	594.4	0.53	220.8	131.222
Barley	24,975.6	110,072	1,152.1	307.6	0.28	221.7	68.199
Rape, turnip rape, and soya	22,786.0	135,877	789.3	380.1	0.28	479.2	182.154
Sunflower seed	4,285.9	6,956	313.7	37.2	0.53	449.1	16.712
Potatoes	1,797.5	55,271	78.0	143.2	0.26	299.1	42.841
Sugar beets	1,661.0	116,017	50.4	327.2	0.28	43.6	14.265
Rye	2,500.3	9,082	66.6	15.9	0.18	200.5	3.202
Rice	894.0	6,091	191.4	104.6	1.72	362.1	37.883
Pulses	2,036.1	5,243	152.7	29.6	0.57	734.9	21.779
Wheat (all types)	90,647.9	422,883	8,141.3	3,037.7	0.72	243.4	739.365
Total	167,287.3		12,059.6				1,257.622

TABLE 6 Estimated annual productivity loss (area, %, and €) per country using direct cost evaluation (year 2010)

Country		Agricultural area severely eroded (1,000 ha)	Total agricultural area (1,000 ha)	% of total agricultural area with severe erosion	Land productivity loss (%)	Crop productivity loss (million €)
AT	Austria	218.4	1,967.7	11.1	0.8878	29.086
BE	Belgium	6.5	1,405.0	0.5	0.0373	1.380
BG	Bulgaria	202.2	5,323.7	3.8	0.3038	17.617
CY	Cyprus	34.4	437.3	7.9	0.6286	1.648
CZ	Czech Republic	67.3	3,814.1	1.8	0.1412	10.564
DE	Germany	286.7	16,857.6	1.7	0.1361	50.763
DK	Denmark	0.1	3,209.4	0.0	0.0003	0.018
EE	Estonia	0.1	1,221.8	0.0	0.0006	0.006
EL	Greece	608.6	5,140.3	11.8	0.9471	43.352
ES	Spain	2,444.3	24,541.2	10.0	0.7968	153.117
FI	Finland	0.1	2,944.4	0.0	0.0003	0.007
FR	France	688.9	24,113.0	2.9	0.2285	130.896
HR	Croatia	178.6	1,966.8	9.1	0.7265	18.778
HU	Hungary	177.5	5,568.7	3.2	0.2550	18.902
IE	Ireland	7.2	1,105.7	0.7	0.0521	0.989
IT	Italy	5,030.5	15,261.7	33.0	2.6369	619.095
LT	Lithuania	0.8	3,564.1	0.0	0.0018	0.079
LU	Luxembourg	4.6	103.3	4.4	0.3530	0.553
LV	Latvia	0.2	1,972.6	0.0	0.0009	0.019
MT	Malta	1.4	15.4	8.8	0.7049	0.116
NL	The Netherlands	0.1	1,415.4	0.0	0.0007	0.033
PL	Poland	264.4	16,892.3	1.6	0.1252	29.078
PT	Portugal	242.6	4,154.6	5.8	0.4671	7.554
RO	Romania	1,146.7	10,960.3	10.5	0.8370	74.058
SE	Sweden	12.2	3,667.0	0.3	0.0266	1.444
SI	Slovenia	242.1	589.3	41.1	3.2869	26.587
SK	Slovakia	160.1	2,098.6	7.6	0.6102	16.903
UK	United Kingdom	38.5	6,975.8	0.6	0.0441	5.314
EU		12,065.0	167,287.3	7.2		1,257.622

Note. EU = European Union.

considered (conservatively) that 10% to 50% of available P lost could be directly uptake by plants yearly. Those are simple examples of estimating the cost of possible fertility loss due to displacement of organic nitrogen and phosphorus in erosive areas addressing partially the replacement costs. An exhaustive estimation of soil organic carbon loss in European soils (and the replacement costs) requests a separate study. The focus of this study is the cost estimation of crop productivity loss and the application of CGE model to quantify the impact of soil erosion on the overall economic activity of the agricultural sector. The consequences of climate change in yield losses (flooded areas, increased temperatures, desertification, property loss, etc.; Ciscar et al., 2011) and in specific the projections for increased erosivity due to rainstorm intensification in Northern and Central Europe by 2050 (Panagos et al., 2017) will further reduce crop productivity.

4.2 | Macroeconomic costs of soil erosion

According to the results of the CGE model simulation (Table 7), the economic loss in agricultural production due to soil erosion in the EU is about 0.12% annually (reference year: 2010), which translates into a loss of about €295.7 million to the agricultural sector. Comparing the results of the two methodologies, the percentage change in the agricultural sector income is much smaller than the value of crop productivity loss in the EU (0.12% vs. 0.43%). This is due to two market-driven adjustments that the model captures. First, the model partially substitutes the less productive land in the agricultural production process with more labour and capital input. This mimics the farmers' autonomous reaction to potential economic losses.

Second, as can be seen in Table 7, notwithstanding the pervasive reductions in land productivity (the highest land productivity loss is the 3.29% recorded by Slovenia, followed by Italy [2.6%] and Greece [0.95%]), agricultural production increases in 15 countries (third column). This increase is due to the effect of trade mechanisms. Those countries for which the decline in land productivity is lower (Table 7: second column) may become more competitive (the price of their agricultural commodities increases less than that of their competitors) and thus experience greater demand and production.

The overall economic value of agricultural production gains in the 15 countries that experienced an increase in the agricultural sector is about €97.3 million, whereas the total loss in the remaining

TABLE 7 Effects of soil erosion in agricultural sector and country GDP using the CGE macroeconomic model (year 2010)

Country	Land productivity loss (%)	Agricultural production change (%)	Agricultural production impact (million €)	GDP % change	GDP impact (million €)
Austria	0.8878	−0.02	−0.845	−0.0012	−3.635
Belgium	0.0373	0.18	8.169	−0.0005	−2.064
Czech Republic	0.1412	−0.01	−0.321	−0.0008	−1.213
Denmark	0.0003	0.12	4.507	−0.0006	−1.636
Finland	0.0003	0.05	1.049	−0.0003	−0.544
France	0.2285	0.03	14.953	−0.0008	−16.801
Germany	0.1361	0.07	21.588	−0.0004	−10.177
Greece	0.9471	−0.16	−17.059	−0.0048	−12.579
Hungary	0.2550	−0.02	−0.836	−0.0026	−3.063
Ireland	0.0521	0.08	1.545	−0.0003	−0.595
Italy	2.6369	−0.75	−251.328	−0.0021	−36.837
The Netherlands	0.0007	0.22	31.535	−0.0005	−3.370
Poland	0.1252	0.01	1.354	−0.0010	−3.467
Portugal	0.4671	−0.04	−2.135	−0.0014	−2.824
Spain	0.7968	−0.20	−60.854	−0.0014	−17.128
Sweden	0.0266	0.07	1.948	−0.0002	−0.707
United Kingdom	0.0441	0.09	9.161	−0.0001	−2.614
Cyprus	0.6286	0.04	0.196	−0.0011	−0.195
Estonia	0.0006	0.03	0.147	−0.0003	−0.049
Latvia	0.0009	0.05	0.383	−0.0004	−0.095
Lithuania	0.0018	0.04	0.712	−0.0005	−0.179
Luxembourg	0.3530	0.03	0.126	−0.0004	−0.161
Malta	0.7049	−0.02	−0.024	−0.0010	−0.063
Slovakia	0.6102	−0.23	−2.884	−0.0020	−1.395
Slovenia	3.2869	−2.09	−15.020	−0.0119	−4.797
Bulgaria	0.3038	−0.04	−0.808	−0.0022	−0.776
Croatia	0.7265	−0.26	−10.783	−0.0143	−7.100
Romania	0.8370	−0.28	−30.153	−0.0149	−21.475
EU		−0.12	−295.677	−0.0011	−155.542

Note. CGE = computable general equilibrium; EU = European Union; GDP = gross domestic product.

13 countries is about €393 million. As a sum, the net impact is a decrease of €295.7 million in total agricultural sector income. Of the 15 countries that experienced positive agricultural production change, the Netherlands, Germany, and France had the highest positive agricultural production impact (Table 7: fourth column). Italy is almost three times less affected than Slovenia in terms of % losses, even though the two countries experienced a similar physical impact (around 3% loss in land productivity). This is mainly due to the higher share of land used in agricultural production in Slovenia compared to Italy. These redistributional mechanisms are what CGE models typically capture and account for the substitution effects in the economy.

In terms of GDP (Table 7: fifth column), losses were found to be widespread in the EU, and no country experienced gains. The explanation of GDP losses is straightforward for countries that experienced losses in agricultural production, as this also negatively affects GDP. However, it is not so obvious for the countries in which the agricultural sector expanded production. In these countries, land is becoming less productive, which decreases the ability of the country to produce, even though, eventually, the effects of international trade (demand) can induce an increase in agricultural production. This can be achieved by putting more resources into a less productive sector at the expense of more productive sectors. Eventually, the overall resource reallocation yields less than the initial allocation. In the majority of cases, the value of GDP losses (Table 7: sixth column) is lower than the value of agricultural production losses (Table 7: fourth column). This is another consequence of the functioning of market mechanisms. When the agricultural sector contracts, factors of production are free to relocate to other sectors, thereby mitigating the overall GDP loss. This is true especially for labour and capital, which are perfectly mobile across all sectors of the economy. As is typical in CGE models, these adjustments tend to be low cost and almost frictionless. In fact, CGE models represent an idealised and fully competitive economy, under the assumption that the European markets continue to be well integrated. Accordingly, the estimated GDP losses should be considered as the lower bound for economic losses.

Overall, soil erosion, through crop productivity loss and total net decrease in agricultural sector income, can entail a loss in GDP of €155 million to the EU at current values. As the CGE database includes

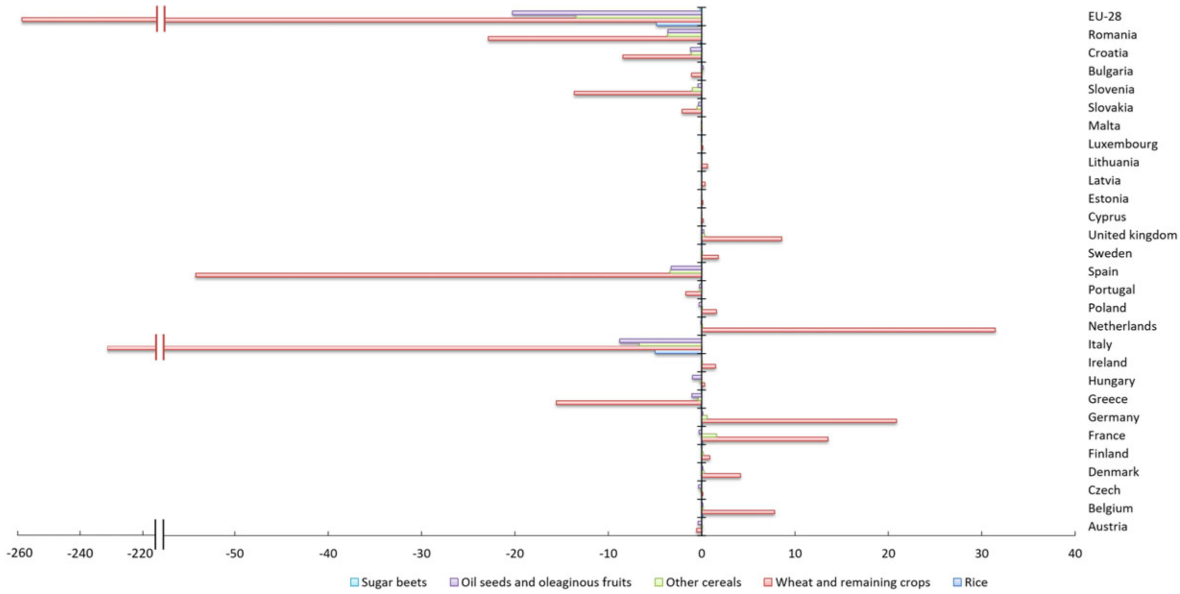

FIGURE 2 Changes in agricultural production levels (million €) in European Union due to soil erosion [Colour figure can be viewed at wileyonlinelibrary.com]

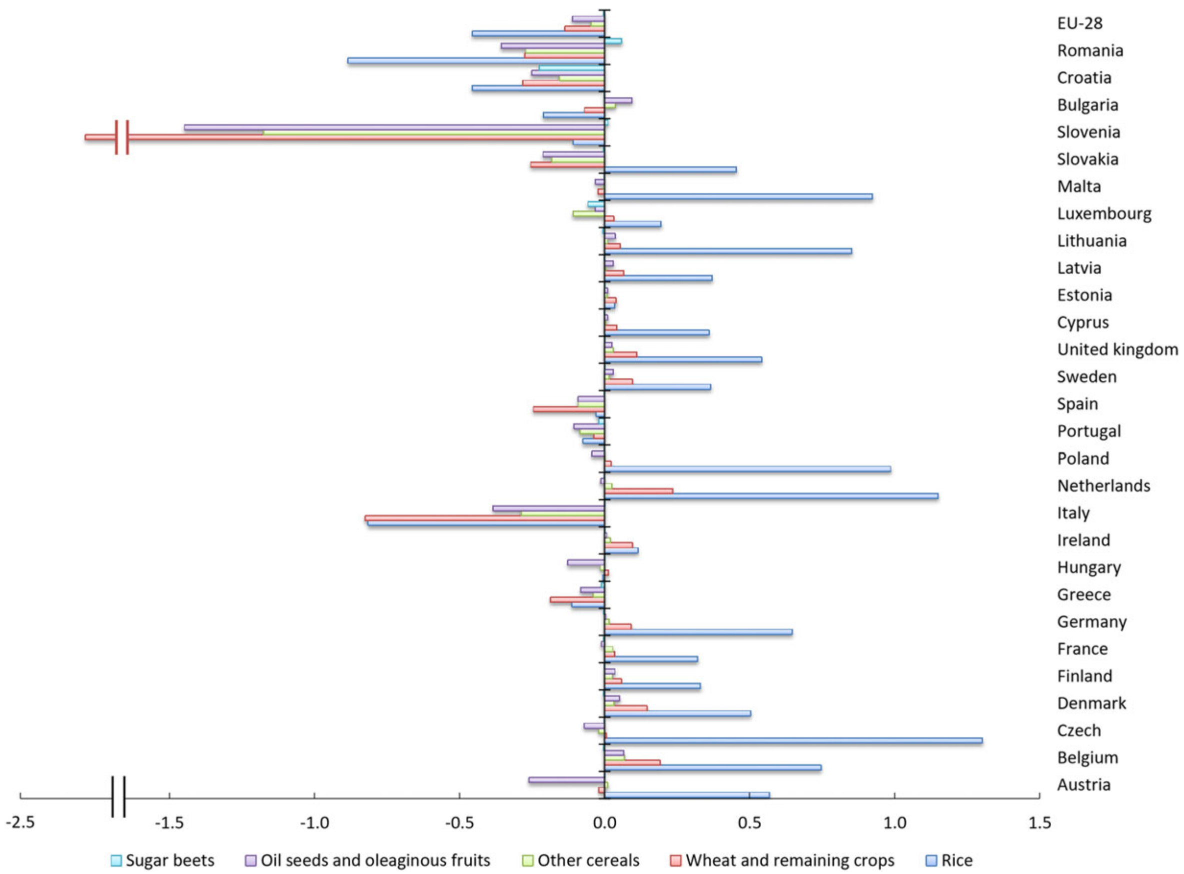

FIGURE 3 Changes (%) in agricultural production in European Union across crop types due to soil erosion [Colour figure can be viewed at wileyonlinelibrary.com]

values expressed in US$ for the year 2007, we used the 2007 exchange rate to convert them into € and then used the Harmonised Index of Consumer Prices (2016) of Eurostat to convert the 2007 € values into 2016 € values.

The analysis also allows for the representation of sectoral effects within agriculture in each country (Figures 2 and 3). In percentage terms (Figure 3), rice exhibits the largest oscillations. This depends on the greater substitutability of rice in consumer preferences, which means that the consumer is more willing to substitute domestic with imported rice compared to other crops. This is called the Armington hypothesis (Armington, 1969), on which CGE models rely. However, rice represents a very small fraction of the EU agricultural sector's added value, and its production is concentrated in Italy and Spain. Accordingly, monetary impacts of reduced rice production are quite small. Monetary impacts are largely driven by wheat and other crops, especially in Italy and Spain, where they account for about 96% of the net agricultural losses in the EU.

4.3 | Uncertainties

The main uncertainties that should be considered in this study are (a) the soil erosion estimates as outputs of the biophysical model, (b) the assumption that crop productivity loss of 8% occurs in agricultural fields with severe erosion, (c) the productivity loss is equally distributed across all crop types within a country, (d) the assumption of assigning the non-widely cultivated crops as wheat in the cost evaluation, and (e) the assumptions in the macroeconomic model and the market prices (described in Section 3).

The first source of uncertainty is the application of RUSLE2015 and the prediction of potential soil erosion rates done with this biophysical model. The calculation of actual erosion rates for more than 4.3 million km^2 (covering the EU) is not possible. That is the reason for using models to estimate erosion rates at continental scale. The estimation of actual erosion rates based on empirical data is feasible in small catchments but more difficult than the use of models that predict potential erosion rates. The choice of the 8% threshold (second uncertainty) is based on the output of the majority of the reviewed studies, which set this as productivity loss percentage. The rest of the reviewed studies have estimated loss of agricultural productivity between 4% and 12% in case of severe erosion. In this uncertainty, we could also add the assumption that low erosion rates have no impact in agricultural productivity loss even if this was repeatedly mentioned in the literature (Den Biggelaar et al., 2001).

The constraint of not having georeferenced available crop data in EU resulted in the third uncertainty of this study. This limitation (equal distribution of agricultural productivity loss to all crops) was somehow narrowed at member state level with use of country crop statistics. Due to huge number of cultivated crops in the study area and the lack of model-requested statistical data (cultivated area, productivity per country, prices, etc.), we could not model the cost of agricultural productivity loss due to erosion for crops such as vineyards, olive trees, and orchards. So, for the 11% of the study area cultivated with al high diversified number of crops, we have assigned wheat as cultivated crop (fourth uncertainty). Of course, this guides to an underestimation of our results as the wheat productivity loss is minor compared to productivity loss in vineyards or orchards.

Regarding the fifth source of uncertainty, this was discussed in the CGE model outputs. Moreover, GDP is not always the most appropriate indicator for assessing economic welfare, population well-being, and sustainability (Kubiszewski et al., 2013). GDP is a measure of flow rather than of stock and the value of soil (or of land, houses, etc.) is not part of GDP.

This study is a significant contribution towards better understanding the impact of soil erosion in land productivity loss. However, the results should be handled with care as they include the uncertainties of the biophysical model and the economical model plus the assumptions of a perfect economic system.

5 | CONCLUSIONS

In the EU, the loss of agricultural productivity due to soil erosion by water is estimated at 0.43% per annum, on the basis of the combined outputs of biophysical and agronomic models. Taking into account the erosion rates, the crop distribution per country, and the mean commodity crops prices, the annual crop productivity loss is estimated to be around €1.2 billion. Using a CGE macroeconomic model, we estimated the annual cost of soil erosion to the EU agricultural sector to be around €295 million (a reduction of 0.12%) and to lead to a loss of around €155 million in GDP. Simpler approaches (market price of soil and erosion control investments) estimate much higher costs of soil erosion in Europe.

In monetary terms, the loss in crop productivity due to soil erosion is four times higher than the loss in the agricultural sector and eight times higher than the GDP loss. This is due to endogenous adjustments or adaptations in the economic system through trading mechanisms (import/export flows, competitiveness, consumer preferences, reallocation of labour and capital between sectors, etc.). These trading mechanisms mitigate initial losses (crop productivity), as macroeconomic models (such as the CGE model) can take them into account. Finally, it is worth noting that such mitigated GDP losses can be attained only as long as perfectly flexible and competitive market conditions hold.

The results of this study suggest that soil erosion by water is not a threat to food security in the EU but imposes particularly high costs on the agricultural sector of countries such as Italy, Slovenia, Spain, and Greece. With about 9 billion people to feed by 2050, global agriculture production will have to intensify, presumably on a reduced proportion of land, as soil erosion, soil sealing, and salinisation increasingly take their toll on the landscape. Although soil erosion rates do not yet pose a food security issue in Europe, anti-erosion measures should continue to be implemented in order to further reduce the current unsustainable erosion rates. Future research is needed to quantify the economic loss incurred due to the off-site effects of soil erosion.

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CONFLICT OF INTEREST

The authors confirm that there is no conflict of interest with networks, organisations, and data centres referred to in the paper.

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SUPPORTING INFORMATION

Additional Supporting Information may be found online in the supporting information tab for this article.

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