COST OF AGRICULTURAL PRODUCTIVITY LOSS DUE TO SOIL EROSION IN THE EUROPEAN UNION: FROM DIRECT COST EVALUATION APPROACHES TO THE USE OF MACROECONOMIC MODELS

Panos Panagos[1*], Gabriele Standardi[2], Pasquale Borrelli[3], Emanuele Lugato[1], Luca Montanarella[1], Francesco Bosello[2]

[1] European Commission, Joint Research Centre, I-21027 Ispra (VA), Italy

[2] Euro-Mediterranean Center on Climate Change, Venice, Italy

[3] Environmental Geosciences, University of Basel, Switzerland

*corresponding author: Tel: 0039-0332-785574, *Fax: 0039-0332-786645,*

E-mail: panos.panagos@ec.europa.eu

ABSTRACT

Much research has been carried out on modelling soil erosion rates under different climatic and land use conditions. While 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 bio-physical 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(CGE) 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 CGE 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, while the agricultural sector in most northern and central European countries is only marginally affected by soil erosion losses.

INTRODUCTION

Soil is subject to a series of degradation processes and threats. The main threats to soil, as identified in the European Union Soil Thematic Strategy (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 (Pimentel, 2007; Graves et al., 2015; FAO, 2015).

Soil degradation causes decline in soil quality and productivity. Among the soil degradative processes (decline in soil structure, compaction, salinization, 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 recognizing 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 et al., 2003). These include losses in production, yields and nutrients, damage to plantations, and reduction of the available planting area (Telles et al., 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., 2003; Telles et al., 2011; 2013).

A simple Google Scholar search for the term "soil erosion" yields around 1,070,000 results (18.12.2017), while 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. Garcia-Ruiz et al. (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 et al., 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 et al., 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, based on estimations made of 13 largest EU Member States 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 Member States. 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 I). The first two simple cost estimation methodologies consider the erosion-control measures and the soil market price (Table I). Kuhlman et al. (2010) used the cost (€296 per ha) of erosion control in areas of severe erosion (> 10 t ha^{-1} yr^{-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 UK, Posthumus et al. (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 United Kingdom. The market price of soil for direct use was estimated at around US$20 per tonne (Robinson et al., 2014). According to Robinson et al. (2014) and Panagos et al. (2015b), 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, Cost benefit analysis), the most well-known methodologies are the replacement cost method (Dixon et al., 1994) and the productivity loss method (Gunatilake & Vieth, 2000). The costs of additional nutrients to soil (nitrogen and phosphorus) to mitigate soil erosion is an example of replacement cost method. Recent studies (Martinez-Casanovas & Ramos, 2006; Hein, 2007) 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 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 (UNCCD) article 1 (UNCCD, 2017). In this vein, a recent study carried out by Nkonya et al. (2015) highlighted the need to estimate the costs of land degradation at the global scale. They promoted the Economics of Land Degradation (ELD) initiative, which aims to develop a scientific basis for assessing the costs of land degradation. The United Nations' System of Environmental and Economic Accounts (SEEA) is a broad-scale 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 gross domestic product (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 macro-economic 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 (Enters, 1998; Bojo, 1996; Gunatilake & Vieth, 2000). In the macro-economic approach (Table I), 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 Member States.

STUDY AREA AND INPUT DATA

The study area is the European Union (EU-28) which, according to CORINE land cover statistics (CLC, 2014), has 167 million ha 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 et al., 2016a). 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 tonnes ha^{-1} yr^{-1}; threshold set by the Organisation for Economic Co-operation and Development - OECD).

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, complex application of macroeconomic models) which are used to quantify the economic impact of soil erosion on land productivity.

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 et al., 2015a). 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, Support practices) which are modelled using the most recently available pan-European datasets (Fig. 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 (REDES), CORINE Land Cover, Copernicus Remote sensing datasets, Eurostat statistical data (crops, tillage, plant residues, cover crops), 270,000 Land Use/Land Cover earth observations, Good Agriculture and Environmental Conditions (GAEC) database and Digital Elevation Model (EEA). In the supporting material, 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 (tonnes ha^{-1} yr^{-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 et al., 2016b). The spatial patterns of erosion rates are mostly influenced mostly 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 (Fig. 1).

RUSLE2015 results are available for our study area (EU-28). Other modelling results such as Pan-European Soil Erosion Risk Assessment (PESERA) model (Kirkby 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., 2015a; 2016a; 2016b) 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, 2016a, Fiener & Auerswald, 2016; Panagos et al., 2016b, 2016c).

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 (t/ha) for 10 commodity crops, predicts 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 (ESTAT, 2016), refer to the 2012-2014 period. We used the following two figures: a) hectares of cultivated area (and harvested production) per country; b) crop yield as tonnes per hectare for each country. The 10 crops considered are: maize (including grain maize, green maize), barley (including winter and spring barley), rape (including rape, 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 ha 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 (FAO) statistics (FAOSTAT, 2016)) as an average price of period 2012-2014 using the exchange rate of 20.11.2016 (€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.

Based on relevant literature findings (Table II), 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} yr^{-1}). This literature review of 16 studies (Table II) takes into account the experimental results of crop productivity loss due to erosion and it is well distributed in the World (U.S.A, 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} yr^{-1}). According to Montgomery (2007), the United States Department of Agriculture (USDA) also considers soil loss rates of less than 12 t ha^{-1} yr^{-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 Member States (MS) 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 Member State (r represents the country index) expressed as %, SEA is the area of severe erosion per Member State (ha), and TAA is the total agricultural areas of the Member State (ha).

This assumes that the productivity loss is equally distributed across all crop types within Member States, and that the variability between them 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 Member State. Once the land productivity loss has been computed using (1), crop productivity loss per crop and Member State is calculated as:

$$CPL_{i,r} = LPL_r * CA_{i,r} * CP_{i,r} \quad (2)$$

where:

CPL is the crop productivity loss per Member State 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 (tonnes/ha). The variables i and r represent the crop (Table IV: 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.

Higher order costs: using a Computable General Equilibrium (CGE) 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 (Fig. 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, Computable General Equilibrium (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 et al., 1997), tourism (Berrittella et al., 2006), and climate change effects such as sea-level rise (Deke et al., 2001; Darwin and Tol, 2001; Bosello et al., 2012). More recently, CGE studies offer an estimation of

a joint set of climate change impacts on growth and GDP: Aaheim & Dokkes (2009), Eboli et al. (2010), Ciscar et al. (2011; 2014), OECD (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, while 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, international trade flows etc. 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, 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 the present 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 (GTAP 8) database (Narayanan et al., 2012). ICES is a dynamic, multi-regional 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 (FEEM, 2017). The country and sectoral detail of the model used in this study are reported in Table III.

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 IV 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.

In the CGE model, land productivity loss is represented as $\tau_{i,r}$, where i and r represent the crop and the country indices respectively. The land productivity loss is derived from eq. (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 (CES) function, which depends on land, capital and labour:

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

where VA is the value added and La, K and L are the values of land, capital and labour, respectively. The CES function is 1-degree homogenous in the primary factors (land, capital, labour) and allows for their substitution depending on σ_i (the higher the value, the higher the substitution). The variables α, β, 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 ($\tau_{i,r}$):

$$\alpha_{i,r}^{New}=(1-\tau_{i,r})\cdot\alpha_{i,r} \qquad\qquad\qquad [4]$$

RESULTS - 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 Gross Domestic Product (GDP) is described in the second subsection, based on the application of the more complex CGE model. A final subsection presents the uncertainties of this study.

Cost of productivity loss of commodity crops

The costs of losses in productivity are presented both per crop type (Table V) and grouped at country level (Table VI). More than 12 million ha 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 V). 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 (Gorlach 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 VI). Spain, France, Germany, Poland and Italy are the countries with the highest absolute agricultural area (> 15 million ha), 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, Ireland, and the smaller states (Luxembourg, Malta and Cyprus) have minor economic losses because their area under severe erosion is relatively small (Table VI).

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 et al. (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 per 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 fertilizations and its low mobility. Considering the average content of available P from the LUCAS dataset (Toth et al., 2013), the erosion rates from RUSLE2015 and the price of P fertilizer (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 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 Computable General Equilibrium (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., 2010) 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.

Macroeconomic costs of soil erosion

According to the results of the CGE model simulation (Table VII), 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. Firstly, 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.

Secondly, as can be seen in Table VII, 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 VII: 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, while the total loss in the remaining 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 VII: 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 re-distributional mechanisms are what CGE models typically capture, and account for the substitution effects in the economy.

In terms of GDP (Table VII: 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 re-allocation yields less than the initial allocation. In the majority of cases, the value of GDP losses (Table VII: sixth column) is lower than the value of agricultural production losses (Table VII: 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 values expressed in US$ for the year 2007, we used the 2007 exchange rate to convert them into €, and then used the Harmonized Index of Consumer Prices (HICP, 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, 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.

Uncertainties

The main uncertainties which 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 macro-economic model and the market prices (described in the methods section).

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 which 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., 2004).

The constraint of not having geo-referenced 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 stated 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, orchards etc. 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.

CONCLUSIONS

In the EU, the loss of agricultural productivity due to soil erosion by water is estimated at 0.43% per annum, based on 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 macro-economic 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, 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. While 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.

REFERENCES

Adhikari B, Nadella K. 2011. Ecological economics of soil erosion: A review of the current state of knowledge. *Annals of the New York Academy of Sciences* **1219 (1)**: 134-152.

Armington PS. 1969. A theory of demand for products distinguished by place of production. *IMF Staff Papers* **16(1)**:159–176.

Bakker MM, Govers G, Rounsevell MDA. 2004. The crop productivity-erosion relationship: An analysis based on experimental work. *Catena* **57(1)**: 55-76.

Bakker MM, Govers G, Jones RA, Rounsevell MDA. 2007. The effect of soil erosion on Europe's crop yields. *Ecosystems* **10(7):** 1209-1219.

Battiston LA, Miller MH, Shelton IJ, 1987. Soil erosion and corn yield in Ontario. I. Field evaluation. *Can. J. Soil Sci.* **67**: 731-745

Berrittella M, Bigano A, Roson R, Tol RSJ. 2006. A General Equilibrium Analysis of Climate Change Impacts on Tourism, *Tourism Management* **27(5)**: 913-924.

Bizoza AR, de Graaff J. 2012. Financial cost-benefit analysis of bench terraces in Rwanda. *Land Degradation and Development*, **23(2)**: 103-115.

Böhringer C, Löschel A. 2006. Computable general equilibrium models for sustainability impact assessment: Status quo and prospects. *Ecological Economics* **60(1):** 49-64.

Bojo J. 1996. The costs of land degradation in Sub-Saharan Africa. *Ecological Economics* **16**: 161-173

Bosello F, Nicholls RJ, Richards J, Roson R, Tol RSJ. 2012. Economic impacts of climate change in Europe: sea-level rise. *Climatic Change* **112:** 63-81.

Bosello F, Roson R, Tol RSJ. 2006. Economy-wide estimates of the implications of climate change: Human health. *Ecological Economics* **58:** 579– 591.

Ciscar JC, Iglesias A, Feyen L, Szabó L, Van Regemorter D, Amelung B, Nicholls R, Watkiss P, Christensen OB, Dankers R, Garrote L, Goodess CM, Hunt A, Moreno A, Richards J, Soria A. 2011. Physical and economic consequences of climate change in Europe 2011. *Proceedings of the National Academy of Sciences of the United States of America* **108(7):** 2678-2683.

Ciscar JC, Feyen L, Soria A, Lavalle C, Raes F, Perry M, Nemry F, Demirel H, Rozsai M, Dosio A, Donatelli M, Srivastava A, Fumagalli D, Niemeyer S, Shrestha S, Ciaian P, Himics M, Van Doorslaer B, Barrios S, Ibáñez N, Forzieri G, Rojas R, Bianchi A, Dowling P, Camia A, Libertà G, San Miguel J, de Rigo D, Caudullo G, Barredo JI, Paci D, Pycroft J, Saveyn B, Van Regemorter D, Revesz T, Vandyck T, Vrontisi Z, Baranzelli C, Vandecasteele I, Batista e Silva F, Ibarreta D. 2014. Climate Impacts in Europe. *The JRC PESETA II Project*. JRC Scientific and Policy Reports, EUR 26586EN.

CLC, 2014. CORINE Land cover dataset for 1990–2000–2006. Available at: http://www.eea.europa.eu/data-and-maps/data/corine-land-cover-2006-raster-2/ (accessed October 2014).

Colombo S, Hanley N, Calatrava-Requena J. 2005. Designing policy for reducing the off-farm effects of soil erosion using choice experiments. *Journal of Agricultural Economics*, **56(1):**81-95

Crosson P. 1995. Soil erosion estimates and costs. *Science* **269(5223)**: 461-465.

Darwin RF, Tol RSJ. 2001. Estimates of the Economic Effects of Sea Level Rise. *Environmental and Resource Economics* **19:** 113–129.

De La Rosa D, Moreno JA, Mayol F, Bonsón T. 2000. Assessment of soil erosion vulnerability in western Europe and potential impact on crop productivity due to loss of soil depth using the Impe1ERO model. *Agriculture, Ecosystems and Environment* **81(3):** 179-190.

Deke O, Hooss KG., Kasten C, Klepper G, Springer K. 2001. Economic Impact of Climate Change: Simluations with a Regionalized Climate-Economy Model. Kiel Institute of World Economics (IfW) 2001: 1065.

den Biggelaar C, Lal R, Wiebe K, Breneman V. 2001. The Global Impact of Soil Erosion On Productivity. I: Absolute and Relative Erosion-induced Yield Losses. *Advances in Agronomy* **81**:1-48.

Dixon JA, Scura LF, Carpenter RA, Sherman PB, 1994. Economic Analysis of the Environmental Impacts, Second edition. *Earthscan Publication Ltd*, London. 224 pp.

EC 2006. European Commission - Thematic Strategy for Soil Protection [SEC(2006)620] [SEC(2006)1165]/* COM/2006/0231 final. Accessed in: http://ec.europa.eu/environment/soil/three_en.htm (Nov 2016).

EC, 2014. COMMISSION IMPLEMENTING REGULATION (EU) No 834/2014 of 22 July 2014 laying down rules for the application of the common monitoring and evaluation framework of the common agricultural policy and COMMISSION IMPLEMENTING REGULATION (EU).

ESTAT, 2016. Eurostat crop statistics. Accessed in: http://ec.europa.eu/eurostat/en/web/products-datasets/-/APRO_ACS_A (Oct 2016).

Eboli F., Parrado R. and Roson R. 2010. Climate Change Feedback on Economic Growth: Explorations with a Dynamic General Equilibrium Model. *Environment and Development Economics* **15(5)**: 515 -533.

Evans R, 1996. Soil Erosion and its Impact in England and Wales. Friends of the Earth Trust, London

Evans R, Boardman J, 2016. A reply to Panagos et al., 2016 (Environmental science & policy 59 (2016) 53–57). *Environ. Sci. Pol.* **60:** 63–68.

Enters T. 1998. Methods for the economic assessment of the on- and off-site impacts of soil erosion. Internat. Board for Soil Research and Management. Issues in Sustainable Land Management no. 2. Bangkok: IBSRAM

FAO, 2015. Status of the World's Soil Resources (SWSR)–Main Report. ISBN 978-92-5-109004-6. Natural Resources and Environment Department, Food and Agriculture Organization (FAO) of the United Nations and Intergovernmental Technical Panel on Soils (ITPS), Rome, Italy. Available at http://www.fao.org/3/a-i5199e.pdf (accessed Dec 2016).

FAO, 2015b. World fertilizer trends and outlook to 2018. Available at : http://www.fao.org/3/a-i4324e.pdf (accessed Dec 2017)

FAOSTAT, 2016. Food and agriculture data statistics. Available at: http://www.fao.org/faostat/en/#data/PP (accessed Nov 2016).

FEEM, 2017. Description of static version of ICES (Inter-temporal Computable Equilibrium System) model. Available at: http://www.icesmodel.feem.it/ (accessed Feb 2017).

Fiener P, Auerswald K. 2016. Comment on "The new assessment of soil loss by water erosion in Europe" by Panagos et al. (Environmental Science & Policy 54 (2015) 438–447). *Environ. Sci. Pol*. **57:** 140–142.

García ‑ Ruiz JM, Beguería S, Lana ‑ Renault N, Nadal ‑ Romero E, Cerdà A. 2017. Ongoing and Emerging Questions in Water Erosion Studies. *Land Degrad. Develop.* **28**: 5-21.

Görlach B, Landgrebe-Trinkunaite R, Interwies E, Bouzit M, Darmendrail D, Rinaudo JD. (2004). Assessing the Economic Impacts of Soil Degradation. Volume III: Empirical Estimation of the Impacts. Study commissioned by the European Commission, DG Environment, Study Contract ENV.B.1/ETU/2003/0024. Berlin: Ecologic.

Graves AR, Morris J, Deeks LK, Rickson RJ, Kibblewhite MG, Harris JA, Farewell TS, Truckle I. 2015. The total costs of soil degradation in England and Wales. *Ecological Economics* **119**: 399-413.

Gunatilake HM., Vieth GR. 2000. Estimation of on-site cost of soil erosion: A comparison of replacement and productivity change methods. *Journal of Soil and Water Conservation*, **55(2)**: 197-204.

Hein L. 2007. Assessing the costs of land degradation: A case study for the Puentes catchment, southeast Spain. *Land Degrad. Develop*. **18**:631-642

Hertel TW. (Ed.) 1997. Global trade analysis: Modeling and applications. Cambridge and New York: Cambridge University Press.

HICP, 2016. Harmonised Index of Consumer Prices. Available at: http://ec.europa.eu/eurostat/cache/metadata/en/prc_hicp_esms.htm (accessed Nov 2016).

Hummels D. 1999. Toward a Geography of Trade Cost, GTAP Working Paper No.17, Center for Global Trade Analysis, West Lafayette, Indiana.

Kibblewhite M.G, Miko L, Montanarella L. 2012: Legal frameworks for soil protection: Current development and technical information requirements. *Current Opinion in Environmental Sustainability* **4(5):** 573-577.

Kirkby MJ, Irvine BJ, Jones RJA. et al. 2008. The PESERA coarse scale erosion model for Europe-model rationale and implementation. *Eur. J. Soil Sci.* **59(6)**, 1293–1306.

Kubiszewski I, Costanza R, Franco C, Lawn P, Talberth J, Jackson T. Aylmer C. 2013. Beyond GDP: Measuring and achieving global genuine progress. *Ecological Economics* **93**: 57-68.

Kuhlman T, Reinhard S, Gaaff A. 2010. Estimating the costs and benefits of soil conservation in Europe. *Land Use Policy* **27(1)**: pp. 22-32.

Lal R. 1995. Erosion-crop productivity relationships for soils of Africa. *Soil Science Society of America Journal*, **59(3)**: 661-667

Lal R. 2001. Soil degradation by erosion. *Land Degradation and Development*, **12(6)**: 519-539.

Larney FJ, Janzen HH, Olson BM, Olson AF. 2009. Erosion-productivity-soil amendment relationships for wheat over 16 years. *Soil and Tillage Research* **103(1)**: 73-83.

Lugato E, Paustian K, Panagos P, Jones A, Borrelli P. 2016. Quantifying the erosion effect on current carbon budget of European agricultural soils at high spatial resolution. *Global Change Biology* **22(5)**: 1976-1984.

Lyles L. 1975. Possible effects of wind erosion on soil productivity. *Journal of Soil and Water Conservation* **30(6)**: 279-283.

Magrath W, Arens P. 1989. The costs of soil erosion on Java: a natural resource accounting approach. Environment Department Working Paper #18. Washington, DC: The World Bank.

Manos B, Bournaris T, Moulogianni C, Arampatzis S. 2013. IA tools applied to impact assessment of EU policies in agriculture and environment. *International Journal of Environment and Sustainable Development*, **12(2)**: 103-123.

Martínez-Casasnovas JA., Ramos MC. 2006. The cost of soil erosion in vineyard fields in the Penedès-Anoia Region (NE Spain). *Catena,* **68(2-3)**: 194-199.

Möller A., Ranke U. 2006. Estimation of the on-farm-costs of soil erosion in Sleman, Indonesia. *WIT Transactions on Ecology and the Environment*, **89**: 43-52.

Montgomery DR. 2007. Soil erosion and agricultural sustainability. *Proceedings of the National Academy of Sciences of the United States of America* **104(33)**: 13268-13272.

Nkonya E. 2015. *Economics of Land Degradation and Improvement: A Global Assessment for Sustainable Development*. Eds. Alisher Mirzabaev, and Joachim Von Braun. Dordrecht: Springer, 2015. ISBN 978-3-319-19167-6.

Narayanan B, Aguiar A, McDougall R. 2012. Global Trade, Assistance, and Production: The GTAP 8 Data Base. Center for Global Trade Analysis, Purdue University.

OECD 2015, The Economic Consequences of Climate Change, OECD Publishing, Paris. http://dx.doi.org/10.1787/9789264235410-en.

Obst C. 2015. Economics: Account for soil as natural capital. *Nature* **527(7577)**: 165.

Oyedele DJ, Aina PO, 1998. A study of soil factors in relation to erosion and yield of maize on a Nigerian soil. *Soil Till Res* **48**:115–125.

Panagos P, Meusburger K, Van Liedekerke M, Alewell C, Hiederer R, Montanarella L. 2014. Assessing soil erosion in Europe based on data collected through a European network. *Soil Sci. Plant Nutr*. **60 (1):** 15–29.

Panagos P, Borrelli P, Poesen J, Ballabio C, Lugato E, Meusburger K, Montanarella L, Alewell C., 2015a. The new assessment of soil loss by water erosion in Europe. *Environ. Sci. Pol*. **54:** 438–447.

Panagos P, Borrelli P, Robinson DA. 2015b. Common agricultural policy: tackling soil loss across Europe. *Nature* **526(7572)**: 195.

Panagos P, Imeson A, Meusburger K, Borrelli P, Poesen J, Alewell C. 2016. Soil Conservation in Europe: Wish or Reality? *Land Degradation and Development* **27(6)**: 1547-1551.

Panagos P, Borrelli P, Poesen J, Meusburger K, Ballabio C, Lugato E, Montanarella L, Alewell C. 2016b. Reply to the comment on "The new assessment of soil loss by water

erosion in Europe" by Fiener & Auerswald. *Environmental Science and Policy*, **57**: 143-150.

Panagos P, Borrelli P, Poesen J, Meusburger K, Ballabio C, Lugato E, Montanarella L, Alewell C. 2016c. Reply to "The new assessment of soil loss by water erosion in Europe. Panagos P. et al., 2015 Environ. Sci. Policy 54, 438–447-A response" by Evans and Boardman. *Environ. Sci. Policy* **58:** 11–15.

Pierce FJ, Larson WE, Dowdy RH, Graham WAP. 1983. Productivity of soils: assessing long-term changes due to erosion. *Journal of Soil & Water Conservation*, **38(1)**: 39-44.

Pimentel D, Harvey C, Resosudarmo P, Sinclair K, Kurz D, McNair M, Crist S, Shpritz L, Fitton L, Saffouri R, Blair R. 1995. Environmental and economic costs of soil erosion and conservation benefits. *Science, New Series*, **267(5201)**: 1117-1123.

Pimentel D. 2006. Soil erosion: A food and environmental threat. *Environment, Development and Sustainability* **8(1)**: 119-137.

Posthumus, H., Deeks, L.K., Rickson, R.J., Quinton, J.N. 2015. Costs and benefits of erosion control measures in the UK. *Soil Use and Management*, **31**: 16-33.

Pretty JN, Brett C, Gee D, Hine RE, Mason CF, Morison JIL, Raven H, Rayment MD, van der Bijl G. 2000. An assessment of the total external costs of UK agriculture. *Agric. Syst.* **65**: 113–136.

Renard KG et al., 1997. Predicting Soil Erosion by Water: A Guide to Conservation Planning with the Revised Universal Soil Loss Equation (RUSLE) (Agricultural Handbook 703). US Department of Agriculture, Washington,
DC, pp. 404.

Robinson DA, Fraser I, Dominati EJ, Davísdóttir B, Jónsson JOG, Jones L, Jones SB, Tuller M, Lebron I, Bristow KL, Souza DM, Banwart S, Clothier BE. 2014. On the value of soil resources in the context of natural capital and ecosystem service delivery. *Soil Science Society of America Journal* **78(3)**: 685-700.

Schumacher TE, Lindstrom MJ, Mokma DL, Nelson WW. 1994. Corn yield: Erosion relationships of representative loess and till soils in the North Central United States. *Journal of Soil and Water Conservation*, **49**: 77-81

SEEA 2016. System of Environmental-Economic Accounting (SEEA). Available in http://unstats.un.org/unsd/envaccounting/seea.asp (accessed Oct 2016).

Scherr SJ. 2000. A downward spiral? Research evidence on the relationship between poverty and natural resource degradation. *Food policy* **25(4)**: 479-498.

Telles TS, de Fátima Guimarães M, Dechen SCF. 2011. The costs of soil erosion [Os custos da erosão do solo]. *Revista Brasileira de Ciencia do Solo*, **35(2)**: 287-298.

Telles TS, Dechen SCF, de Souza LGA, Guimarães MF. 2013. Valuation and assessment of soil erosion costs. *Scientia Agricola* **70(3)**: 209-216.

Tsigas ME, Frisvold GB, Kuhn B. 1997. Global Climate Change in Agriculture in Global Trade Analysis: Modeling and Applications. Thomas W. Hertel, editor, Cambridge University Press.

UNCCD, 2017. United Nations to Combat Desertification. Available at: http://www.unccd.int/en/about-the-convention/Pages/Text-Part-I.aspx (Accessed April 2017)

van den Born GJ, de Haan BJ, Pearce, DW, Howarth A. 2000. Technical Report on Soil Degradation in Europe: an integrated economic and environmental assessment. RIVM report 481505018, National Institute of Public Health and Environment, RIVM, Netherlands.

Table I. 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 & conservation tillage)	Kuhlman et al. (2010); Posthumus et al. (2015) Bizoza & De Graaf (2012)
Market price of soil	Commercial price of soil	Robinson et al. (2014); Panagos et al. (2015b)
Crop productivity loss	Decreased crop production due to soil erosion	Gunatilake & Vieth (2000); Evans (1996); Enters (1998); Möller & Ranke (2006); Current study; 16 studies in Table II
Replacement cost	Cost of fertilizers (N, P) to replace nutrient loss due to soil erosion	Martinez-Casanovas & Ramos (2006); Möller & Ranke (2006) Hein (2007); Graves et al. (2015); Dixon et al. (1994); Enters (1998); Bojo (1996)
Macro-economic models (Computable General Equilibrium)	Estimate the cost represented by soil erosion loss in the agricultural sector	Current study

Table II. 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 c.a 6% per 2.5 cm of soil loss	Experiments in U.S.A
Pierce et al. (1984)	2-4% productivity loss in case of severe erosion (>25 tons t ha^{-1} yr^{-1})	U.S.A croplands ; NRI survey
Battiston et al. (1987)	8% productivity loss due to soil erosion	Corn yield experiments in Ontario
Magrath & Arens (1989)	0-12% annual productivity loss in case of severe erosion	Analysis of 3 comparable studies in Java, Indonesia
Schumacher et al. (1994)	8% yield reduction in corn fields 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} yr^{-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 (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 & Aina (1998)	Maize yield reduction of 10–17% on severely eroded	Plot experiments in Africa
van den Born GJ et al. (2000)	9% productivity loss for maize and other grains under high erosion risk	European Union 15 countries based on ICONA 1991
De La Rosa et al. (2000)	12% reduction on crop productivity will be reached in 2100 with erosion rates of 16 t ha^{-1} yr^{-1}.	Based on results in Andalusia region (Spain)
Bakker et al. (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 et al. (2004)	crop productivity based on past plot studies for different crops in all	Analysis of soil erosion-productivity experiments

	continents, showing negligible effects for erosion rates < 2 t ha^{-1} yr^{-1}.	
Bakker et al. (2007)	4.9% yield loss in case of 10cm soil erosion	Based on available water capacity analysis
Montgomery (2007)	Soil loss rates less than 12 t ha^{-1} yr^{-1} as tolerable for maintain the crop productivity	Based on the U.S Department of Agriculture values
Larney et al. (2009)	grain yields may fall by 2.1% annually per cm of soil removal	Experiments in Alberta, Canada

Table III. Country and sectoral detail of the ICES model

Country	Sectors
1) Austria	1) Rice
2) Belgium	
3) Czech Republic	
4) Denmark	
5) Finland	2) Wheat and remaining crops
6) France	
7) Germany	
8) Greece	
9) Hungary	3) Other cereals
10) Ireland	
11) Italy	
12) Netherlands	
13) Poland	4) Oil seeds and oleaginous fruits
14) Portugal	
15) Spain	
16) Sweden	
17) UK	5) Sugar beets
18) Cyprus	
19) Estonia	
20) Latvia	
21) Lithuania	6) Livestock
22) Luxembourg	
23) Malta	
24) Slovakia	
25) Slovenia	7) Industry and Extraction of natural resources
26) Bulgaria	
27) Croatia	
28) Romania	
29) Rest of the world	8) Services

Table IV. Correspondence between crops across the agronomic analysis and the CGE model

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

Table V. Estimated annual productivity loss per crop using direct cost evaluation (year 2010)

Crop	Total area (1,000 ha)	Actual productivity (1,000 tons)	Area severely eroded (1000 ha)	Crop productivity loss in affected areas (1000 Tons)	% of Tons lost	Price (€/ton)	Crop productivity loss (Million €)
Maize	15,703.0	111,586	1,124.0	594.4	0.53%	220.8	131.221
Barley	24,975.6	110,072	1,152.1	307.6	0.28%	221.7	68.199
Rape, turnip rape, 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	16.711
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	14.264
Rye	2,500.3	9,082	66.6	15.9	0.18%	200.5	3.201
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	739.364
Total	**167,287.3**		**12,059.6**				**1,257.622**

Table VI. Estimated annual productivity loss (area, %, €) 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 are 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	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**

Table VII. Effects of soil erosion in Agricultural sector and country GDP using the CGE macroeconomic model (year 2010)

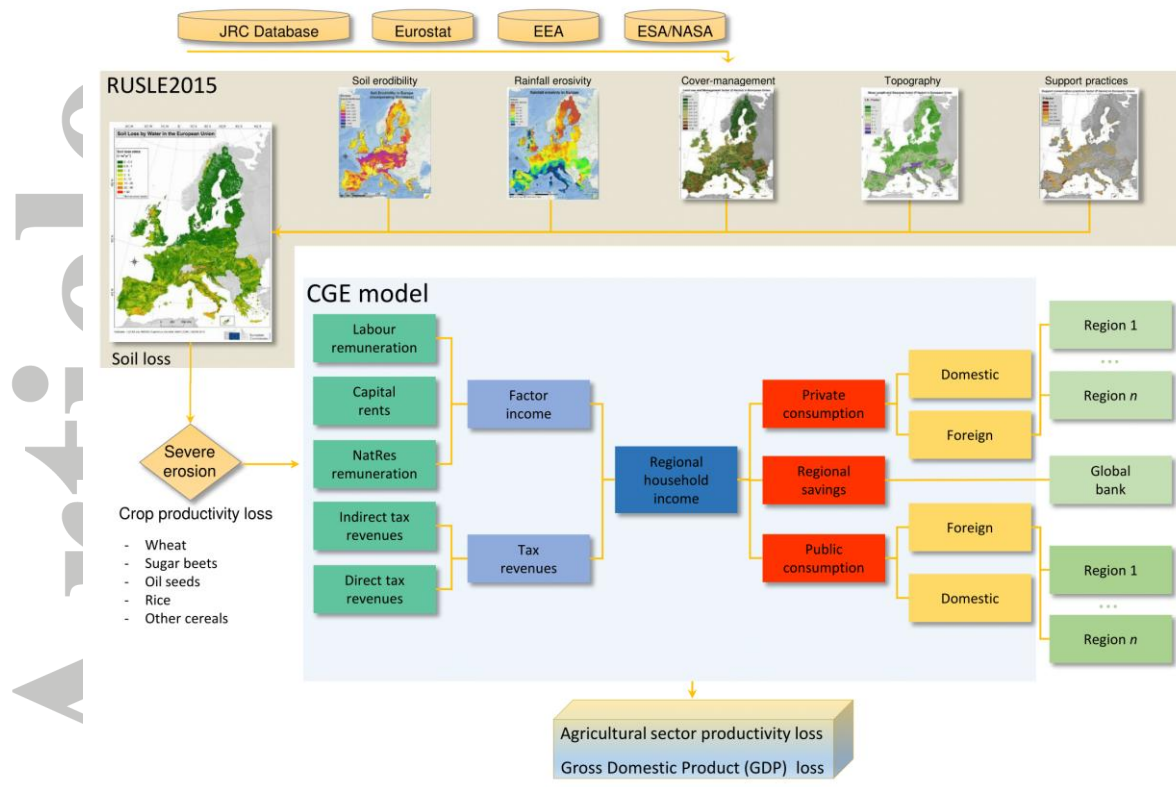| Country	Land productivity loss (%)	Agricultural Production Change (%)	Agricultural Production Impact (Million €)	GDP % Change	GDP Impact (Million €)
Austria	0.8878	-0.02	-0.845	-0.0012	-3.635
Belgium	0.0373	0.18	8.169	-0.0005	-2.064
Czech	0.1412	-0.01	-0.321	-0.0008	-1.213
Denmark	0.0003	0.12	4.507	-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
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
UK	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**

Fig. 1: Workflow of soil erosion (RUSLE2015) and macro-economic(CGE) integration for the cost evaluation of agricultural productivity losses.
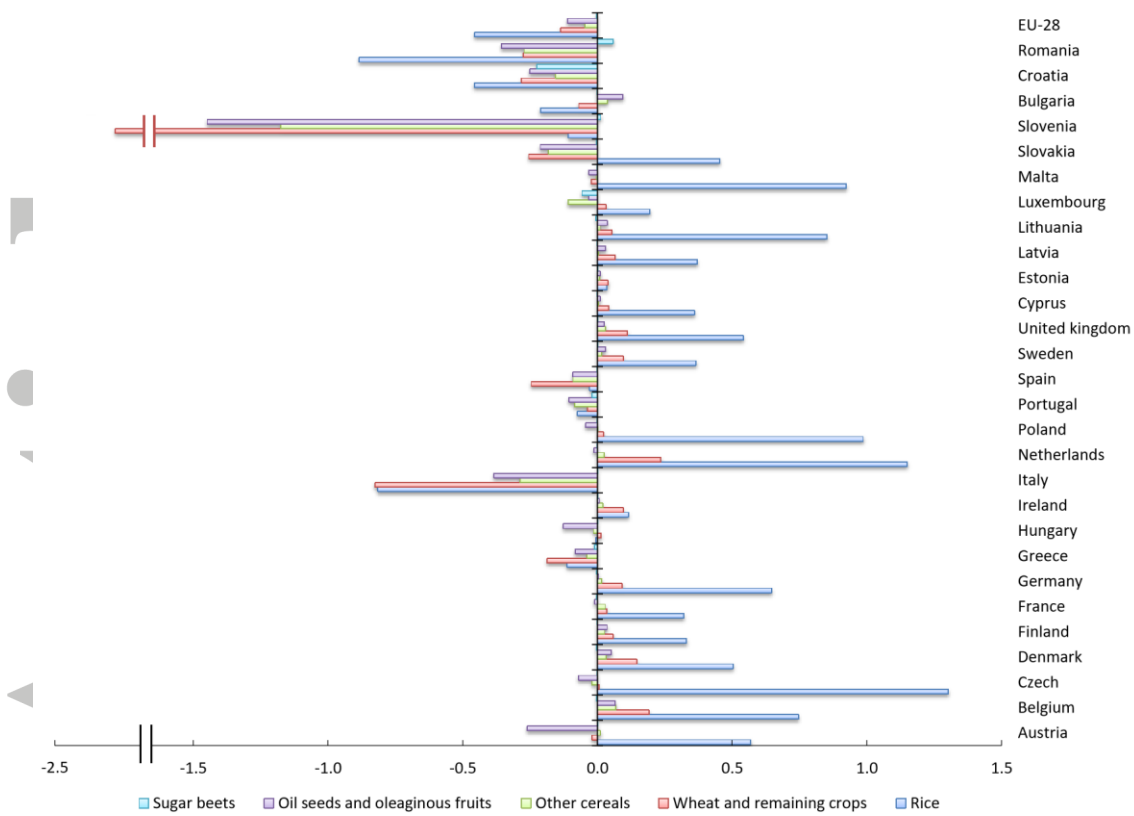
Fig. 2: Changes (%) in agricultural production in EU across crop types due to soil erosion.
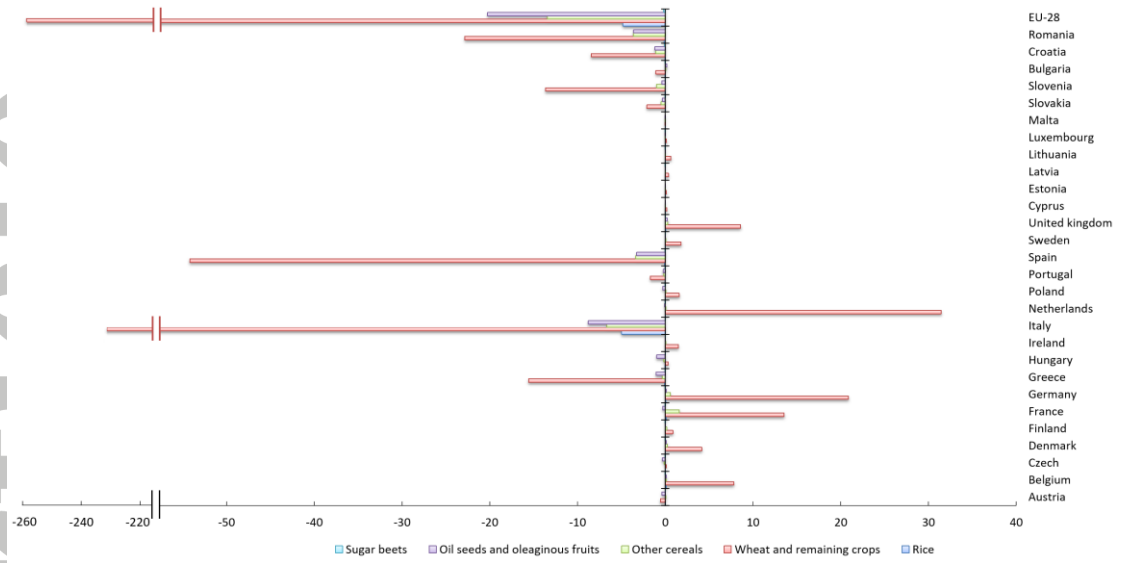
Fig. 3: Changes in agricultural production levels (million €) in EU due to soil erosion.