Soil erosion modelling: A global review and statistical analysis

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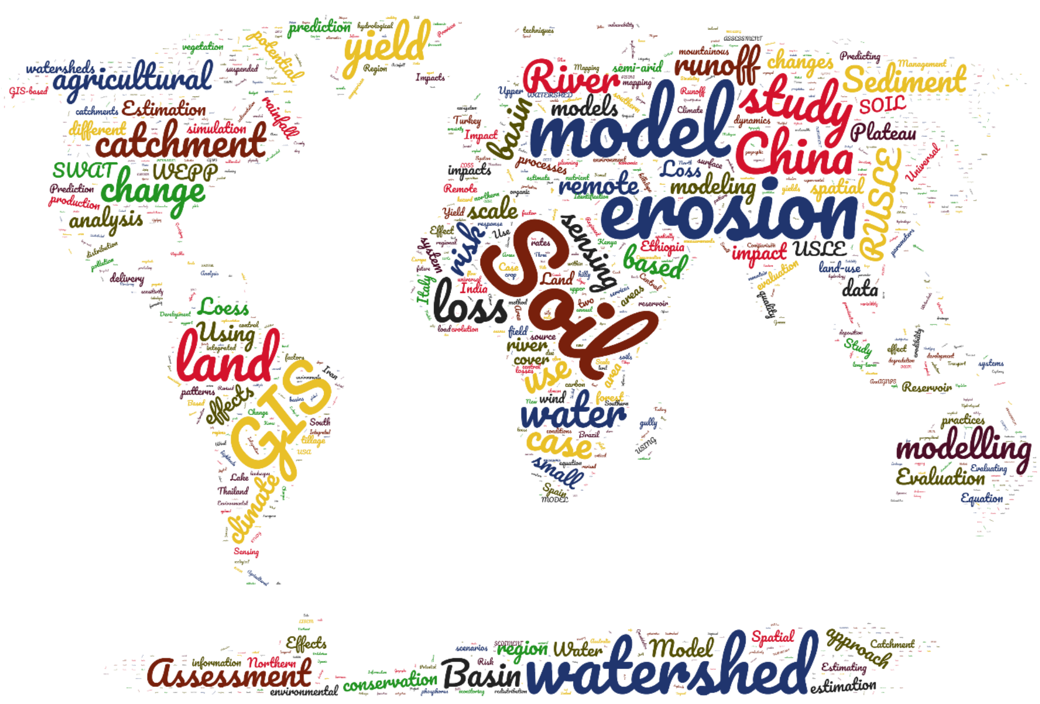
Abstract

To gain a better understanding of the global application of soil erosion prediction models, we comprehensively reviewed relevant peer-reviewed research literature on soil-erosion modelling 1994-2017. Our aim was to identify (i) processes and models most frequently addressed in the literature, (ii) regions within which models are primarily applied, (iii) what regions remain unaddressed and why, and (iv) how frequently studies are conducted to validate/evaluate model outcomes relative to measured data. To perform this task, we merged the knowledge of a group of 66 soil-erosion scientists from 67 research institutions and 25 countries. The resulting database 'Global Applications of Soil Erosion Modelling Tracker (GASEMT)' includes 3,030 individual modelling records from 126 counties encompassing all continents (except Antarctica). Out of 8,471 articles identified as potentially relevant, we reviewed 1,697 articles and transferred relevant information from each into the database. For each record reported in the GASEMT database, 42 attributes were evaluated. The GASEMT database provides insights into the state-of-the-art of soil-erosion models and model applications worldwide. The database is also intended to support the upcoming country-based United Nations global soil-erosion assessment. This database may help inform soil erosion research priorities in that it builds a foundation for future targeted in-depth analyses. GASEMT is an open-source database that anyone can use to develop research, rectify errors, and expand.

Graphical abstract



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Keywords

Erosion rates; modelling; GIS; land sustainability; land degradation; policy support.

1. Introduction

Humans affect natural erosion processes and have induced a relevant increase in soil erosion rates (Poesen, 2018). The scientific community has addressed soil erosion, the occurrence of accelerated soil erosion, and the negative socio-environmental impacts of erosion for more than a century (Bennett and Chapline, 1928; Smith, 1914). Research on the mechanics and geography of soil erosion has benefited from cognitive contributions of several adjoining disciplines, such as physical geography, soil science, engineering, hydrology, and biogeochemistry as well as human sciences and economics. The numerous scientific approaches presented in the literature to gain a better understanding of soil erosion phenomena vary in temporal and spatial scales, methodologies, and research goals (Boardman and Poesen, 2006; Morgan, 2009). Qualitative and quantitative descriptions of soil erosion have been performed through field observations and measurements (Toy et al., 2002) and laboratory experiments (Mutchler et al., 2017), as well as through a meta-analysis of soil erosion rates across the world (García-Ruiz et al., 2015). In a nutshell, the vast and diversified scientific literature states that soil erosion includes a number of widely diversified processes (Poesen, 2018), comes in different forms, intensities, and frequencies and encompasses all continents (Oldeman, 1994; Wuepper et al., 2020).

With the increase of observed data, the aim of mapping spatially distributed rates, and a better understanding of soil erosion mechanics (Cook, 1937), scientists started to develop quantitative soil-erosion prediction equations using physical factors such as climate, soil characteristics, vegetation type, and topography (Zingg, 1940). Since the 1940s, when scientists proposed one of the earliest quantitative soil-erosion prediction equations, several mathematical models classified as empirical, conceptual, or process-oriented have been developed to predict soil erosion processes at different spatial and temporal scales (Merritt et al., 2003; Morgan and Nearing, 2011; Nearing, 2013). As reported by Batista et al. (2019), today 'there is no shortage of soil erosion models, model applications, and model users' but there is still a knowledge gap on the validity, quality and reliability of the modelling application results'. Despite significant progress in input parameterization and model development, output uncertainties persist due to the non-linear relationships and thresholds between factors and processes, and difficulties of upscaling model findings from the local scale to larger ones (De Vente and Poesen, 2005).

Part of the challenge of improving soil-erosion modelling is the need to develop baseline information on how models are used. Important questions are: What do we know about soil-erosion model applications worldwide? What processes and models are mainly addressed? What are the regions where models are mainly applied? What are the regions that remain unaddressed?

How frequently and how well are model outcomes validated? In short, we lack a clear picture of the worldwide state-of-the-art of soil-erosion model applications.

Today, with the well-established use of geospatial technologies like Geographic Information Systems (GIS) and spatial interpolation techniques, and the ever-growing range of environmental data, soil-erosion models play an increasingly important role in the design and implementation of soil management and conservation strategies (Panagos et al., 2015). The application of soil erosion models is growing (Auerswald et al., 2014) and so is the scale of their applications (Borrelli et al., 2017; Naipal et al., 2018). These models gain importance as tools to support decision-makers in policy evaluations (Olsson and Barbosa, 2019). The Sixth Session of the Global Soil Partnership (GSP) Plenary Assembly, under the solicitation of its Intergovernmental Technical Panel on Soils (ITPS) voted in favour of a resolution to put the development of a new country-driven global soil-erosion (GSER) assessment (GSP, 2019) on the agenda for 2019-2021. Unlike previous United Nations (UN) assessments based on expert judgements carried out in the 1990's, such as the Global Assessment of Human-induced Soil Degradation (GLASOD, Oldeman, 1994), the new UN Global Soil Erosion map (GSERmap) will rely on modelling that will be supported and validated by field and/ or remote observations using satellite imagery and aerial photography. GSERmap will address the three major soil erosion driven processes, i.e., water erosion, wind erosion and redistribution due to mechanization of agriculture (referred to as tillage erosion).

The new country-based UN global soil erosion assessment has the potential to involve hundreds of soil erosion experts worldwide (FAO, 2019). This is an opportunity to enhance the understanding on global soil erosion, identify soil-erosion hotspots, and gain momentum for new policies at all levels. The upcoming UN project on soil erosion can also be used to strengthen the collaborative efforts of the soil-erosion scientific community in terms of boosting the development and applicability of models. The achievement of these goals, however, could be challenged due to the lack of global knowledge about soil erosion model usage. Such knowledge would be useful to help pave the way for a more structured modelling, and to further identify the need for additional efforts into validating, measuring, monitoring, and mapping soil-erosion processes.

In this study, we systematically reviewed soil-erosion modelling applications worldwide and performed a statistical analysis to narrow the knowledge gaps and to facilitate the acquisition of information for the new country-based UN global soil erosion assessment. The provided database presents the current state of knowledge on soil-erosion modelling applications worldwide. Our aim was to create and share a comprehensive and unprecedented database on soil erosion applications worldwide with an open science participatory approach. Sixty-six scientists from 25 countries representing all continents (except Antarctica) have contributed their findings, systematically reviewed all available peer-reviewed literature, and merged their knowledge. The database is shared as Appendix A of this article. In our study, we provide an evaluation of (i) processes and models most frequently addressed in the literature, (ii) regions within which models are primarily applied, (iii) what regions remain unaddressed and why, and (iv) how frequently studies are conducted to validate/evaluate model outcomes relative to measured data. In short, we provide insights into worldwide state-of-the-art soil-erosion model applications as well as information on which processes, models, and regions are under evaluated and need more scientific attention and focus in the future.

2. Methods

2.1 Data collection and GASEMT Tracker Database

In this study, we report the results of an in-depth review of scientific peer-reviewed literature on soil-erosion modelling published in international journals between the 1st of January 1994 and the 31st of December 2017, which are present in Elsevier's Scopus bibliographic database. We used the following criteria to identify articles potentially suitable for our statistical analysis: keywords *soil erosion* and *model* or *name of the model* (Box 1) in the title, abstract, or the keywords of the Scopus indexed articles. All articles matching the selected keywords have been downloaded and reviewed by one of the 66 soil erosion experts involved in the study. The review phase started in early 2018 and followed a participatory approach open to the entire scientific community, without restrictions of any kind. The group of authors is composed of scientists who responded to an open call for expression of interest published on ResearchGate and advertised through mailing lists and word-of-mouth. Within a first step, all authors were instructed to pay close attention to the following criteria: (i) verifying the relevance of the articles with regard to the objective of the review study, (ii) recording the entries' information (hereinafter also referred to as records) and (iii) extract all information listed in Table 1 for each relevant article. In a second step, P. Borrelli randomly inspected about 5% of total the articles reviewed by the authors and verified whether the gathered information was complete. In addition, a harmonization procedure was carried out by P. Borrelli to identify and rectify most evident inconsistencies, misclassifications and typos among the individual reviews.

Box 1. Scopus query and list of the acronyms of the soil erosion models used for the literature search (in the title, abstract, and the keywords of the Scopus indexed articles).

Scopus search
"soil erosion" AND "model" OR: AGNPS, ANSWERS, APSIM, CREAMS, EGEM, EPIC, EROSION-3D, EUROSEM, GeoWEPP, GLEAMS, GUEST, KINEROS, KINEROS2, LISEM, MIKE-11, MMF, MMMF, MOSES, MUSLE, PERFECT, PESERA, RHEM, RillGrow, RUSLE, RUSLE2, RUSLE-3D, RWEQ, SEDEM, SEDEM/WaTEM, SERAE, STREAM, SWAT, TMDL, USLE, USPED, WATEM, WATEM/SEDEM, WEPP, WEPS, WEQ.

Table 1. List of information collected for each entry in the GASEMT database.

	Group	Entry	Types of data	Options
i	Entry info	ID	Open (numeric)	-
		Reviewer ID	Open (alphanumeric)	-
		General ID	Open (alphanumeric)	-
ii	Bibliography	Year of publication	Open (numeric)	-
		List of authors	Open (alphanumeric)	-
		Title	Open (alphanumeric)	-
		Journal	Open (alphanumeric)	-
		DOI	Open (alphanumeric)	-
iii	Modelling exercise	Erosion agent	Multiple choice	Humans (harvest or tillage), water, wind, water and wind
		Modelling type	Multiple choice	Sheet and rill, rill, gully, mass movement, stream bank, tunnel erosion, riparian erosion, sediment budget, sediment yield, sensitivity mapping, wind soil displacement, dust
		Gross/ net estimate*	Multiple choice	Net erosion, gross erosion, soil redistribution
		Quantitative/ qualitative estimate$	Multiple choice	Quantitative, qualitative, unknown
		Estimated soil erosion rate converted to (Mg ha^{-1} yr^{-1})	Open (numeric)	-
		Soil erosion rate (note)	Open (alphanumeric)	-
		Model name	Open (alphanumeric)	-
		Modelling aim	Multiple choice	Climate change, construction site, forest harvesting, general, grazing, land use change, land use change and climate change, mining, ploughing, soil and water conservation, topographic change, unknown, wildfire
		Modelled period	Multiple choice	Present, present & past, present & future, unknown, past, future
iv	Study area	Continent	Multiple choice	Asia, Oceania, Europe, Africa, North America, South America, Global, NA, unknown, North America, South-America
		Country	Open (text)	-
		Name of the study area	Open (alphanumeric)	-
		Latitude (decimal degrees)	Open (numeric)	-
		Longitude (decimal degrees)	Open (numeric)	-
		Area (km^2)	Open (numeric)	-
v	Climate	Data indicative period	Open (numeric)	-
		Type of data	Multiple choice	Gridded, point, unknown

		Time resolution	Multiple choice	Annual, daily, event, hourly, monthly, season, sub-hourly, unknown
		Rainfall amount (mm)	Open (numeric)	-
		Rainfall (note)	Open (alphanumeric)	-
vi	Land use/ cover	Type of data source	Multiple choice	Existing map, remote sensing & GIS mapping, field mapping, remote sensing & GIS mapping, unknown
		Modelled area	Multiple choice	Agriculture, generic, agroforestry, all land uses, arable land, bare soil, forest, grassland/ rangeland, mines, pasture, riverbank, unknown
vii	Fieldwork activities	Field activities	Multiple choice	Yes, no, unknown
		Type of activities	Multiple choice	Field mapping, field observations, general field visits, measurements, multiple activities, none, sampling, unknown
viii	Soil info	Soil sampling	Multiple choice	Yes, no, unknown
		Type of soil information	Multiple choice	Point, gridded, maps, shapefile, unknown
ix	Topography	DEM cell size (m)	Open (numeric)	-
x	Modelling outcomes	Scale§	Multiple choice	Continental, farm, global, hillslope, national, plot, regional, unknown, watershed (understood as hydrologic unit)
		Cell size (m)	Open (numeric)	-
		Modelled years	Open (numeric)	-
		Modelled period	Multiple choice	≤2000, >2000, both periods, unknown
		Validation/evaluation attempt of model results	Multiple choice	Yes, no, unknown
		Type of validation/evaluation	Multiple choice	Comparisons with results from other models, expert knowledge, measured erosion rates, measured SY, NA, unknown
		Model calibration	Multiple choice	Yes, no, NA, unknown

*Gross erosion is on-site soil erosion potential without considering re-deposition. Net erosion is difference between erosion and deposition processes at a given point. $Qualitative refers to an assessment of temporal trends, spatial patterns and/or driving factors, while quantitative refers to quantitative assessment of sediment detachment and or transport. §Definitions provided in the Supporting Information (Table S1).

The database name is Global Applications of Soil Erosion Modelling Tracker (GASEMT). In the case of studies reporting multiple model applications or multiple study sites, multiple individual data entries were created in the GASEMT database. Each entry in the database reports information on the 42 attributes listed above, unless such information could not be found in the article. If so, the term ‘unknown’ was reported, while the term ‘NA’ is used as the acronym of ‘not applicable’.

Importantly, only the studies presenting soil-erosion modelling applications with spatiotemporally defined conditions were considered and reported in the database. Articles reviewed that exclusively report technical descriptions of models, methodological improvement without practical applications, laboratory tests, or refinement of individual model parameters were not considered and included in the database. Articles not written in English were also excluded from the analysis.

2.2 Statistical analysis

In order to improve understanding of the distribution soil-erosion prediction models over time and space, we analysed trends and patterns of the predicted soil erosion rates recorded in the GASEMT database. This was done based on a GASEMT subset dataset exclusively containing records about (i) modelled soil erosion rates (Mg ha^{-1} yr^{-1}), (ii) geographical coordinates, and (iii) size of the study area (km^2).

GASEMT's records indicate that soil-erosion prediction modelling studies have been conducted in globally diverse locations. We found a large variability in GASEMT in terms of erosion agents and processes, model types, modelling input parameters, as well as significant variability in observation periods and site details. Therefore, our statistical analysis of the compiled soil-erosion rates focused on the identification and description of the main trends with respect to land cover/ use types, model types, and geographical regions. Boxplots were used to document variation in distributions of predicted erosion rates among land use/ land cover categories for the most commonly used models of GASEMT database. Temporal trends were identified by means of simple linear regression. The non-parametric Kruskal–Wallis test was used for testing the difference between groups of independent samples (for both modelled and measured soil erosion rates). A meta-regression analysis *sensu stricto* (Gurevitch et al., 2018) of the GASEMT data was not part of our analysis scope as the aforementioned heterogeneity of the database and the lack of georeferenced information about the study areas precluded this option.

3. Results

The literature search in the Elsevier's Scopus bibliographic database resulted in 8,471 articles potentially reporting applications of soil-erosion modelling. The review process revealed that 6,042 articles (71%) were not relevant for the study, as they did not report actual soil-erosion modelling applications. The number of articles not in English language or not accessible totalled 513 (6%) and 241 (3%), respectively. As a result, the number of articles found to be suitable for the study was 1,697 (20%). From these articles 3,030 data entries, equal to individual modelling applications, were identified and inserted in GASEMT.

3.1 Geography of the modelling applications

Fig. 1 illustrates the geographical distribution of the modelling applications grouped using a hexagonal grid to visualize the density of the observations optimally. The 3,030 individual modelling records are spread across 126 countries and all continents except Antarctica. Based on the database records, we identified meaningful clusters in well-defined geographical regions. More precisely, three major application areas can be observed around North America, Central/ Southern Europe and Northeast/ Far East Asia. In contrast, smaller clusters can be observed in the eastern sectors of South America, Africa and Oceania. Numerically, Asia (n = 976) and Europe (n = 929) show the highest number of modelling applications, followed by North America (n = 613) and to a lesser extent Africa (n = 251), South America (n = 123) and Oceania (n = 104). A cross-country analysis shows that the United States of America (USA) and China have by far the highest number of records in the GASEMT database, with 537 and 450 studies, respectively. India follows on the list with 161 sites. Considering the European Union (EU-28, including United Kingdom) as a single geographical entity, it shows the highest amount of modelling applications totalling 841 entries. In the EU the highest frequencies are observed in the Mediterranean countries such as Italy (n = 173), Spain (n = 125) and Greece (n = 84). By contrast, little information is available for the large sectors of South America, Western and Central Africa, and North/ Central Asia. Overall, we noted a general tendency of the studies to be located within the main global cropland districts, as corroborated by further observations carried out and reported in the Discussion section.

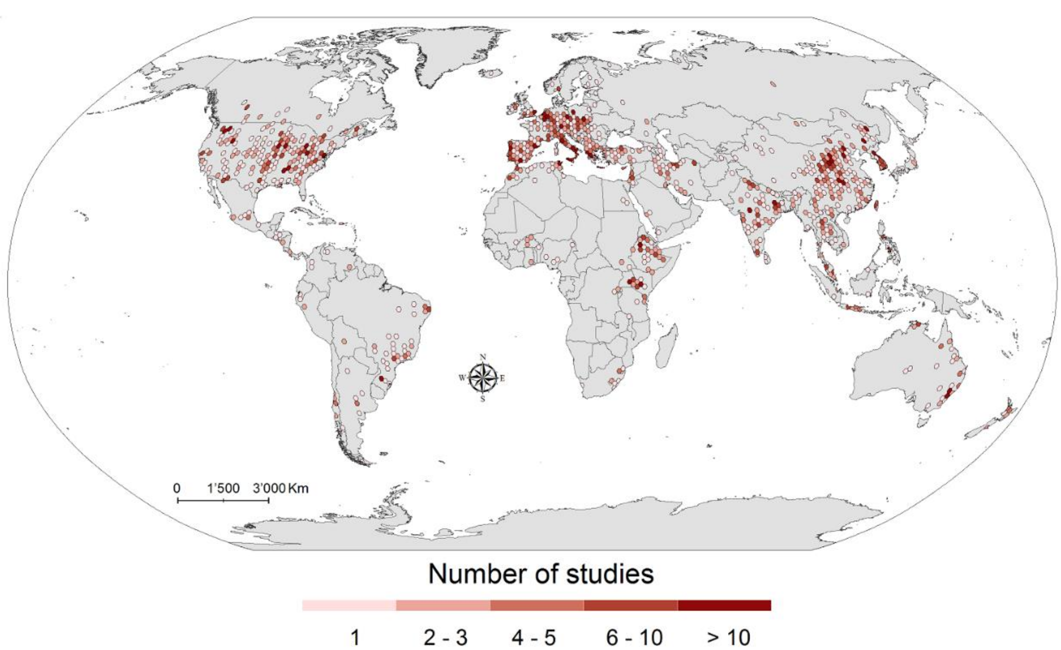

Fig. 1. Geographical distribution of 1,833 of the 3,030 GASEMT database records for which the geographical coordinates of the study areas could be obtained. The modelling applications are

grouped using a hexagonal grid to optimally represent the density of observations. Robinson projection.

3.2 Temporal trends

According to the GASEMT database, 1,697 articles applying soil-erosion models at local/ regional/ national or larger scale were published within the 24 years (1994-2017) under observation, with an average rate of 70 articles per year. The database split into 4-year time windows reveals a clearly increasing trend of publications (Fig. 2), except for the 4-year period 2010-2013. The maximum number of annual publications was recorded for the last evaluated year 2017 (158 articles, 340 modelling applications). Studies on soil erosion by water dominate all 4-year time windows. In the early period (1994-1997), all 55 modelling applications reported in the database addressed soil erosion by water. Most of them were performed around the three major clustering areas i.e., USA (n =17), India (n = 16), European Union (n = 12) and Canada (n = 6). Models were mostly applied at watershed (n = 23) and plot scale (n =19), with the median size of the investigated study areas being 0.43 km^2. Interestingly, during the pioneering stage in the mid-nineties, soil erosion modelling did not lack large-scale applications (>1000 km^2), e.g., Sharma and Singh (1995) in India and Pinheiro et al. (1995) in France. In this early period, Batjes (1996) published the first global assessment of land vulnerability to water erosion using a simplified version of the USLE model (Wischmeier and Smith, 1978). The most applied models during 1994-1997 belonged to the Universal Soil Loss Equation family (USLE/RUSLE; (Renard et al., 1997; Wischmeier and Smith, 1978), Productivity, Erosion and Runoff Functions, to Evaluate Conservation Techniques (PERFECT; Littleboy et al., 1989), Water Erosion Prediction Model (WEPP; Flanagan and Nearing, 1995), the Limburg Soil Erosion Model (LISEM; De Roo et al., 1996) and the Areal Nonpoint Source Watershed Environment Response Simulation (ANSWERS; Beasley et al., 1980).

In subsequent 4-year time windows, modelling applications investigating wind, tillage (sediment redistribution due to tillage activity, usually displacement from upslope to downslope) and harvest erosion (export of sediments with harvested plants due to soil sticking to roots or machine parts) estimates make their entrance in the GASEMT database. In most periods, the applications of models for these processes are below ten applications per time window. Only in 2006-2009 and 2014-2017 did tillage (n = 30) and wind erosion (n = 41) exceed ten database entries, respectively. Within 2014-2017, wind erosion models show an evident increment reaching a level of applications higher than the one observed in the previous 20 years. Most of the study areas of wind erosion modelling are located in the USA (n = 32) and China (n =18). Wind modelling applications are mostly regional (n = 34) and plot scale (n = 30). Large scale modelling applications include five national (Baade and Rekolainen, 2006; Borrelli et al., 2015; Hansen, 2007; Hansen et al., 2002; Mezosi et al., 2015), two continental (Borrelli et al., 2017, 2016) and one global scale application (Chappell and Webb, 2016). The most commonly applied wind erosion models are the Wind Erosion Equation ((R)WEQ; Fryrear et al., 2001; Woodruff and Armbrust, 1968), the Single-event Wind Erosion Evaluation Program (SWEEP; Wagner, 2013), and the Wind Erosion Prediction System (WEPS; Wagner, 1996).

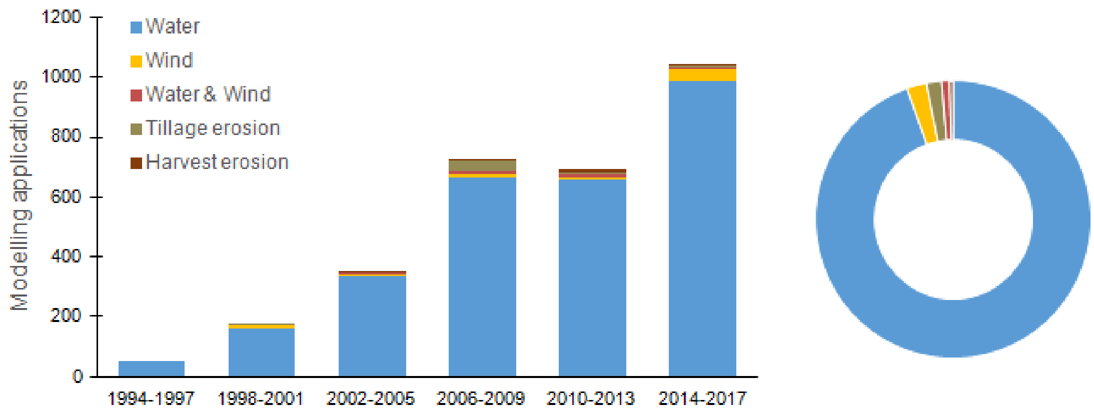

Fig. 2. Number of publications according to types of erosion in the GASEMT database through time (left panel, 4-year time windows) and overall 1994-2017 (right panel). Both panels share the same legend.

3.3 Erosion processes and type of predictions

The analysis of the individual records of the GASEMT database shows a marked dominance of water-erosion studies, constituting 94.6% of the total entries. About 0.9% of the data entries reported combined estimates of water and wind erosion, while wind erosion, tillage erosion, and harvest erosion are modelled in 2.3%, 1.8% and 0.4% of the cases, respectively (Fig. 2). Concerning the type of modelling estimates, the vast majority of the applications estimate sheet and rill erosion processes (~54%), followed by sediment yield (~27%), and sediment budget (net erosion/deposition) (~10%). The remaining 10% of modelling applications can be classified as stream bank erosion (1%), mass movement (0.6%), rill (0.5%) and gully (0.3%), or more generally as sensitivity mapping (2.8%), soil displacement due to wind erosion (2.3%), and others (2.5%). Overall, the vast majority of modelling applications yield quantitative estimates of erosion (water erosion ~95%; wind erosion ~85%), while qualitative assessments are ~5% of the entries (qualitative refers to an assessment of temporal trends, spatial patterns and/or driving factors, while quantitative refers to quantitative assessment of sediment detachment and or transport). Despite the reliance of around 95% of the entries on quantitative soil-erosion prediction models, estimated soil-erosion rates (reported in Mg ha^{-1} yr^{-1}) could be retrieved only for one third of the studies (n = 1,890; 67% of the quantitative models); because the information was missing, not found by the reviewer or only illustrated in a figure.

3.4 Spatial scale

Application of global scale soil erosion prediction models represents ~0.6% (n = 20) of the total entries in GASEMT (Fig. 3). The vast majority of these global studies performed water-erosion estimations (n = 18) using (R)USLE family models (n = 17). Because the (R)USLE family is limited to sheet and rill processes, most of the global applications model only sheet and rill processes. The only non (R)USLE global water-erosion modelling application in GASEMT estimates the delivery of fluvial sediments to the coastal ocean through the BQART model (Syvitski and Milliman, 2014). The remaining two global modelling applications quantitatively estimate soil displacement due to water and tillage operations (Quinton et al., 2010) and the land vulnerability to wind erosion (Chappell and Webb, 2016).

Modelling applications at continental scale represent 0.5% (n = 13) of the entries. Most of these studies address soil erosion by water (n = 10) and, to a lesser extent, wind erosion (n = 2) and tillage erosion (n = 1). The estimates occur mostly in Europe (n = 11), followed by Africa (n =1) and Oceania (n =1). The models applied show a more heterogeneous scenario compared to the global ones. In addition to classic models such as (R)USLE and (R)WEQ, eight other large-scale models for the estimation of soil erosion at continental scale have been applied (Borrelli et al., 2015, 2016, 2017; Bosco et al., 2015; Cerdan et al., 2010; Gericke, 2015; Hessel et al., 2014; Kirkby, 2006; Li et al., 2017; Oost et al., 2009; Panagos et al., 2015a; Podmanicky et al., 2011; Symeonakis and Drake, 2010; Teng et al., 2016). Eleven out of 13 modelling applications rested on quantitative estimation of soil erosion.

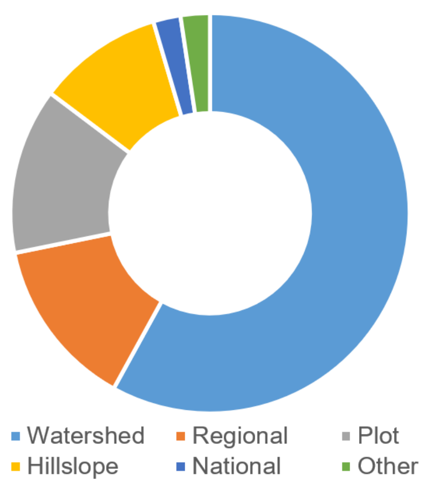

Fig. 3. Distribution of the GASEMT database modelling applications according to spatial scale (other includes continental, farm and global scale).

We identified 67 (~2%) national-scale modelling applications, mostly applied in Europe (n = 34), Asia (n = 12), and North America (n = 9). Except for three wind erosion studies in the USA and Spain (Baade and Rekolainen, 2006; Hansen et al., 2002), all other quantitative (n = 48) and qualitative (n = 3) applications focus on water erosion. USA (n = 6), Czech Republic (n = 4), and Hungary (n = 4) are countries with higher modelling applications

About 14% (n = 418) of the recorded modelling exercises fall into regional-scale applications ($\tilde{x}$ = 6,131 km^2). Although smaller in size, the watershed-scale applications have the largest share of entries in the database (~59%), also including some very large study areas ($\tilde{x}$ = 128.5 km^2). The three remaining small-scale application categories are hillslope (~10%; $\tilde{x}$ = 1 km^2), farm/ landscape (~0.4%; $\tilde{x}$ = 0.65 km^2), and plot scale (~12.8%; $\tilde{x}$ = 0.0018 km^2).

3.5 Aims of the modelling application

In ~40% of the GASEMT modelling applications the authors did not describe a specific aim for their modelling applications. Classified as 'general' these modelling exercises are to be considered as modelling applications carried out to generically assess the risk or magnitude of soil erosion without a specific aim. Studies specifically addressing land-use change, climate change, or their combined effects, represent 20.4%, 3.5% and 3% of the total, respectively. Studies addressing topographic change total 3.7%. Studies generally aim for soil and water conservation and ploughing represent 13.7% and 4.5%, respectively. Forest harvesting, wildfire, and mining are targeted in 1.7%, 1.4% and 0.3% of the studies.

Studies dealing with present (52.4%), past (26.7%), or both (8.4%) soil-erosion dynamics cover most of the entries in the database (i.e., 87.5%). Although less common, studies providing future or combined present and future projections of soil erosion still cover relevant shares of the entries with 3.8% and 5.9%, respectively. For the remaining entries (~2.8%) a temporal frame of the modelling application was not specified (classified as 'unknown' in GASEMT).

More than half of the modelling applications estimate soil erosion considering all types of land use/ land cover present in the investigated area (n =1,575; ~54.4%). Agricultural areas in general and exclusively arable land are modelled in only about 13.6 % and 9.3% of the cases, respectively. The remaining modelling applications addresses forests (5.1%), grassland/ rangeland (4.7%) and to a lesser extent bare soil (2.4%), pasturelands (1.4%), agroforestry (0.8%), riverbank (0.6%), and mine soil (0.1%). For the remaining ~7.5% it was impossible to retrieve land-use/cover information.

Concerning the procedures employed to describe land-use/ cover conditions, according to the studies that explicitly provided this information (~79% of the total), most of the studies used existing land-use maps (25.4%), created their maps through remote sensing (23.8%), or combined the two (12.3%). A considerable number of studies (18.1%), however, performed field mapping/ observations. For the remaining ~20%, classification information was not available.

3.6 Models, input data and outcomes

Overall, 435 distinct models and model variants are listed in the GASEMT database although several cases indicated that different nomenclature referred to the same modelling approaches. Table 2 lists the 25 most applied models and offers an example of the issue related to the redundancy of names (e.g., USLE, RUSLE and USLE-SDR, RUSLE-SDR, SEDD).

In their different forms and applications, the models belonging to the (R)USLE-family are by far the most widely applied soil erosion prediction models globally, with over 1,200 applications (~41% of the total). These numbers could be even higher if models such as WaTEM/SEDEM, EPIC, SWAT and USPED, which are based on the USLE data/concept, but expand numerical simulation beyond estimating soil loss, would be accounted as members of the (R)USLE-family. Modelling approaches independent from the USLE such as the process-based WEPP (n = 224; 7.4%), LISEM (n = 58; 1.9%), EROSION-3D (n =30; 1%), the Pan European Soil Erosion Risk Assessment (PESERA, Kirkby et al., 2004) (n=24; 0.8%), and the European Soil Erosion Model (EUROSEM, Morgan et al., 1998) (n = 17; 0.6%) together cover ~12% of total models. The next most common empirical models after (R)USLE are the Soil and Water Assessment Tool (SWAT, Arnold et al., 1998) (n = 183; 6%), the Water and Tillage Erosion Model and Sediment Delivery Model (WaTEM/SEDEM, van Oost et al., 2000) (n = 139; 4.6%), and the Morgan-Morgan–Finney ((R)MMF, Morgan et al., 1984) n = 61; 2%).

The split into time windows of 4-years (Fig. 4) indicates an evident increasing trend of (R)USLE, SWAT, and WaTEM/SEDEM, and to a lesser extent, WEPP, AGNPS, MMF, Erosion 3D, and LISEM. By contrast, use of EUROSEM shows a negative trend over time.

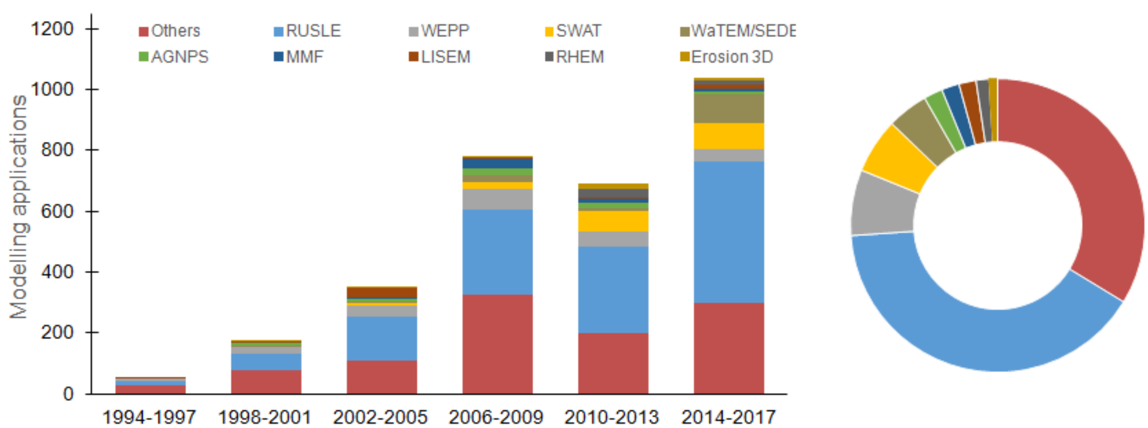

Fig. 4. Number of publications according to models in the GASEMT database through time (left) (4-year time windows) and overall (right).

With regard to the spatial resolution, surprisingly such information was not reported by more than half of the modelling applications (~56%). From the reported studies, very high (≤ 5m cell size) and high (> 5m and ≤ 25m cell size) spatial resolution modelling outputs represent about 7.2% and 11.9% of the total, respectively. In most of the cases, these models are applied at the watershed, hillslope, and plot levels although there are also a few national-scale applications (n = 10) and a pan-European one. Medium (> 25m and ≤ 150m) and moderate cell size (> 150m and ≤ 300m) outcomes were used for about 19.8% and 1.6% of the records, respectively. The remaining model applications (~3%) predicted soil-erosion rates with a coarse cell size between 330 and 60,000 m. The temporal analysis of the database shows a trend towards decreasing cell size of modelled study areas at watershed and smaller scales. Affinities between models and scale of application were not except for the large-scale applications which are mainly performed using empirical models of the (R)USLE and (R)WEQ families for water and wind erosion, respectively.

According to the information reported in the 1,697 articles thoroughly reviewed to fill the GASEMT database, validation/evaluation of the modelling results was performed in most of the cases (~58%). The most frequently used method of validation/evaluation is the comparison of the modelling estimates against the measured sediment yield (SY) values (~26%). Comparisons against field-measured erosion rates, results of other models, and expert knowledge formed a total of ~18, ~10 and ~3%, respectively. Linear regression indicated in the early period (1994-2000) of soil-erosion modelling the percentage of studies accompanied by validation/evaluation was higher. Although not statistically significant, a slightly decreasing trend starting in 2015 could be observed. The vast majority of non-traditional models – those only applied around one to five times – provide a validation/evaluation of the results. Of the most applied models the one with the highest share of validation/evaluation (>85%) are ANSWERS, PERFECT, USLE-M, DSESYM, and EUROSEM. SWAT and WaTEM/SEDEM both have values around 80%, while LISEM, WEPP, and MMF total 72, 66 and 63.3%, respectively. Application of USLE and RUSLE models show fairly high (63-69%) validation/evaluation values when applied to simulate SY. However, the values drop considerably when validating/evaluating hillslope gross erosion estimates (RUSLE: 41%; USLE: 34%). Except for the modelling results validated/evaluated through measured SY and comparisons with results from other models, the other forms of validation/evaluation are not detailed in the current version of GASEMT. These were classified as 'measured erosion rates' or 'expert knowledge'. Two categories that are too broad and generic when considered *a posteriori*, which should be further refined in future versions of the database. This is because a large set of techniques are included, ranging from volumetric loss measurement (e.g., pins, cross-sections, contour gauge, and terrestrial laser scanning) to qualitative observations performed through field observations as well as remote sensing. Model calibration was performed in about one third of the entries. The models with the highest shares of calibration are SWAT, LISEM, WaTEM/SEDEM, and MMF. Specific information about the calibration techniques were not collected, as these were found to be highly variable and difficult to classify given the large range of models considered.

Some level of field-based data collection exists in over half of the modelling application cases. In-situ soil erosion measurements are the most common field activity associated with modelling, followed by field observation and soil sampling for modelling parametrization. Mapping of erosion features is quite infrequent totalling less than 3% of the field activities.

Table 2. Lists of the top 25 most applied soil erosion prediction models according to the records reported in the GASEMT database.

Model	Records	%	References
RUSLE	507	17.1	(Renard et al., 1997)
USLE	412	13.9	(Wischmeier and Smith, 1978)
WEPP	191	6.4	(Laflen et al., 1991)
SWAT	185	6.2	(Arnold et al., 2012)
WaTEM/SEDEM	139	4.7	(van Oost et al., 2000)
RUSLE-SDR	115	3.9	-
USLE-SDR	64	2.2	-
LISEM	57	1.9	(De Roo et al., 1996)
Customized	53	1.8	-
MUSLE	52	1.7	(Williams and Berndt, 1977)
MMF	48	1.6	(Morgan et al., 1984)
AnnAGNPS	47	1.6	(Young et al., 1989)
RHEM	44	1.5	(Nearing et al., 2011)
Unknown	36	1.2	-
Erosion 3D	29	1.0	(Schmidt, 1991)
EPIC	25	0.8	(Williams et al., 1983)
PESERA	23	0.8	(Govers et al., 2003)
USPED	22	0.7	(Mitasova et al., 1996)
GeoWEPP	20	0.7	(Renschler, 2003)
RUSLE2	20	0.7	(Foster et al., 2001)
EPM	19	0.6	(Gavrilovic, 1962)
STREAM	19	0.6	(Cerdan et al., 2002)
RUSLE/SEDD	16	0.5	(Ferro and Porto, 2000)
DSESYM	15	0.5	(Yuan et al., 2015)
EUROSEM	15	0.5	(Morgan et al., 1998)

3.7 Statistical analysis

In order to examine the trends and the behaviour of the predicted soil erosion rates, we compared the results of 1,586 GASEMT's estimates, compiled from 786 individual publications and conducted in globally diverse locations. The records taken into account report information about soil erosion estimates, geographical coordinates and size of the study area (km^2). Continental and global scale modelling applications were excluded.

Overall, the model area covers an approximated total surface of 48.3 million km^2. This would cover about 32% of the World's land area (i) estimated at 149 million km^2 and (ii) assuming a marginal overlap between the modelled areas of the considered GASEMT records. Predicted annual soil erosion totals 80.4 billion Mg yr^{-1}, with an average area-specific soil erosion of 16.6 Mg ha^{-1} yr^{-1} ($\tilde{x}$ = 7.4 Mg ha^{-1} yr^{-1}; σ = 39.8 Mg ha^{-1} yr^{-1}). The removal of outlier values (i.e., <10th and >90th percentile) results in important changes in both the average ($\bar{x}$ = 13.8 Mg ha^{-1} yr^{-1}) and standard deviation (σ = 13.1 Mg ha^{-1} yr^{-1}) values. As expected, a significant difference between median values of gross ($\tilde{x}$ = 10 Mg ha^{-1} yr^{-1}) and net ($\tilde{x}$ = 5.4 Mg ha^{-1} yr^{-1}) erosion can be observed. In the gross erosion category all modelling applications that did not consider re-deposition are included (e.g., traditional (R)USLE-based models)). By contrast, in the net erosion category the modelling applications that predict sediment yield from a plot, hillslope or watershed are included. Models spatially predicting explicit net soil erosion/ deposition rates (named in GASEMT as sediment budget models, e.g., WaTEM/SEDEM) show a lower median value equal to 4 Mg ha^{-1} yr^{-1} ($\bar{x}$ = 14.1 Mg ha^{-1} yr^{-1}).

Analysis of soil-erosion estimates suggests that moderate to severe erosion is a common phenomenon under all climatic conditions encompassing all continents (except Antarctica). Fig. 5a shows that the vast majority of predicted soil-erosion rates refer to water erosion and to a much lesser extent to tillage (n = 37) and wind (n = 18) erosion. The predicted median values are 30.1 and 6.3 Mg ha^{-1} yr^{-1} for tillage and wind erosion, respectively. With regard to the geographical regions, higher occurrences of high and severe soil-erosion rates have been modeled in Asia and Europe and to a lesser extent Africa, South America and North America (Fig. 5b). Fig. 5c shows the distribution of the predicted soil erosion rates by scale categories. Extremely high average rates (greater than 100 Mg ha^{-1} yr^{-1}) of soil erosion are reported in 57 of the studies (76 entries). These high values are mostly predicted for watershed- scale applications in Europe (~40%), Asia (~30%) and Africa (~17%). Surprisingly, most of the applications with extremely high erosion rates (73%) are so-called 'generic modelling assessment' which typically indicates that a model has been applied to heterogeneous land cover/ use including natural and semi-natural vegetation (e.g., unmanaged grassland, bushland). Therefore, these studies did not target specific land disturbances such as wildfires, forest logging, or land-use changes for which severe soil erosion can be associated. Approximately 18% of the modelling applications reported in the GASEMT database aimed at land use or climate changes as the modelling objective.

Comparing soil-erosion rates by land cover/ use types (Fig. 6), we observe a substantial decline in soil-erosion rates (reported in mm yr^{-1} assuming an average bulk density of 1.35 g cm^{-3}) from bare soil ($\tilde{x}$ = 1.2 mm yr^{-1}) to agricultural areas (generic, $\tilde{x}$ = 0.3 mm yr^{-1}; arable land, $\tilde{x}$ = 0.5 mm yr^{-1}; agroforestry, $\tilde{x}$ = 0.1 mm yr^{-1}), forests ($\tilde{x}$ = 0.2 mm yr^{-1}) and other forms of semi-natural vegetation ($\tilde{x}$ = 0.2 mm yr^{-1}). When all land uses are modelled, we obtain a median value of 0.75 mm yr^{-1}. This soil erosion rate distribution and the patterns among the different land cover/ use units fit those reported by Montgomery (2007) and Borrelli et al. (2017) for values observed through field measurements. Agreement is better, however, for the values predicted in agricultural areas than the ones predicted in grass- and forestland areas.

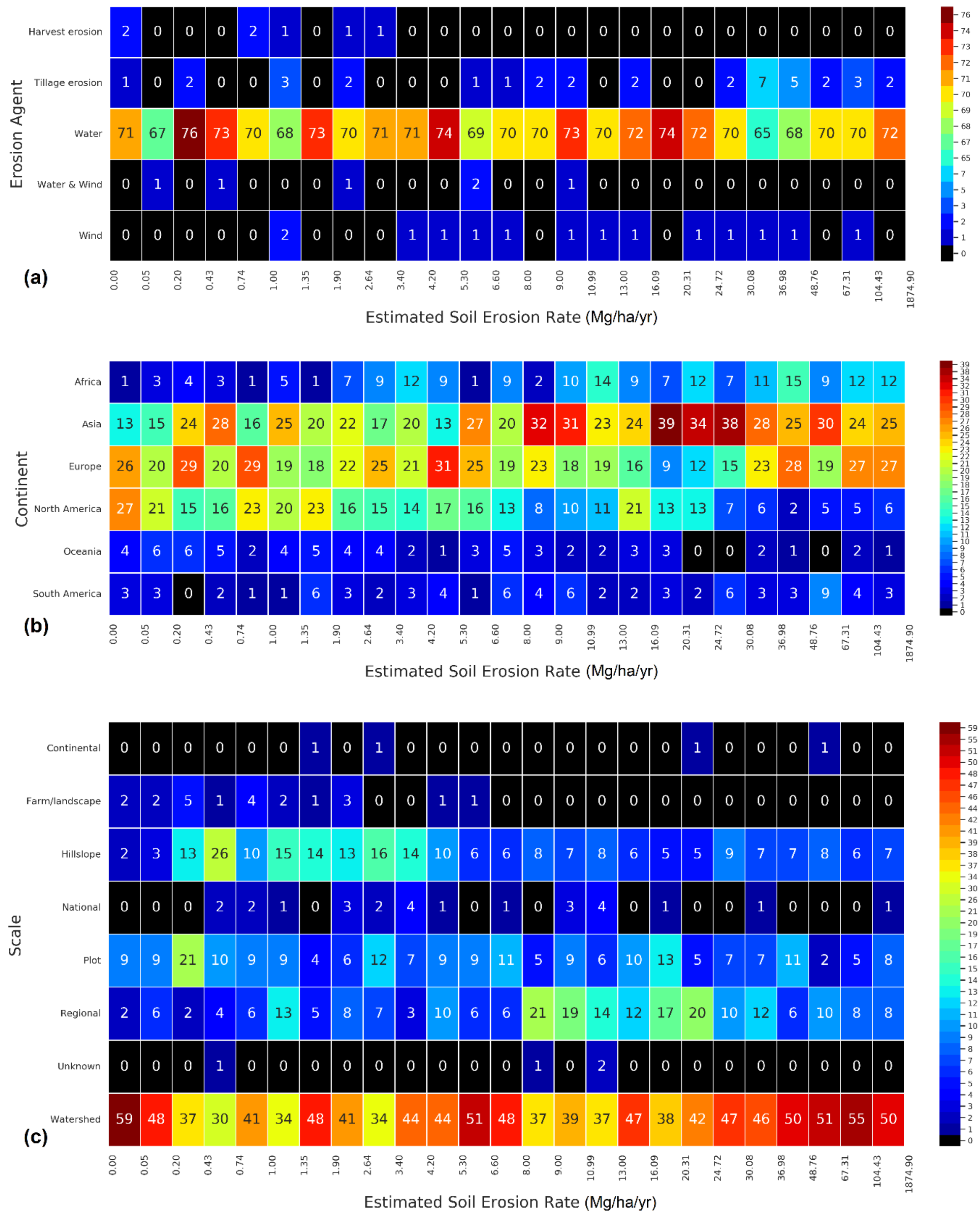

Fig. 5. Distribution of the estimated soil-erosion rates (gross and net) categorized by erosion agent (panel a), continent (panel b) and spatial scale (panel c). Values in the cells and colour legend represent the numbers of occurrence in the database.

The non-parametric Kruskal-Wallis test confirmed the absence of statistically significant difference between soil erosion rates modelled and measured in arable lands. Grass- and forestland show both a tendency to higher modelled erosion rates compared to the field measurements with median values in the order of 0.2 mm yr^{-1}. Here, values are considerably higher than those observed in the field measurements with an order of 0.001 and 0.01 mm yr^{-1} for forest and semi-natural vegetation, respectively. The disagreement between modelling results and field measurements could be partially explained by the fact that in more than 50% of the modelling exercises considering forestland and grassland areas changes in land cover/ use or vegetation disturbances are reported. Cerdan et al. (2010) made the hypothesis that field measurements in arable lands could be biased towards areas known to be exposed to erosion processes. Similarly, the results of our analysis lead us to hypothesize that the modelling applications explicitly addressing forestland and grasslands could be biased towards areas experiencing human-induced disturbances.

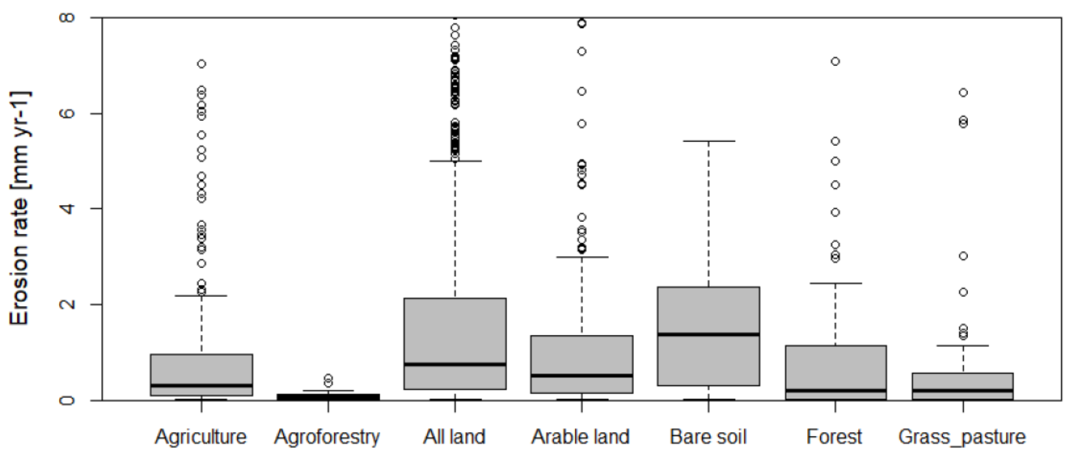

Fig. 6. Comparison of modelled erosion rates under different land covers. Note that the outliers > 8 mm yr^{-1} are excluded in the graphic. The boxplots display the interquartile range (grey boxes), the median (horizontal bold black lines), the 10th and 90th percentile (horizontal black lines) and outliers (dots).

The boxplots in Fig. 7 illustrate descriptive statistics of the soil-erosion estimates of the nine models most commonly encountered in the GASEMT database. Soil erosion rates predicted by models classified within the 'net erosion group' (and thus evaluating the budget between soil erosion and deposition either on plot scale or as net sediment transfer to downscale locations), such as AnnAGNPS ($\tilde{x}$ = 3.3 Mg ha^{-1} yr^{-1}), LISEM ($\tilde{x}$ = 3.5 Mg ha^{-1} yr^{-1}), SWAT ($\tilde{x}$ = 6.4 Mg ha^{-1} yr^{-1}), WaTEM/SEDEM ($\tilde{x}$ = 1.4 Mg ha^{-1} yr^{-1}), and WEPP ($\tilde{x}$ = 4.0 Mg ha^{-1} yr^{-1}), show both lower spread and median values compared to the models classified within 'gross erosion group', i.e, RUSLE ($\tilde{x}$ = 12.6 Mg ha^{-1} yr^{-1}) and USLE ($\tilde{x}$ = 9.6 Mg ha^{-1} yr^{-1}). Models using sediment delivery ratios (SDR) modules to adjust soil erosion rates estimated by (R)USLE to quantify the sediment yield, in GASEMT classified as RUSLE-SDR ($\tilde{x}$ = 8.3 Mg ha^{-1} yr^{-1}) and USLE-SDR ($\tilde{x}$ = 1.8 Mg ha^{-1} yr^{-1}), show average values lower than their equivalents predicting gross erosion (RUSLE and USLE). This is clearer for the USLE-SDR models compared to the RUSLE-SDR models. Erosion rates predicted by the RUSLE-SDR are relatively more similar to those of the RUSLE-type models. Only a small change in the 25th percentile was found. A further observation of the boxplots shows that, except for the RUSLE model, which remains the model most commonly employed with 345 records (32% of the total), all other models have a median value below the 10 Mg ha^{-1} yr^{-1}. Overall, models simulating gross erosion rates result in higher values with more variability among the studies compared to net erosion models, which reflects (i) the consideration of deposition processes within the landscape and (ii) the smoothing of extreme values incorporating topographic variability in the net erosion models.

Fig. 8 shows the geographical distribution of the modelling estimates from the subset of 1,586 studies. The size of the circles is proportional to the size of the study area, while the chromatic scale symbolizes the magnitude of the predicted erosion rates. As inferable from the illustration, quantitative estimates of soil erosion occur for all continents and under all climatic conditions (except Antarctica) although the distribution is highly non-uniform. Aggregating estimates per general climate zones shows latitudinal trends, with the highest average value in the tropical zones ($\bar{x}$ = 29.1; $\tilde{x}$ = 11.2; σ = 51.3Mg ha^{-1} yr^{-1}; 20.5% of the sites), steadily decreasing through subtropical zone ($\bar{x}$ = 29.5; $\tilde{x}$ = 9.1; σ = 102.2 Mg ha^{-1} yr^{-1}; 34.4% of the sites), temperate zone ($\bar{x}$ = 16.1; $\tilde{x}$ = 4.1; σ = 33.7 Mg ha^{-1} yr^{-1}; 44.2% of the sites), and polar and subpolar zone ($\bar{x}$ = 3.0; $\tilde{x}$ = 1.4; σ = 3.7 Mg ha^{-1} yr^{-1}; 0.9% of the sites). High predicted values ($\tilde{x}$ > 20 Mg ha^{-1} yr^{-1}) can mainly be observed in Africa (Rwanda, Mauritius, Burkina Faso, Ghana, Kenya, Congo, Malawi and Somalia), and to a lesser extent in Asia (Lebanon, Tibet and Jordan), Europe (Portugal, Italy and Greece), Southeast Asia (Malaysia and Indonesia), and South America (Nicaragua).

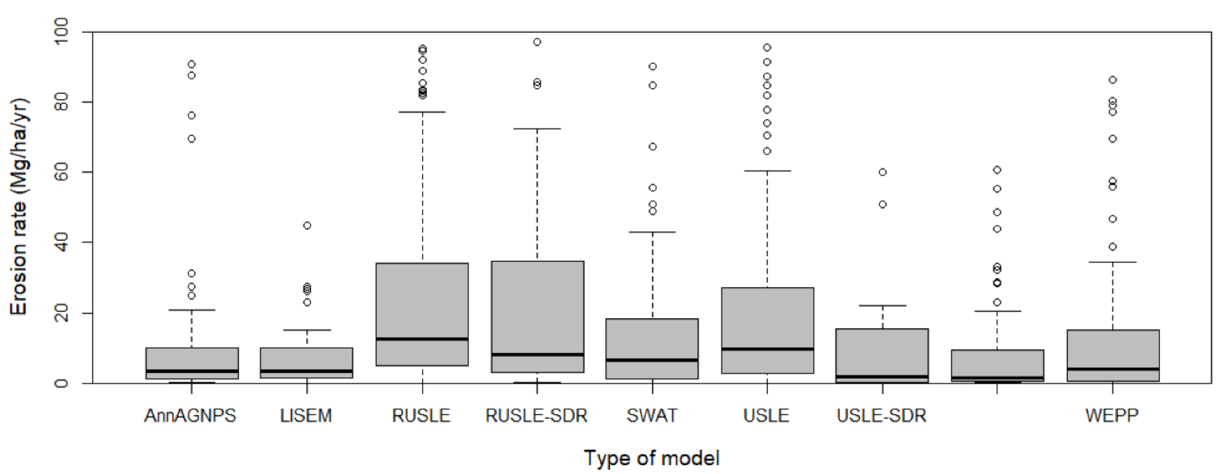

Fig.7. Comparison of the predicted soil erosion rates of the nine models most commonly occurring in the GASEMT database. Note that the outliers > 100 Mg ha^{-1} yr^{-1} are excluded in the graphic. The boxplots display the interquartile range (grey boxes), the median (horizontal bold black lines), the 10th and 90th percentile (horizontal black lines) and outliers (dots).

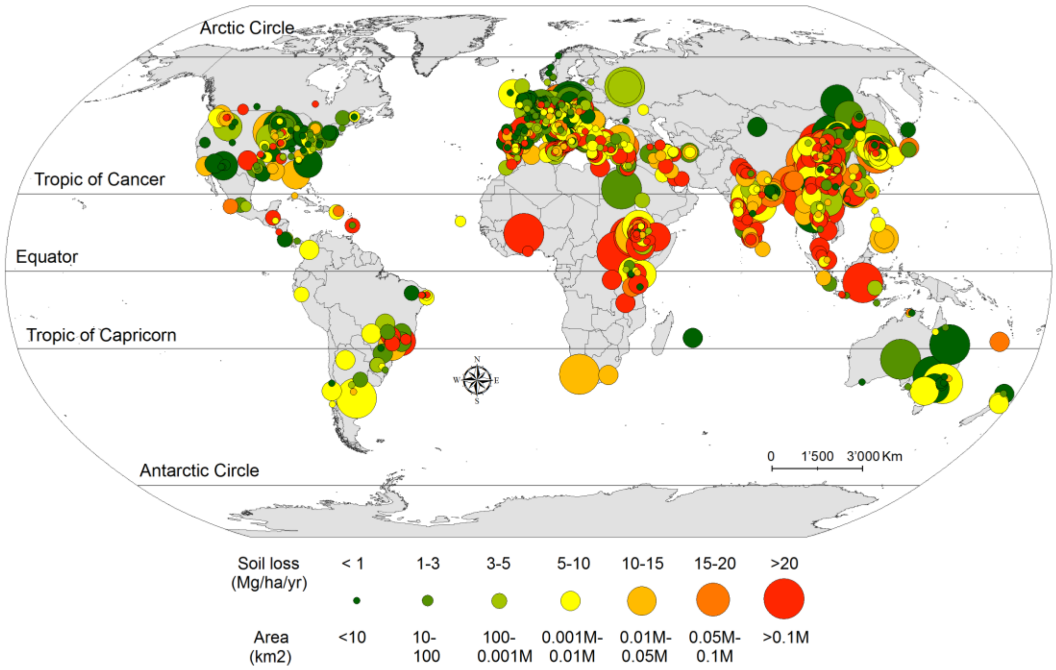

Fig. 8. Geographical distribution of the 1,586 quantitative modelling estimates, including size of the study area (proportional to the size of circles) and predicted soil erosion rates (chromatic scale). Robinson projection.

4. Discussion

The collaboration of 66 scientists from 25 countries representing all continents (except Antarctica) allowed the creation of GASEMT. A database composed of 3,030 individual modelling records (applied in 126 countries) retrieved from 1,697 articles that were thoroughly reviewed. The database contains information on most of the existing peer-reviewed literature reporting spatially explicit soil- erosion modelling applications. Accordingly, studies reporting only theoretical descriptions of models or enhancements of single models, components, or parameters were not considered suitable for the analysis. Similarly, studies reporting on measurements only, e.g. the analysis of fallout radionuclides as indicators of erosion processes (Lizaga et al., 2018; Mabit et al., 2019), were not taken into account.

With a set of 42 different attributes retrieved from each article reviewed (depending on availability), GASEMT constitutes a source of pre-structured literature information and references. The large number of records of this database together with the significant variability in terms of erosion processes, model types, modelling input parameters as well as a significant variability among the modelled study areas and relative soil erosion drivers, makes it an important source of information and a powerful tool upon which to base further research. Here, our attention and interest mainly address the observation and description of the general aspects of the soil-erosion modelling applications worldwide. However, we believe that GASEMT can be useful for a wider number of targeted in-depth studies and observations. Further analysis could disaggregate the information reported in GASEMT to address specific erosion agents and processes, methodologies, or geographical regions., We provided all details in the Supplementary Information (Appendix A) of this study. A practical example of further use of the GaSEM database is provided by Bezak et al. (2020), who investigate the relationship between soil erosion modelling and bibliometric characteristics applying a generalized boosted regression tree model.

In the following, we discuss the implications of our results linking the findings obtained by the analysis of GASEMT to (i) evaluate which processes and models are primarily addressed in the literature, (ii) in which regions models are mainly applied, (iii) what regions remain unaddressed and (iv) how frequently validation/evaluation attempts of the model outcomes were performed with measured data.

Evaluation of the processes and models primarily addressed in the literature. In a recent review study, Poesen (2018) addressed the need for more research in understanding both natural and anthropogenic soil erosion processes. Borrelli et al. (2017) noted an imbalance between literature about wind and water erosion in Europe, in terms of knowledge depth, number of peer-reviewed publications as well as the amount of ongoing field experiments. Today, a search in Scopus using the terms 'erosion and water' results in 52,730 mentions in publications, 'erosion and wind' is found in ca. 9,488, 'erosion and gully' in ca. 3,896 publications while 'erosion and piping' and 'erosion and harvest' are found only in 1,556 and 1,037 documents, respectively (Scopus, 21.02.2020). Although these numbers refer to mentions of the indicated terms in the peer-reviewed (internationally available) scientific literature, they provide a primary indication that over the last decades there has been more attention, and presumably more research, description, and understanding of the mechanics and spatial distribution of soil loss by water erosion. Other erosion processes, by contrast, seem to remain local environmental threats and thus have attracted less interest (Bernatek-Jakiel and Poesen, 2018; Panagos et al., 2019; Poesen, 2018; van Oost et al., 2004). Information on spatial modelling applications reported in GASEMT confirms a lack of variety of soil-erosion processes addressed. About 95% of the modelling applications predicted processes with water as the erosional agent. Only 39, 23 and 3 of the model applications or variants in the GASEMT database were found to deal with wind, tillage, or harvest erosion processes. This means that ~85% of the variants of models developed so far address water erosion. More precisely, the vast majority of models developed so far predict sheet and rill processes, with an estimated range between 50 to 80% of the total predictions. We argue that the unequal distribution of modelling studies among different soil-erosion agents and processes, may not necessarily reflect the importance of these processes in spatial and magnitude terms (Boardman and Poesen, 2006; Lal, 2007; Oldeman, 1994). Instead, the focus on sheet and rill erosion may be attributed to i) the current state-of-the-art process understanding and applicability to agricultural decision making, ii) the availability of measurement and modelling tools, as well as iii) their successful coupling with GIS interfaces. In addition, the lack of literature on soil-erosion modelling from large regions where wind erosion is widespread, such as Asia (e.g., Russia), may contribute to this inequality.

Further analysis indicates that during the last few decades, water-erosion models have been increasingly coupled with GIS interfaces, thus allowing the upscaling of soil erosion assessment from field level to watershed or larger scale. Upscaling has helped focus land-management decisions, e.g., allowing for greater precision in areas with higher erosion risk. At the same time, quantitative attempts to integrate wind and tillage erosion prediction models into GIS environments have been less straightforward, although quite a few applications reached beyond field scale. For instance, the latest reference document of the /UN (FAO and ITPS, 2015) reports that a likely range of global soil erosion by water is 20–30 Gt yr^{-1}, while tillage erosion may amount to ca. 5 Gt yr^{-1}. These numbers, presumably based on the study of Quinton et al. (2010) reported in GASEMT, suggest that tillage erosion could account for up to 25% of water erosion globally. Modelling results reported by Borrelli et al. (2017) indicated that wind erosion can be a relevant phenomenon for Europe, although this land-degradation process has been overlooked until very recently. The estimates in the latter study indicated for the arable land of Denmark (~3 Mg ha^{-1} yr^{-1}), the Netherlands (2.6 Mg ha^{-1} yr^{-1}), and the United Kingdom (~1 Mg ha^{-1} yr^{-1}). This indicates that wind erosion may be a possible major soil erosion agent. Quantitative assessments of wind erosion over large areas in China and Iran reported in GASEMT show average soil-erosion values well above 10 Mg ha^{-1} yr^{-1} (Jabbar et al., 2006; Rezaei et al., 2016; Zhang and McBean, 2016). In addition, the 37% of the GASEMT records reporting wind and tillage erosion predicted high soil erosion rates ($\tilde{x}$ = 10.2 Mg ha^{-1} yr^{-1}) that may locally represent a threat to agriculture productivity and the sustainability of the Earth's natural resources.

An additional aspect worth mentioning is the spatiotemporal trend of most applied models. In their different forms and applications, models belonging to the (R)USLE-family are by far the most widely applied soil-erosion models globally. They cover ~41% of the total records in the database. This value could increase to more than 55% if associated models such as WaTEM/SEDEM, EPIC, SWAT were included in the (R)USLE-family, which could be justified because these models show a similar structure. In line with the observation of Alewell et al. (2019), we also found a strong rising trend (R^2 .82 significance level < .001) of (R)USLE-type applications across all continents. Other models showing both rising trends and worldwide applications are SWAT (R^2 .78 significance level < .001), WEPP-type (R^2 .27 significance level < .01) and WaTEM/SEDEM (R^2 .27 significance level < .01), and to a lesser extent RHEM (R^2 .21 significance level < .02) which remains almost exclusively applied in the United States of America. Other models had either no significant trend (MMF-type, LISEM) or had slightly negative trends (EUROSEM). In 2017, the last year of our observations, RUSLE-type applications (n = 153) were about seven times the most commonly applied process-based models, compared to WEPP (n = 11), RHEM (n = 6), PESERA (n = 2), LISEM (n = 1), EUROSEM (n = 0).

Regions where models are mainly applied. The analysis of the spatial distribution of modelling applications relies on a subset of 1,833 records for which the spatial coordinates of their centroids could be gathered (shown in Fig. 1). We observed that the worldwide increase of models with low demand for input data, such as (R)USLE-type, SWAT, and WaTEM/SEDEM, is accompanied by a significant rise in the size of the modelled areas (R^2 .41 significance level < .001). The geographical distribution of soil-erosion modelling itself is clustered with well-defined geographical regions in North America, Europe and Southeast Asia. Six countries were found to possess about 50% of the total modelling studies (i.e., United States of America, China, Italy, India, Spain and Australia). A higher incidence of modelled sites in temperate and subtropic zones can be also observed; occurrence in tropical regions is notably lower (~15%). This situation contrasts with general understanding of the geography of soil-erosion processes emerging from field observations (Boardman, 2006), global expert-based qualitative assessments such as (GLASOD; Oldeman, 1994), and quantitative descriptions of major soil-erosion drivers (Chappell and Webb, 2016; Panagos et al., 2017), which indicate that tropic regions are highly susceptible to soil erosion (Labrière et al., 2015). The GASEMT data base clearly demonstrates the lower incidence of studies in the tropics and subtropical regions, which is even more critical as it is paired with the findings of this study, that latitudinal trends indicate highest soil erosion average in the tropics (Fig. 8). As such, the gradually increasing erosion rates from the subpolar zones to the temperate, the subtropical and finally the tropically is paired with decreasing investigation intensity and thus an obvious lack of knowledge. This indicates that erosion modelling is not necessarily driven by the urgency of environmental impact assessment, but more so by the spatial occurrence and frequency of studies in the countries publishing the most science articles in peer-reviewed journals (Forbes, 2020). As already observed by García-Ruiz et al. (2015) in a similar study evaluating soil erosion rate measurements, the spatial pattern does not necessarily reflect the regional relevance of soil erosion processes, but rather the spatial concomitance of soil -erosion processes with scientific groups interested in this topic and publishing their research outcome in Scopus-indexed journals. The overall volume of research on soil erosion modelling may be considerably larger as suggested by the 419,000 results obtained searching for '*soil erosion modelling'* in Google Scholar.

A comparison of the spatial patterns of the soil erosion rate measurements collected by García-Ruiz et al. (2015) (Fig. 9) and the modelling applications gained in this study (Fig. 8) indicates that the latter is more distributed globally. Although a significant spatial agreement between the two datasets can be observed in North and South America, Western Europe, and Eastern Africa, models appear to be considerably more applied in regions that rarely report field measurements, such as India, China, and Southeast Asia, among others. While it is generally agreed in the scientific world, that models should be validated/evaluated with measured data, erosion measurements are often as uncertain as modelling (Batista et al., 2019; Alewell et al., 2019), and in many areas of the world not even existing. As such, modelling endeavours must be seen as hypothesis on temporal trends, spatial patterns, driving factors and triggering processes.

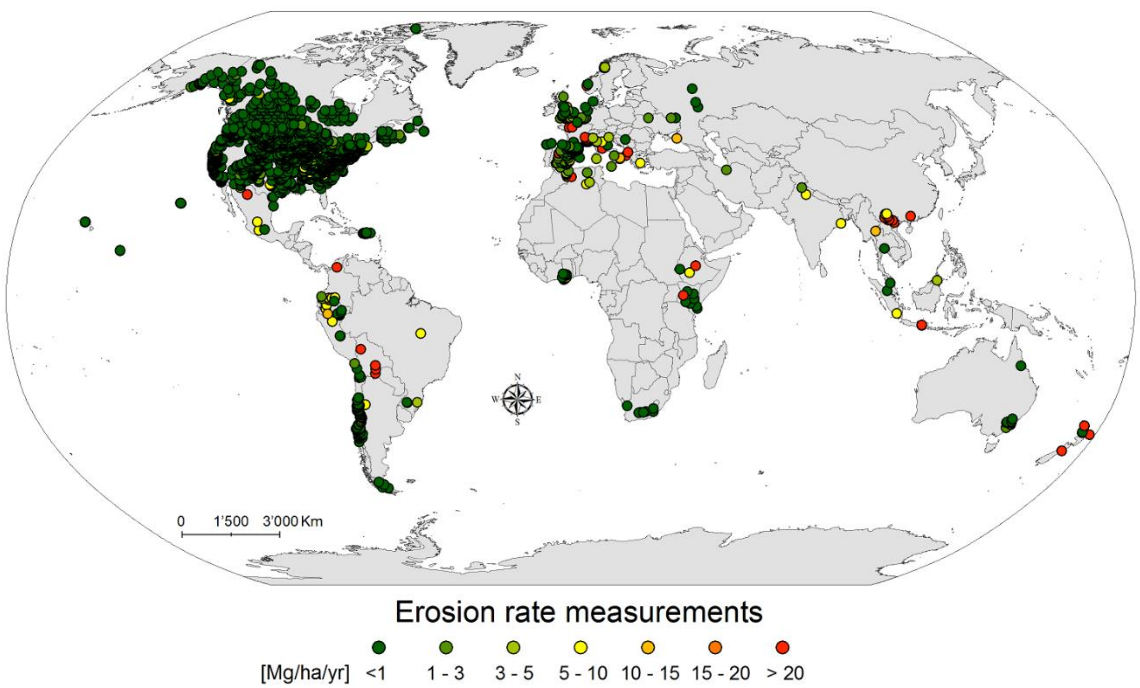

Fig. 9. Spatial distribution (Robinson projection) of the sites reported in García-Ruiz et al. (2015) database on field measurements of soil erosion.

Regions unaddressed by modelling. Leaving global and continental scale studies unconsidered, plot- to national-scale modelling applications would jointly cover a surface of approximately 48 million km^2, equal to 32% of the world's land. This estimate assumes marginal overlap between the modelled areas within the GASEMT records. Further analysis of the data, excluding the most obvious overlaps, results in about 35 million km^2, indicating a relevant range of 25 to 35 million km^2 that have been modelled. Of the 35 million km^2, about 66% is due to national-scale studies in the USA (~28.4%), China (~27.7%), and India (~9.5%). With regard to the soil-erosion agents, as expected, soil erosion by water dominated most of the modelled area, leaving wind and tillage erosion with values at approximately 2.5 and 0.12 million km^2, respectively.

Our first analyses indicated a general tendency of studies to be located around the main cropland areas. These insights are corroborated by Fig. 10a which overlaps the hexagonal pixels of modelled areas to global croplands (Hurtt et al., 2019; Stehfest et al., 2014). Based on the available peer-reviewed English-language journals, large areas exploited for crop production in Russia and East Europe, Central Asia, throughout most of Africa, and South America seem to be poorly studied through soil-erosion modelling. However, this can also be the result of more publishing in the local language or technical reports.

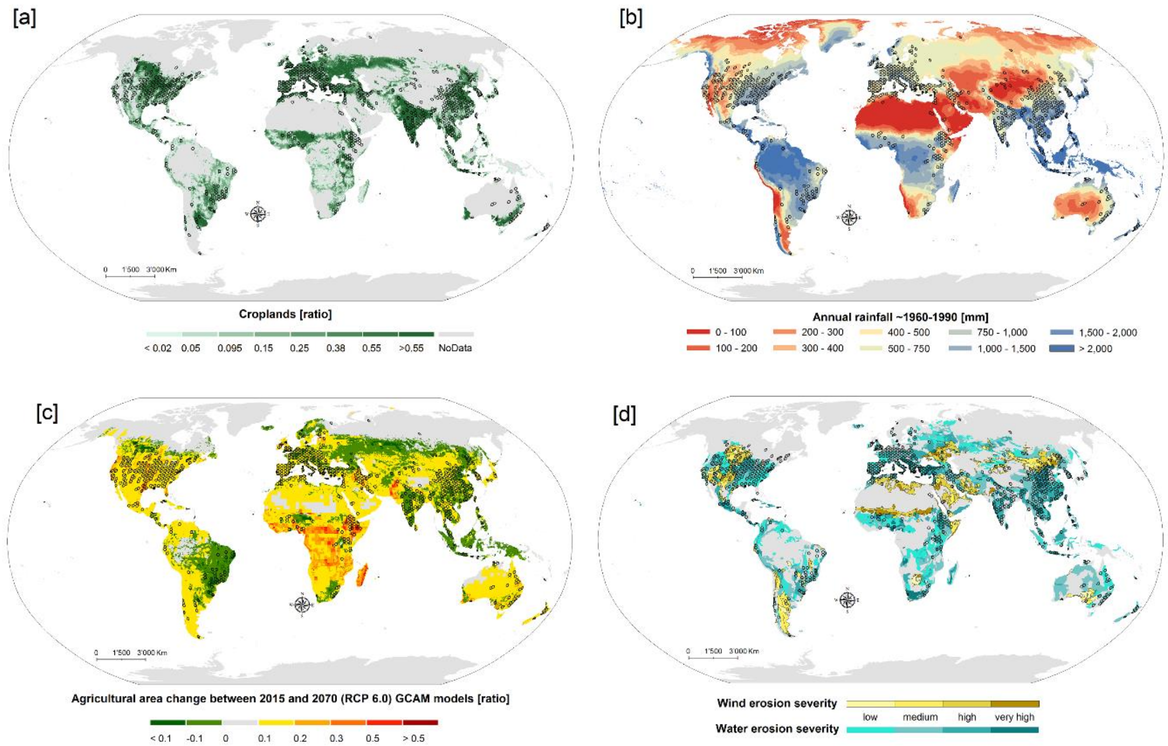

Fig. 10. Geographical distribution (Robinson projection) of 1,833 Global Applications of Soil Erosion Modelling Tracker (GASEMT), grouped using a hexagonal grid, superimposed on (panel a) the global cropland according to the IMAGE model year 2015 (Hurtt et al., 2019; Stehfest et al., 2014), (panel b) global annual rainfall (Hijmans et al., 2005), (panel c) global annual changes in agricultural area between the reference period 2015 and 2070 projections (Global Change Assessment Model (GCAM) RCP 6.0, Hurtt et al., 2019), and the water and wind erosion severity according to the Global Assessment of Soil Degradation (GLASOD) (panel d). The degree of damage is indicated from low (1) to severe (4). This figure is available at high-resolution in the Supplementary Information (Fig S3).

Fig. 10b presents the average annual rainfall for the period 1960-1990 (www.worldclim.org). Comparison of rainfall patterns in Fig. 10b with the soil-erosion modelling applications indicates that areas characterized by low to medium rainfall values have been more intensely studied compared to areas in wet climates covered or formerly covered by tropical rainforest. These conditions are particularly noticeable along areas characterized by high rainfall erosivity in South-Eastern Asia (Cambodia, Indonesia, Malaysia, the Philippines and Bangladesh), Central Africa (Congo and Cameroon), South America (Brazil, Colombia and Peru), Central America, and the Caribbean (Panagos et al., 2017). Some of the regions poorly represented by soil-erosion modelling studies have experienced, and will probably continue to experience (Global Change Assessment Model (GCAM) RCP 6.0, Hurtt et al., 2019) (Fig. 10c), increasing trends of forest logging and cropland expansion (Hansen et al., 2013). This could also be accompanied by a trend towards increasing rainfall intensities in these regions as predicted by several future projections (Hijmans et al., 2005). Modelling projections suggest that tropical countries such as Peru, Brazil, several countries in Western Africa, Cameroon, Ethiopia, Somalia, Kenya, Yemen, Southern Pakistan, India, Myanmar, Southeast China, Philippines, and Indonesia may be significantly affected by increased soil erosion (Borrelli et al., 2020). In addition, roughly two and a half billion people currently live in these countries and populations show signs of significant expansion (Bongaarts, 2016). Fig. 10d shows strong spatial agreement between areas of soil-erosion modelling and the areas reported to be affected by water and wind erosion by the expert-based GLASOD promoted by United Nations Environmental Programme. GLASOD was developed from the combination of data provided by more than 300 scientists from several countries. Although qualitative in nature, and potentially affected by the different perceptions of the contributing scientists, the GLASOD is still based on extensive field observations. The comparison between the patterns of the application of soil-erosion modelling and the independent GLASOD map provides insights into where modelling is being applied compared to perceived needs. It should be noted that GLASOD refers to observations made during the 1980s and important global land-use changes have occurred in the following decades, which GLASOD does not reflect.

Frequency of model validation/evaluation attempts of modelling outcomes against measured data. Validation/evaluation of modelling results was applied in most of the cases in GASEMT (~58%). Plot-scale modelling (13% of the total records) show higher levels of validation/evaluation (~68%) and calibration (~38%), mostly performed through volumetric measured erosion rates (37.8%) and collecting sediment yield (25%). Rising trends for studies reporting validation /evaluation (R^2 .77 significance level < .001) and calibration (R^2 .92 significance level < .001) procedures could also be observed, with recent higher values related to sediment-delivery models such as SWAT, WaTEM/SEDEM and LISEM. However, as a proportion of total annual modelling applications, the trend of number of models validated/evaluated and calibrated is negative. For example, a transition from the 80-90% of studies validated/evaluated in the period 1995-2000 compares to 60-70% in 2015-2017. The latter trend might partly be due to the recent increase in modelling studies from countries and regions with low measurement density (Fig. 8 and 9).

Validation/evaluation procedures based on the comparison of observed versus simulated sediment loads at the outlet cover the largest share (n = 798 GASEMT records). While the application of this type of validation /evaluation seems most logical for prediction at plot scale (n = 102) (Nearing, 2000), outlet-based validations /evaluations applied to watershed scale (n = 605) leaves room for concerns about the effectiveness of the validation /evaluation procedure (Borrelli et al., 2014; De Vente and Poesen, 2005). As derived from our analysis, most of the models validated/evaluated through outlet-based procedures (SWAT, WaTEM/SEDEM, and (R)USLE-SDR, among others) provide estimates of soil erosion only due to sheet and rill processes. Most of the models are unable to directly, or indirectly, account for the soil displacement due to gully and tillage erosion processes. Most do not model other geomorphic processes such as landslides, riverbank erosion, and riverbed and floodplain deposition. The other methods of validation/evaluation more commonly encountered in GASEMT records are based on measured erosion rates (n = 536). Unexpectedly, a substantial proportion evaluated performance through comparisons with other model simulations (n = 305).

Published studies profusely described the lack of data and knowledge which currently limits the capacity to perform validations *sensu strictu* ~~(Auerswald et al., 2003)~~ of modelling results beyond plot and hillslope scales (please see detailed discussion of the term validation/evaluation in the context of soil erosion modelling in (Alewell et al., 2019; Auerswald et al., 2003; De Vente et al., 2013; De Vente and Poesen, 2005)). Knowledge gained from our analysis indicates that although soil-erosion models are applied deterministically (without validation/evaluation of the results). However, both small- (plot and hillslope) and large-scale applications (watershed and regional) show rather high levels of validation /evaluation attempts (understood here as a comparison of modelled to observed data or modelled to a second independent modelled data set) of the results (above 45% in all cases). Nevertheless, while the comparisons versus *in situ* measured erosion rates result in appropriate validation/evaluation procedures for plot and hillslope scale predictions, the lack of long-term observations and measurements at watershed to regional scale poses serious limits to models applied at such scales.

5. GASEMT database: Data availability and limitations

All data supporting the findings of this study can be extracted from the Supplementary Information file (reporting GASEMT database in Appendix A).

Our evaluation of the GASEMT database revealed some shortcomings. First, some missing data (reported as *unknown* in the database) are due to unavailability of information in the reviewed publications. Although this affects only some attributes, key information such as predicted soil-erosion rates, coordinates of the study area, and size of the study area can be missing. A meta-regression analysis using GASEMT data could not be performed due to restrictions imposed by heterogeneity of the records and, more importantly, due to a lack of detailed georeferenced information about the study areas. Due to capacity bottlenecks (our project relied on volunteer participatory approach without funding), the scientific team refrained from defining the shape and perimeter for each study area. This limited the possibility to compile variables for the modelled sites and to investigate relationships between predicted erosion rates and environmental factors (e.g., climate data, slope, vegetation cover) through exploratory analysis. A further shortcoming relates to potential inconsistencies in the database. Although a harmonization procedure has been carried out to identify and rectify most inconsistencies and misclassifications among experts, some of these may still affect some records in the final database of this publication. The limited number of studies compiled dealing with spatial modelling of gully and other erosion processes (e.g., harvest erosion, tillage erosion, piping) may also have been diminished by the criteria used for the Scopus search. Our decision to consider only research work validated/evaluated through peer-review excluded all grey literature from GASEMT, such as scientific reports, government publications, proceedings, conference abstracts, and journals of national associations. We recognize that this decision could be influenced by scientific communication practices and 'epistemic cultures' (Cetina, 1991) that are more oriented towards peer-reviewed journals. The exclusion of grey and non-English peer-reviewed literature in GASEMT may have affected the geographical representation of some regions in the database where publishing in local and national language/ literature is more frequent. However, in light of the 419,000 results obtained searching for '*soil erosion modelling'* via Google Scholar, we recognize that this large amount of literature would have been an unrealistic amount to evaluate without aids such as artificial intelligence and would have probably still not been optimal for a harmonized and systematic review like the one performed in this study. An internal debate among the authors also highlighted the question of whether the use of Elsevier's Scopus bibliographic database, instead of Thomson Reuters' Web of Science (WoF), or both, may have contributed to bias in the geographical distribution of the GASEMT records. The decision to use Scopus in this analysis was based on the information available in the literature indicating that Scopus has greater coverage of specific subjects in Earth and Atmospheric Sciences and a larger match with compared to WoF (Barnett and Lascar, 2012; Mongeon and Paul-Hus, 2016). A recent Scopus and WoS query (17.03.2020) searching `soil erosion models` in the title, abstract, and keywords resulted in 13,474 and 12,972 articles potentially reporting applications of soil erosion modelling, respectively. Considering only the period 1994-2017, the query returned similar results with 10,010 (Scopus) and 10,187 (WoS) documents. This document the similarity of Scopus and WoS and further supports the validity of our choice.

6. Conclusions

The systematic literature review, compilation of the GASEMT database, and its analysis allowed for the first time to gain data-driven insights on worldwide applications of soil erosion modelling and shed light on the current state-of-the-art. The statistical analysis showed that models tend to predict erosion rates that are significantly greater in the tropics, with values that tend to decrease towards higher latitudes. The application of models, however, shows an inverse trend with geographic patterns outlining a greater incidence of studies in the temperate and Mediterranean zones. The results of the analysis suggest that industrialised and highly developed countries, generally in temperate latitudes with lower erosion rates show a higher incidence of studies. The database reports fewer studies in less-developed, tropical and subtropical countries, where modelling findings suggest a possible greater exposure to erosive processes.

Unlike previously reported work, our findings suggest that non-sustainable soil-erosion rates not only occur due to a lack in policy governance (Alewell et al., 2019) but in many regions of the world may also result from a lack of knowledge. Detailed information on soil erosion, through both modelling and measurement, is lacking for large parts of the world. This is particularly true for regions most susceptible to high levels of soil erosion. For many of these regions we only have information from global modelling applications, which may not adequately represent local causes and drivers of soil erosion nor provide a basis for policy solutions.

Our findings also indicate that (R)USLE-type models have been extensively used and modified during the last two decades and remain the most employed modelling tool today. It emerges that most of the current knowledge on spatial soil-erosion patterns and trends derived from models relies on (R)USLE-type approaches. This, in turn, means that our understanding of spatial soil erosion mostly relies on empirical models dealing with water as the erosion agent and focusing on sheet and rill as dominant processes. Applications of process-based physical models appear far more constrained, although some models such as WEPP, RHEM, and LISEM show increasing trends. Nevertheless, the scale of applications of the process-based physical models ($\tilde{x}$ = ~1 km^2) suggests that the required input data are lacking for large-scale applications.

While soil erosion measurements are often connected to high uncertainty, high efforts in work/time or might be even unfeasible on large scales, many modelling studies, by contrast, lack a direct validation/evaluation attempt of modelled versus measured data. As such, many soil erosion modelling applications should be considered as indications of the best hypotheses currently available rather than predictive models. Such models are useful in times and/ or locations where soil erosion measurement and monitoring data are not yet available. This, however, should be only a transitory state as one thing became apparent during this review study: The ease at which one can use off-the-shelf soil-erosion models using remotely sensed data and GIS creates an inflated number of models that lack field activities and validation/evaluation of the results. True knowledge gain can only the achieved by a scientific community that accepts the challenge to rethink its approach towards modelling applications. This challenge is reflected in the UN GSERmap which represents an opportunity to overcome some of these shortcomings by introducing new region and country-based modelling assessments supported by well-defined field-based data collection to validate/evaluate the results.

Author contributions

Pasquale Borrelli developed the research concepts, coordinated the review activities and wrote the paper. Panos Panagos and all other authors (listed in alphabetical order) contributed with ideas, reviewed the papers, worked on the development of the GASEMT database, discussed the results and contributed to improve the text and the discussions of the results.

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Supplementary Information

Fig. S1. Distribution of the estimated gross soil-erosion rates categorized by erosion agent (panel a), continent (panel b) and spatial scale (panel c). Values in the cells and colour legend represent the numbers of occurrence in the database.

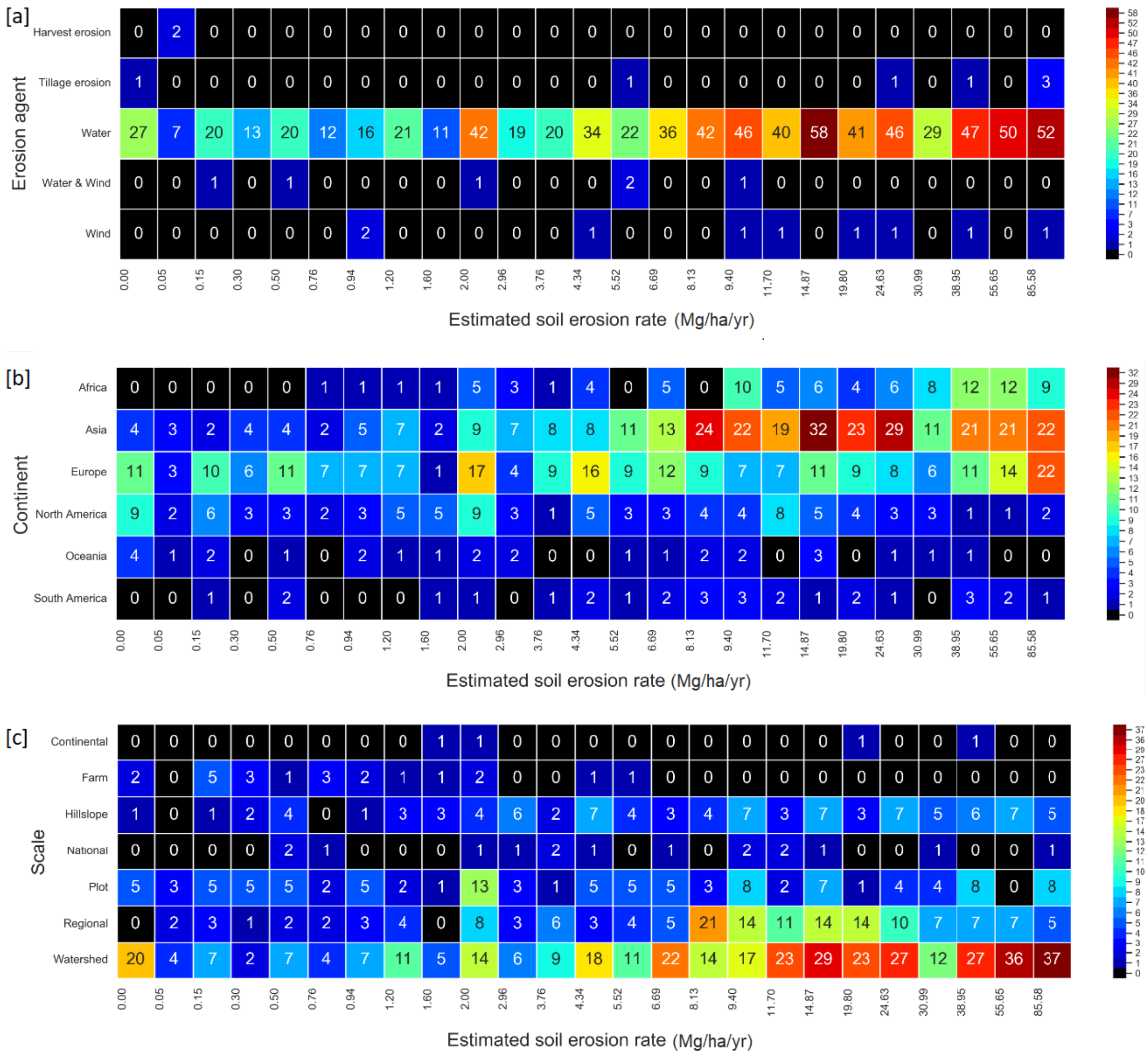


Fig. S2. Distribution of the estimated net soil-erosion rates (including the estimated classified in the 'soil redistribution' group) categorized by erosion agent (panel a), continent (panel b) and spatial scale (panel c). Values in the cells and colour legend represent the numbers of occurrence in the database.

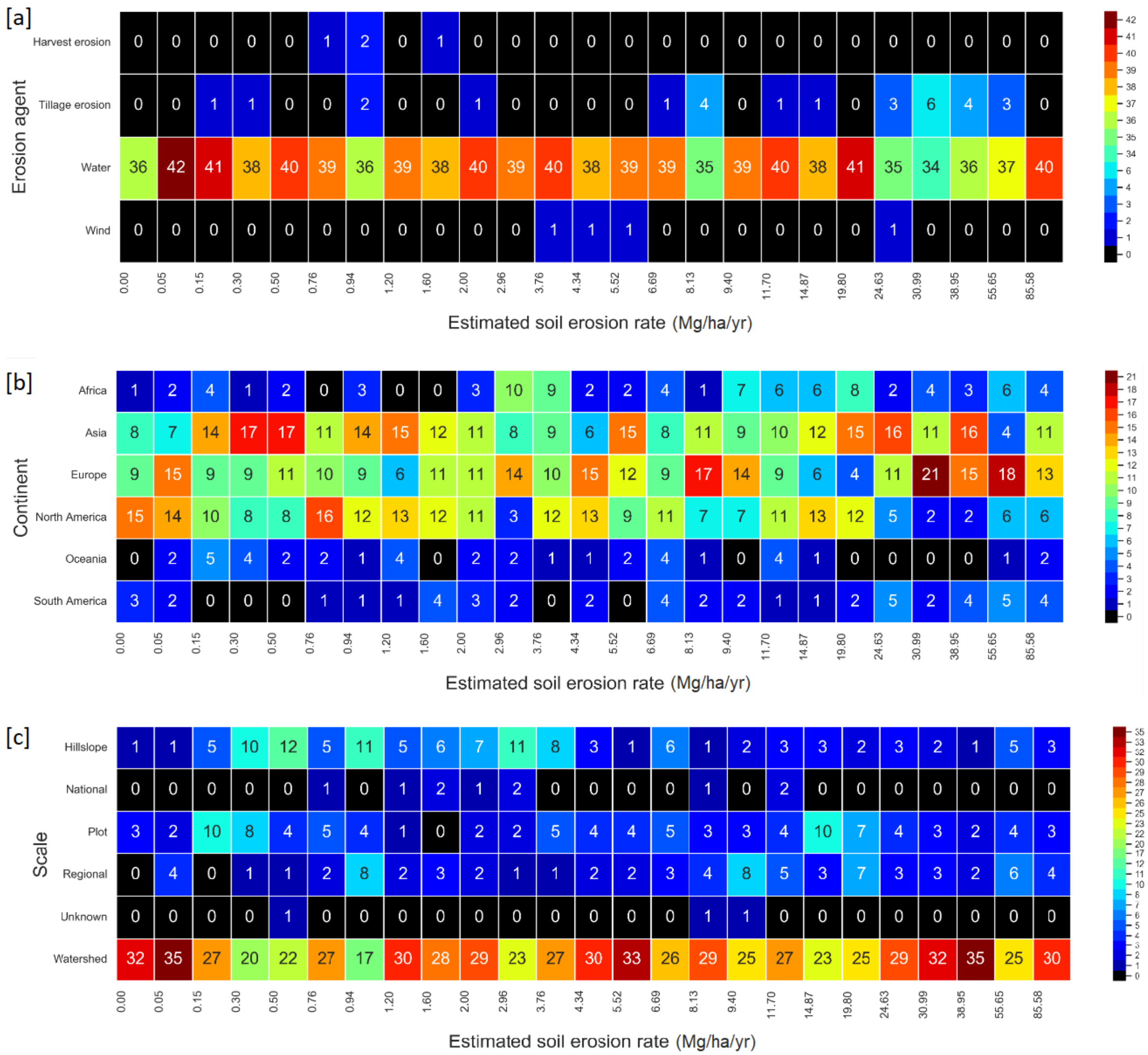
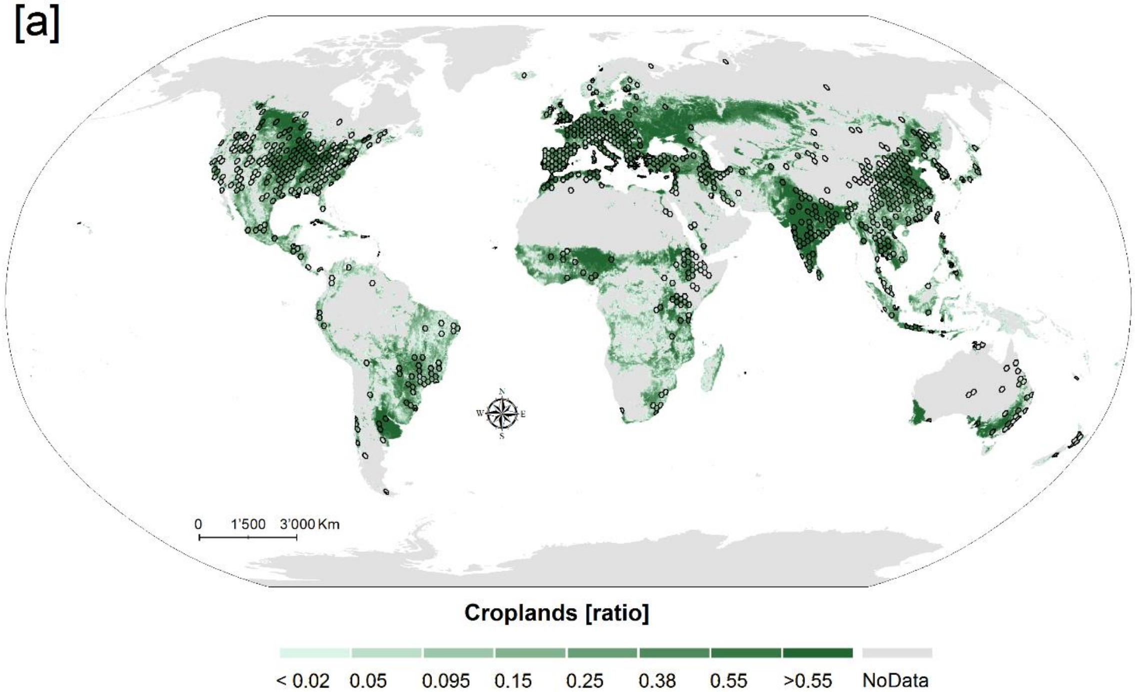
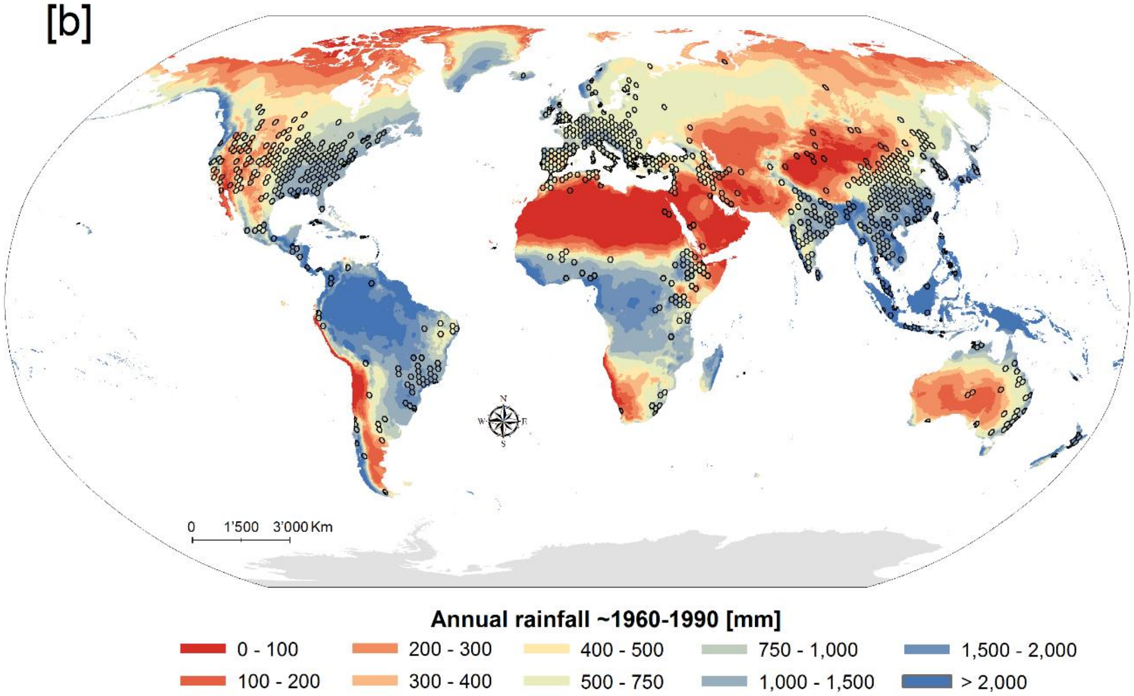


Fig. S3. High-resolution representation of the four panels illustrated in the Figure 10 (Robinson projection). All panels report the geographical distribution of 1,833 Global Applications of Soil Erosion Modelling Tracker (GASEMT), grouped using a hexagonal grid, superimposed on (panel a) the global cropland according to the IMAGE model year 2015 (Hurtt et al., 2019; Stehfest et al., 2014); (panel b) global annual rainfall (Hijmans et al., 2005); (panel c) global annual changes in agricultural area between the reference period 2015 and 2070 projections (Global Change Assessment Model (GCAM) RCP 6.0, Hurtt et al., 2019); and (panel d) the water and wind erosion severity according to the Global Assessment of Soil Degradation (GLASOD). In the latter case, the degree of damage is indicated from low (1) to severe (4).

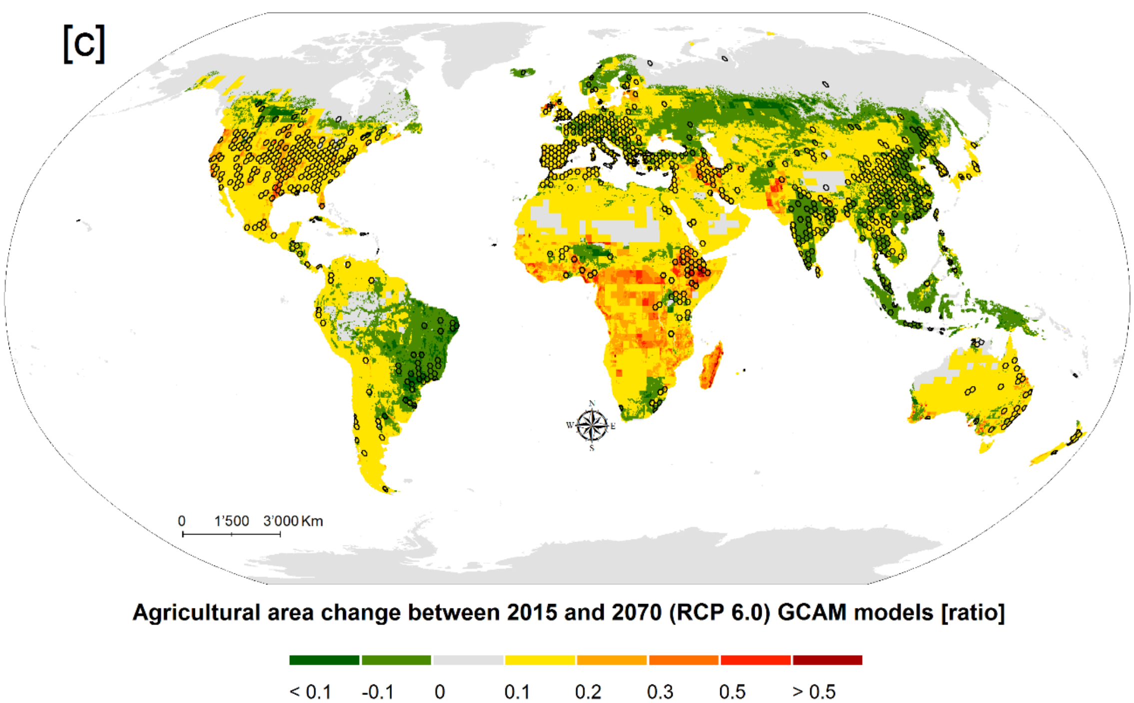
[a]



[b]


0 1'500 3'000 Km
Annual rainfall ~1960-1990 [mm]
0 - 100
100 - 200
200 - 300
300 - 400
400 - 500
500 - 750
750 - 1,000
1,000 - 1,500
1,500 - 2,000
> 2,000

[c]


0 1'500 3'000 Km
Agricultural area change between 2015 and 2070 (RCP 6.0) GCAM models [ratio]
< 0.1
-0.1
0
0.1
0.2
0.3
0.5
> 0.5

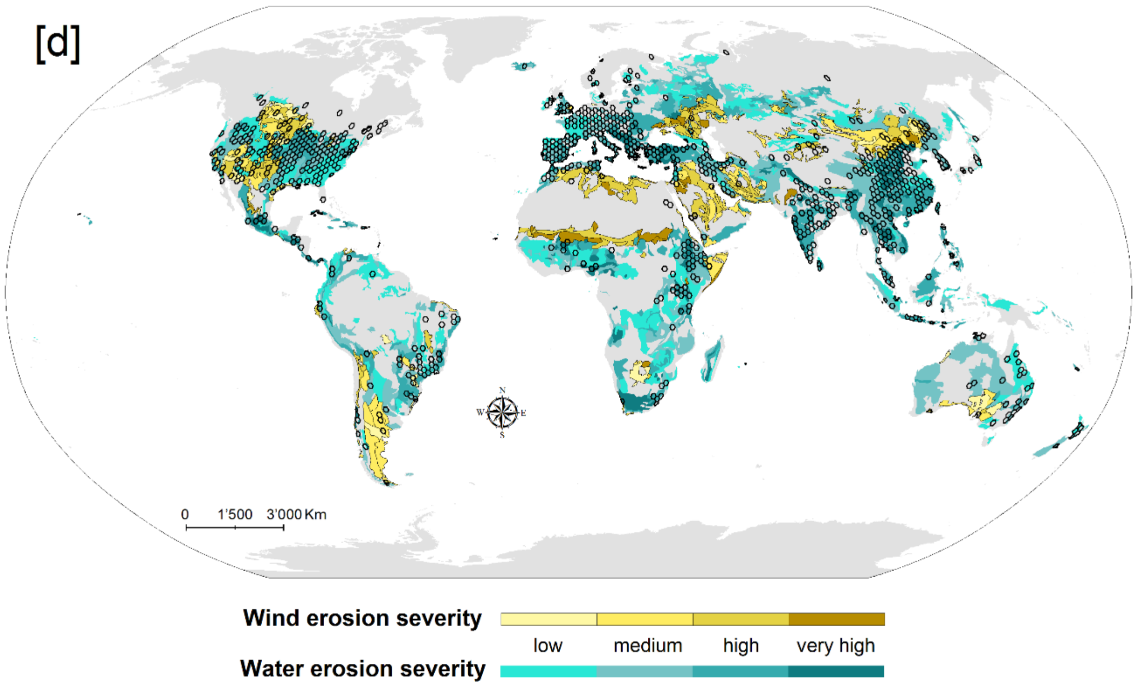


Table S1. Scale definition.

Scale	**Definition**
Continental	encompassing the total area within the boundaries of a continent
Farm	Agricultural parcel
Global	Terrestrial surface of the earth
Hillslope	Plot that extends towards the upper topographic boundary of a slope
National	Encompassing the total area within the boundaries of a nation
Plot	Defined area within a slope
Regional	Larger than watershed, smaller than national
Watershed	Surface area from which runoff resulting from rainfall is collected and drained through a common point. It is synonymous with a drainage basin or catchment area

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