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Global impact of climate change on soil erosion and potential for adaptation through soil conservation

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ABSTRACT

Climate change is expected to lead to increased soil erosion in many locations worldwide affecting ecosystem services and human well-being. Through a systematic review of 224 modelling studies, we provide a global assessment of the impact of climate change on soil erosion and the adaptation potential through land use change and soil conservation. We account for the robustness of each study based on a statistical analysis of ten methodological aspects and an expert consultation. Results show a global increasing trend in soil erosion towards the end of the 21st century, with the highest increase projected in semi-arid regions. Land use change characterized by agricultural expansion and deforestation aggravate the impact. Reforestation, agricultural land abandonment and soil conservation practices can entirely compensate the impact of climate change on soil erosion. This stresses the need for soil conservation and integrated land use planning. From the obtained weights per study we can conclude that there is a lot of uncertainty in the methods applied, without a clear trend towards more robust studies. Based on the results of the expert consultation, we recommend to use a climate model ensemble of at least five climate models, based on the latest CMIP6 climate scenarios. These data should be downscaled and bias corrected using trend preserving quantile methods. Finally, the post-processed climate data should be applied in a soil erosion model forced by precipitation and runoff. Considering the most robust methodologies of the different aspects of the uncertainty cascade will lead to better spatial evaluation of the impact of climate change on soil erosion and identification of most effective adaptation strategies.

1. Introduction

Land degradation is a global threat that is negatively affecting ecosystem functioning and their capacity to provide ecosystem services (Lal, 2010), such as nutrient cycling, water retention and provision of habitat (Blum, 1995). Soil erosion is one of the main processes leading to land degradation (Koch et al., 2013) and mostly affects the fertile top soil layer, which plays an essential role in productivity of (agro)ecosystems and is fundamental for the provision of food security (Amundson et al., 2015). Soil erosion also affects biogeochemical cycles and, therefore, interacts with climate change itself (e.g., Regnier et al., 2013; Tan et al., 2020; Zhang et al., 2020). The on-site impact of soil erosion includes the loss of organic matter, which reduces the water and nutrient-holding capacity of the soil (Pimentel, 2006). Moreover, soil erosion also has important off-site impacts on habitat, including fluvial habitat (Scheurer et al., 2009; Whitehead et al., 2009), coastal habitat (Harborne, 2013), and coral reefs (Fisher et al., 2019). The transported sediment affects human activities, such as the sedimentation of reservoirs for irrigation and drinking water purposes (Vörösmarty et al., 2003), the damage to housing and infrastructure (Boardman, 2010), and activities employed in river deltas (Syvitski et al., 2009). Climate change is expected to lead to increased soil erosion in many locations worldwide (Nearing et al., 2004) affecting ecosystem services and human well-being. Despite numerous case studies, there is however a lack of knowledge regarding the global differences in impacts of climate change on soil erosion, the potential of land use and soil conservation practices to mitigate these impacts, and the uncertainties involved.

Soil erosion under climate change is most directly affected by changes in extreme precipitation (Nearing et al., 2004). Extreme precipitation is projected to increase as a result of the increasing moisture-holding capacity of a warmer atmosphere, resulting in a more vigorous hydrological cycle (Trenberth, 2011). Long-term observations already show an increasing trend in extreme precipitation globally (Papalexiou and Montanari, 2019), while climate model projections suggest a further increase in the coming decades (Sun et al., 2007). Extreme precipitation not only affects soil erosion through the detachment of soil particles by

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raindrop impact, but also through the detachment by runoff (Morgan and Nearing, 2010). Climate change most likely causes an increase in infiltration excess surface runoff (Eekhout et al., 2018), promoting rill and (ephemeral) gully erosion, which are reported to contribute most to total sediment yield (de Vente and Poesen, 2005).

It is well established that land use change has a significant impact on soil erosion as well, and interacts with climate change (Favis-Mortlock and Boardman, 1995; Mullan et al., 2012). However, projecting how land use will change under future climate conditions is not a straightforward exercise (Li and Fang, 2016), because of the large number of drivers (e.g. socioeconomic, cultural, environmental, political) that act at local to global scales (Lambin et al., 2001). Due to these complexities, it is not surprising that only a few studies consider land use change and vegetation development in combination with the impact of climate change on soil erosion (Li and Fang, 2016). Soil conservation measures are often promoted as a solution to adapt to the projected increase of soil erosion under climate change (Amundson et al., 2015; Eekhout and de Vente, 2019a), which may include land use change, such as reforestation, and a range of on-site and off-site measures (Xiong et al., 2018). Soil conservation measures are not only beneficial to reduce soil erosion, but can provide additional ecosystem services, including carbon and nitrogen sequestration, contributing to climate change mitigation (Lal et al., 2011) and protection of biodiversity (Albaladejo et al., 2021).

Previous research has shown that the methodology used in climate change impact assessments may have a significant impact on the projected change in soil erosion (Zabaleta et al., 2014; Francipane et al., 2015; de Oliveira et al., 2019; Zhang et al., 2019). Due to the variability in the climate projections themselves, climate models are shown to have a significant impact on the soil erosion projections. Often positive and negative changes in soil erosion are reported depending on the climate model used (Op de Hipt et al., 2018; Eekhout and de Vente, 2019b) and, in general, many studies report high variability within the climate model ensemble (Zhang et al., 2012; Mukundan et al., 2013; Shrestha et al., 2013, 2018; Teng et al., 2018). Likewise, emission scenarios are found to provide divergent projections of future soil erosion as well (Segura et al., 2014; Amanambu et al., 2019; Duulatov et al., 2019).

Downscaling and bias correction are used to make climate model data applicable in soil erosion impact assessments. Downscaling involves the transformation of coarse-scale climate model data to fine-scale model domains and may involve temporal and/or spatial downscaling. Downscaling can be classified into dynamical downscaling (associated with Regional Climate Models) and statistical downscaling (Boé et al., 2007). Commonly, climate models produce a bias between the historical model output and observations, which can be corrected by applying bias-correction methods (Teutschbein and Seibert, 2012). Many studies use downscaling and/or bias correction techniques to post-process climate model data, however, various studies have demonstrated that the selected downscaling or bias correction methods affect the resulting soil erosion projections (Zare et al., 2016; Op de Hipt et al., 2018; Eekhout and de Vente, 2019b). Lastly, soil erosion models also contribute to the uncertainty in the future projections, for instance due to the time-step used in the precipitation forcing (Nearing, 2001; Biasutti and Seager, 2015) and soil erosion model conceptualization (Berteni and Grossi, 2020; Eekhout and de Vente, 2020; Eekhout et al., 2021).

Soil erosion is expected to increase in the coming decades, considering the projected increase of extreme precipitation and the possible negative impact of land use change. The few available global modelling studies project an increase in soil erosion between 9 and 56% (Yang et al., 2003; Borrelli et al., 2020), but have several conceptual limitations (Alewell et al., 2019; Quine and Van Oost, 2020). Moreover, these global studies apply the same erosion model concepts and do not capitalize on the knowledge of numerous field to continental scale modelling studies that assess the impact of climate change on soil erosion worldwide. Here we aim to assess the global impact of climate change on soil erosion and the adaptation potential through land use change and soil conservation, while accounting for the methodological robustness of the studies. Our global assessment is based on a systematic review of soil erosion projections from 224 studies spanning all the continents (except Antarctica) and climate zones. From these studies, we obtained 979 soil erosion projections, divided over different greenhouse gas emission scenarios, future periods, land use scenarios and soil conservation practices. We account for the robustness of each study through a statistical analysis of ten methodological aspects and an expert consultation, that we then used to assess the weighted impact of climate change on soil erosion.

2. Material & methods

2.1. Systematic review

The systematic review process was performed following the SALSA framework (Search, AppraisaL, Synthesis and Analysis; Grant and Booth, 2009), which is a structured and contextual approach widely used for systematic literature reviews. It includes the definition of the research questions, the search term, the criteria used on which publications are included or excluded, the list of variables extracted from the publications, and the way the data were used to extract conclusions from the publications. The variables of interest were divided over seven main themes, including bibliographic information, objective, study area, climate models, soil erosion model, land use change, soil conservation practices and soil erosion projections (Supplementary Table 1). A detailed description of the systematic review process is provided in Supplementary Text S1.

The projected relative change in soil erosion (Supplementary Table 2) was calculated from the reported reference (or baseline) values and the projected values under climate change. Data were extracted from the reported text, tables and graphs, using image analysis software (WebPlotDigitizer) when necessary. In the case relative changes were reported, we used those values directly. We determined the ensemble average from the ensemble members when the values were reported per individual climate model. We determined the average among the methods in the case of method comparison studies.

2.2. Data

The projected change in soil erosion was determined per climate zone, which was obtained from a Köppen-Geiger climate classification map with a 1 km resolution (Beck et al., 2018). The 30 Köppen-Geiger climate classes were subdivided over seven climate zones (Fig. 1). For the analysis of the results per climate zone, we only included those study areas that were defined with a dominant climate zone of at least 50% coverage. The study area polygons were obtained from the HydroSHEDS database (Lehner et al., 2008) in the case of study areas defined by a river catchment. Study areas defined by country borders were obtained from Natural Earth (https://www.naturalearthdata.com/). For study areas smaller than 100 km^2 we obtained the climate zone at the geographic centre of the study area.

2.3. Uncertainty

To account for the differences in methodology and their uncertainty, we assigned robustness scores to the methods used in the soil erosion impact assessments, which were subsequently used to determine the weighted statistics of the projected change in soil erosion. We first established which methodological aspects resulted in significantly different soil erosion projections among their methods. We determined if the soil erosion projections obtained using different methods originate from the same distribution through the non-parameteric Kruskal-Wallis test. Then we applied the Wilcoxon rank-sum test to show the pairwise differences among the methods. The methodological aspects that showed significant differences among their methods were selected as

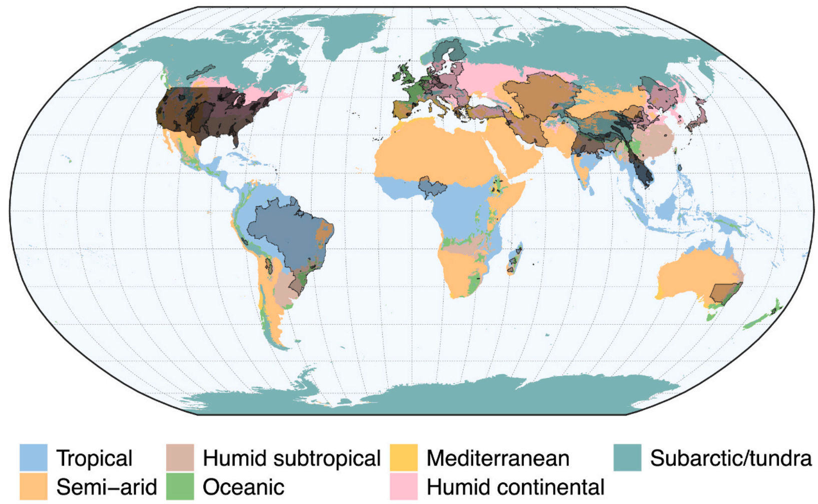

Fig. 1. Location of the 261 study areas and the climate zones (Beck et al., 2018). The study areas are projected on top of each other, where darker colours indicate repeated occurrences of the study area in the dataset.

robustness criteria to be used in the second step, where we determined the weight to be applied through an expert consultation.

To determine the weights to be applied to each robustness criteria, we asked a selection of expert authors to fill in a questionnaire (Supplementary Text S2) and assess the robustness (on a scale between 1 and 10) of each of the methodological aspects identified as robustness criteria. The selection of expert authors was based on the number of (co-)authored publications among the 224 publications that were obtained from the systematic review. We selected those authors who either (co-) authored at least three publications or (co-)authored at least two publications from which at least one as first author. A total of 60 authors met these requirements and were contacted to fill out the online questionnaire. The questionnaire was filled in by 19 experts originating from 12 countries (two authors did not provide their country), i.e. Spain (3), Italy (2), USA (2), Australia (1), Brazil (1), France (1), Kyrgyzstan (1), Netherlands (1), Northern Ireland (1), Poland (1), Portugal (1), and Wales (1). The majority of the experts were senior researchers (12), followed by postdoctoral researchers (4), environmental consultant (1), research associate (1), and one expert preferred not to say.

3. Results & discussion

3.1. Description of the dataset

The first two climate change impact assessments on soil erosion were published in 1995 (i.e. Asselman, 1995; Favis-Mortlock and Boardman, 1995), which is three years after the first climate change emission scenarios were defined, i.e. the IS92 emission scenarios (Leggett et al., 1992). A total of 224 studies were published since 1995 (Fig. S1). Between 1995 and 2009 only 20 studies were published. From 2010 onwards, the number of published studies per year started to increase, with a maximum of 39 in 2020. The majority of the studies were published as journal articles (206 out of 224 studies), from which the most common journals are listed in Table S4. Other studies were published as conference papers (14 studies) or as book chapters (4 studies).

The study areas are located in 51 countries (Fig. 1), not accounting for the transboundary studies (e.g. Yang et al., 2003; Panagos et al., 2017; Borrelli et al., 2020). The studies were performed in a total of 261 different study areas, with the majority located in the United States (Table S5). Most studies were performed in North America (28.1%), Asia (24.7%) and Europe (24.7%) (Fig. 2a and S2). The majority of the study areas are located in the humid continental climate zone (28.7%) (Fig. 2b and S3). The study areas are well-distributed among the other climate

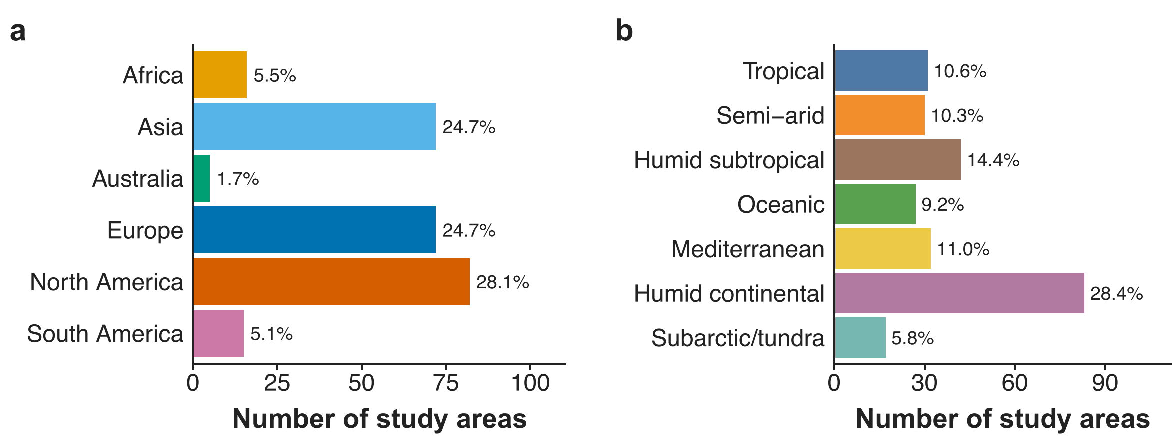

Fig. 2. Number of study areas per (a) continent and (b) climate zone.

zones, except for the subarctic/tundra climate zone (5.8%).

The largest study areas are obviously from the two global assessments (Yang et al., 2003; Borrelli et al., 2020). Other large study areas are Brazil (Almagro et al., 2017), Conterminous United States (Nearing, 2001; Segura et al., 2014; Biasutti and Seager, 2015), Europe (Panagos et al., 2017), Central Asia (Duulatov et al., 2019) and the Tibetan Plateau (Teng et al., 2018). Most studies were performed in large-scale study areas ($\geq$ 10,000 km^2; 35.8%), while smaller scale study areas were less common (Fig. S4). Before 2008 most studies were performed at the field-scale ($<$ 0.05 km^2), however, from 2017 onwards no studies were performed at this scale. This might suggest that there is a trend towards larger study areas.

Only a few studies (5.0%) use the first generation of emission scenarios, i.e. IPCC Scenarios 1992 (IS92; Leggett et al., 1992) (Fig. S5). The first studies that applied the second generation of emission scenarios, i.e. Special Report on Emissions Scenarios (SRES; IPCC, 2000), appear in 2005 and have been used until 2020. The SRES emission scenarios have the largest contribution among the three generations with 50.9%. The third generation of emission scenarios, i.e. Representative Concentration Pathways (RCP; Moss et al., 2008), were first applied in 2014 and are gradually replacing the SRES emission scenarios in soil erosion impact assessments.

When looking at the individual emission scenarios, it appears that RCP scenarios are more often applied than the SRES scenarios (Fig. S6). This means that the studies that apply the RCP scenarios more often consider multiple scenarios. The most applied scenarios are RCP8.5 (20.2%), RCP4.5 (16.9%), A2 (16.4%) and A1B (13.3%) (Fig. 3a). Most studies only apply a single climate model (41.3%) and the number of studies with larger ensemble sizes reduces (Fig. 3b and S7). However, still a fair share of studies (16.1%) apply an ensemble consisting of more than 9 climate models.

Only a small fraction (8.5%) of the studies do not apply downscaling (dynamical and statistical) or bias correction, while the largest share of studies apply both (37.1%) (Fig. 4a and S8). The majority of the studies that apply statistical downscaling use stochastic weather generators (65.9%), such as CLIGEN (Nicks and Gander, 1994), LARS-WG (Semenov and Barrow, 1997) and SDSM (Wilby et al., 2002) (Fig. S9). The number of studies that apply statistical downscaling is gradually decreasing. This is most likely linked to a decrease in the use of the SRES emission scenarios, where both the use of the SRES emission scenarios and statistical downscaling peak around 2016. While the SRES emission scenarios were available at a daily time step, most studies used the more common SRES climate data at a monthly time step, which required temporal downscaling for the application in soil erosion models with a (sub-)daily time step (Mullan et al., 2012). Because of the introduction of the RCP emission scenarios with daily time steps and the availability of dynamically downscaled Regional Climate Model data, the use of statistical downscaling is gradually decreasing from 2016 onwards. Delta change (or change factor (Chen et al., 2011)) is the most used bias correction method (65.5%; Fig. 4b and S10). Since 2014 other methods have increased in popularity, most notably quantile mapping (Themeßl et al., 2012) (26.8%) and since 2016 trend preserving quantile methods, such as detrended quantile mapping (Hempel et al., 2013) and scaled distribution mapping (Switanek et al., 2017).

On average the reference periods are centred around the year 1990, with a mean period of 26.4 years. The future periods are evenly distributed among near-century (27.5%), mid-century (41.1%) and end-century (31.4%) (Fig. S11). The future periods have a mean period of 23.7 years.

MUSLE (Williams, 1995) is the most applied soil erosion model (81 studies; Table S6), from which the majority are studies that apply MUSLE implemented in the SWAT model (Arnold et al., 2012). Other common models are RUSLE (Renard et al., 1997) (40 studies) and WEPP (Nearing et al., 1989) (23 studies). A total of 35 different soil erosion models have been applied. Most studies apply a model forced by runoff (42.4%; Fig. S12), from which the majority are those studies that apply the MUSLE erosion model. Almost a quarter of the studies apply soil erosion models forced by precipitation and runoff (23.7%) and the remaining studies (33.9%) were forced only by precipitation. The majority of the studies apply a soil erosion model that runs on a daily time step (63.7%; Fig. S13). Most studies report hillslope erosion (41.5%) to represent soil erosion, which is followed by sediment yield (35.3%; Fig. S14).

A total of 34 studies apply future land use change scenarios in combination with projected climate change, from which 25 are from 2015 onwards (Fig. S15). The majority of these studies (54.3%) apply a land use model to obtain the future land use maps. The most popular models are the CA-Markov model (Sang et al., 2011), CLUE-S (Verburg et al., 2002) and Land Change Modeler (Eastman and Toledano, 2018). Other common methods are based on linear extrapolation of historical trends (20.0%) and through stakeholder consultation (14.3%). The most common land use scenarios are agricultural expansion (38.2%), reforestation (20.0%) and agricultural abandonment (20.0%; Fig. 5a and S16).

A total of 43 studies evaluate the effectiveness of soil conservation practices to reduce soil erosion under climate change (Fig. 5b and S17). The most common evaluated practices are structural measures (26.8%), no tillage (25.0%) and conservation tillage (23.2%). Structural measures include terrace construction, hedgerow planting and buffer strips. Sustainable agriculture (14.3%) includes crop rotation, strip and double

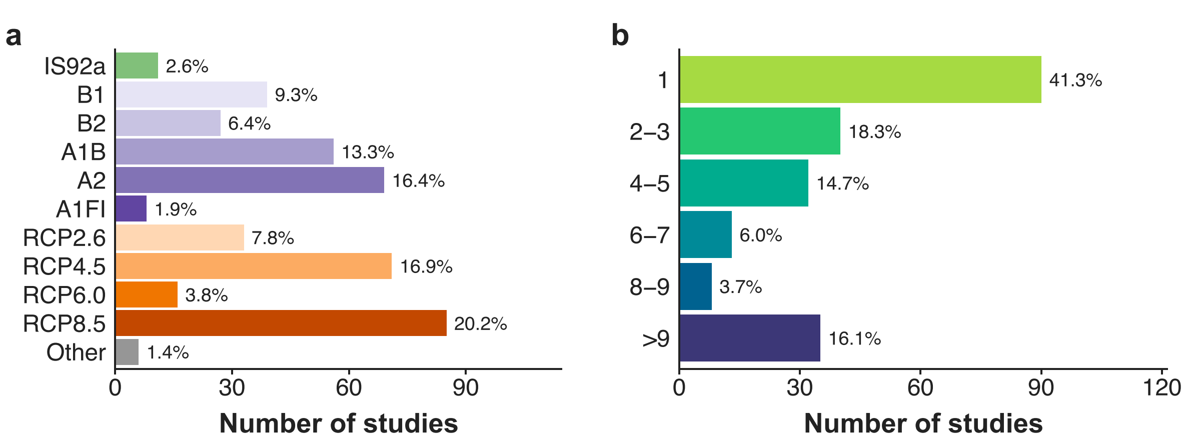

Fig. 3. Number of studies per (a) emission scenario and (b) climate model ensemble size class.

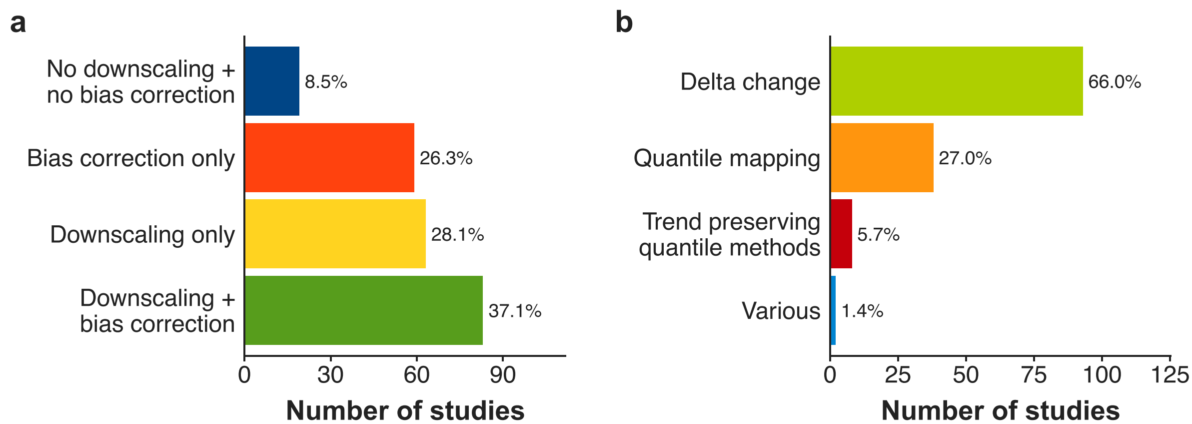

Fig. 4. Number of studies (a) that apply downscaling and bias correction, and (b) per bias correction method.

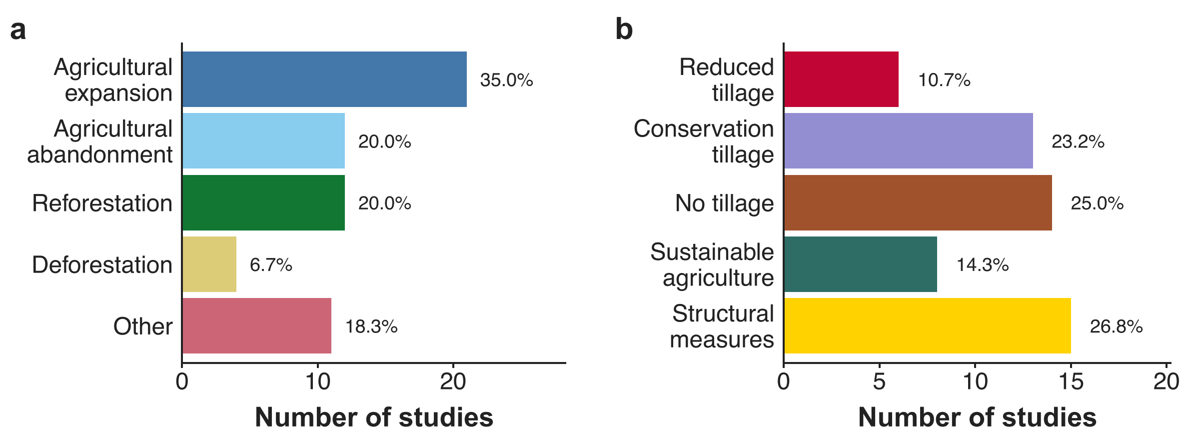

Fig. 5. Number of studies per (a) land use scenario, and (b) soil conservation practice.

cropping, organic farming and cover crops. There is generally an increasing tillage intensity from no tillage, to conservation tillage and reduced tillage.

3.2. Impact of methodological aspects on soil erosion projections

We identified and categorized ten methodological aspects related to the uncertainty of the applied methodology to assess the impacts of climate change on soil erosion. Here we show how soil erosion projections are affected by these methodological aspects. We also indicate which methodological aspects show significant differences in the projected changes in soil erosion and were, therefore, used to determine the robustness of each study.

Study area size - Field-scale studies generally show higher increase in soil erosion (+19.5%) than those studies performed in larger study areas (+5.1 to +11.8%), however, no significant differences were found among the study area size classes (Fig. S18; *not included*).

Generation of emission scenarios - The three generations of emission scenarios are significantly different, with most increase projected by the IS92 studies (+38.3%), followed by the RCP (+11.6%) and SRES studies (+7.0%) (Fig. S19; *included*).

Emission scenarios - The highest change in soil erosion is projected with the IS92a scenario (+38.3%), followed by the A1FI scenario (+28.9%) (Fig. S20). There are a few significant differences between the individual scenarios. Scenario IS92a (+38.3%) is significantly different from A1B (+4.8%), A2 (+4.5%), B1 (+8.2%) and B2 (+11.3%). More interestingly, there are no significant differences between the scenarios from the same generation of emission scenarios, i.e. within the SRES family (A1B, A1FI, A2, B1 and B2) and within the RCP family (RCP2.6, RCP4.5, RCP6.0 and RCP8.5). Because of the limited number of significant differences between the scenarios, we decided not to include the climate scenarios as a robustness criteria in the questionnaire (*not included*).

Climate model ensemble size - The size of the climate model ensemble shows significant differences between the classes, for instance, between a size of 1 (+14.3%) and 2–3 (+5.1%) (Fig. S21; *included*).

Application of downscaling and bias correction - Most increase in soil erosion is projected by studies that apply bias correction only (+15.2%), while studies that do not apply downscaling or bias correction project a decrease in soil erosion (−1.7%) (Fig. S22). The latter category is significantly different from the other three categories, while there are also significant differences between studies that apply bias correction only and studies that apply downscaling and bias correction (*included*).

Bias correction methods - Most increase in soil erosion is projected by studies that apply trend preserving quantile methods (+37.0%), followed by quantile mapping (+20.0%) (Fig. S23). Significant differences are shown between delta change and the two other methods (*included*).

Statistical downscaling methods - No significant differences are found between the statistical downscaling methods (Fig. S24; *not included*).

Soil erosion model concepts - Soil erosion is projected to increase most with models that are forced by precipitation and runoff (+17.5%) and least with models that are forced by runoff only (+5.4%) (Fig. S25). Studies that are forced by runoff are significantly different from the other two model concepts (*included*).

Soil erosion model time step - Small and insignificant differences in soil erosion projections are shown between the time step classes (Fig. S26; *not included*).

Output variables - Studies that calculate the rainfall erosivity show the largest relative increase (+18.5%), followed by hillslope erosion (+11.1%) (Fig. S27). Rainfall erosivity is significantly different from sediment yield and suspended sediment (*included*).

Based on the identified significant differences between methodological aspects we identified the following six robustness criteria

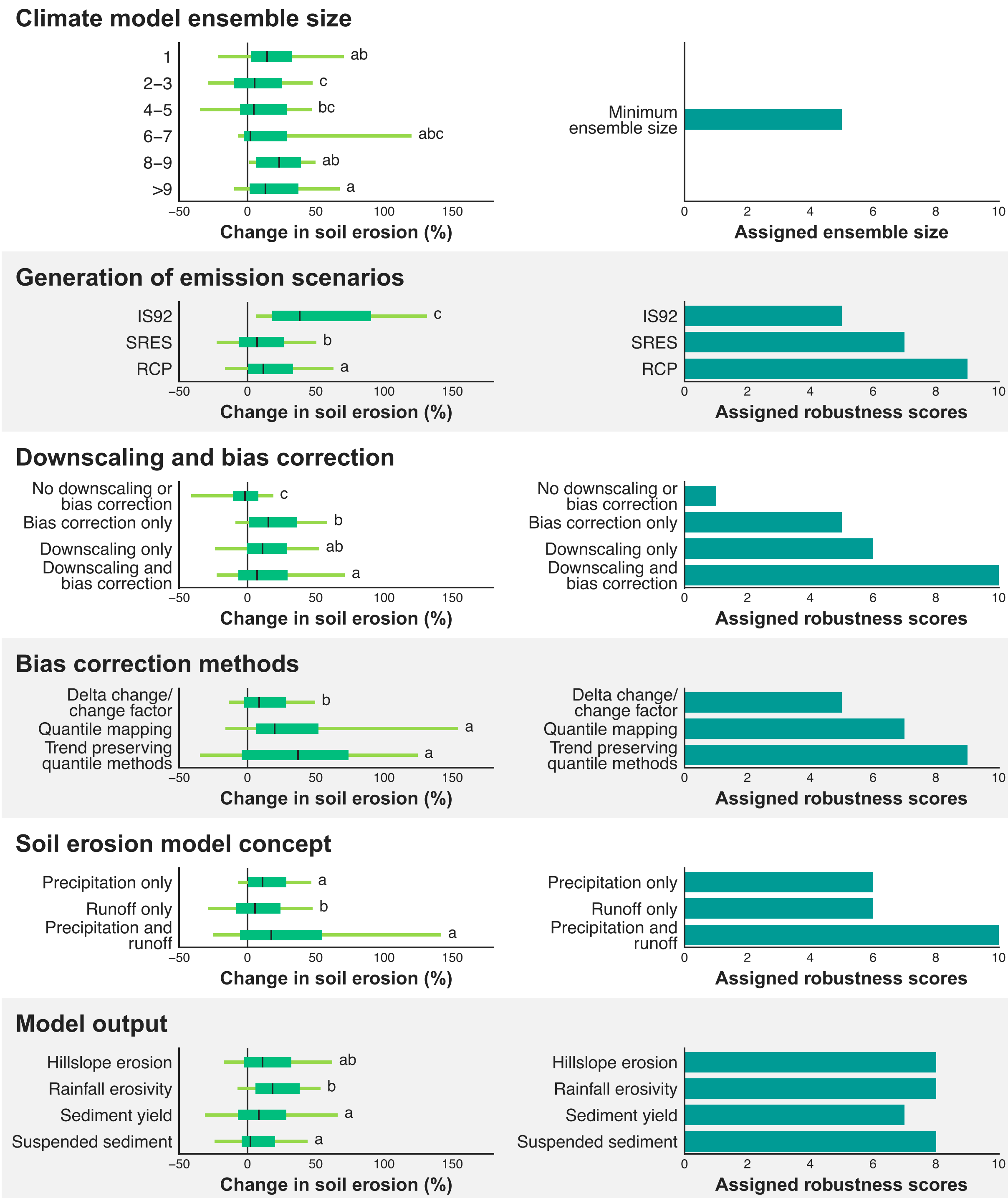

Fig. 6. Change in soil erosion (%, left) under climate change for the six robustness criteria. The colored boxes indicate the inter-quantile range (25th and 75th percentiles), the black line the median (50th percentile) and the whiskers extend to the 10th and 90th percentiles. The box-plots followed by a common letter are not significantly different by the Wilcoxon rank-sum test at the 5% level of significance. Assigned ensemble size and robustness scores (right) for the six robustness criteria obtained from the questionnaire.

(Fig. 6):

- Generation of emission scenarios
- Climate model ensemble size
- Application of downscaling and bias correction
- Bias correction methods
- Soil erosion model concepts
- Output variables

These 6 robustness criteria were subsequently used to determine the robustness of each study through an online questionnaire (Fig. 6). According to the response to the questionnaire the minimum size of the climate model ensemble required seems normally distributed around the median value of 5 (Fig. S28). The first generation of emissions scenarios was considered least robust (IS92; median robustness score of 5), followed by the second (SRES; 7) and the last generation (RCP; 9; Fig. S29). The application of downscaling and bias correction showed most consensus among the results of the questionnaire, where the application of both methods was assigned the maximum robustness score (10) and the application of neither of the two methods was assigned the lowest robustness score (1; Fig. S30). The application of only downscaling was assigned a slightly higher robustness score (6) than the application of only bias correction (5). Bias correction methods showed an increasing trend from delta change/change factor (5) to quantile mapping (7) and trend preserving quantile methods (9; Fig. S31). Models that are forced by precipitation and runoff were assigned the highest robustness score (10), while models forced by either precipitation or runoff were assigned the same robustness score (6; Fig. S32). The output variables showed least consensus among the results of the questionnaire (Fig. S33). Suspended sediment was assigned a slightly lower robustness score (7) than the other three output variables (8).

The robustness scores obtained from the questionnaire were used to determine the weights per study. Studies that apply a climate model ensemble size of five or higher (the median value from the questionnaire) were assigned a weight of 1. The weights were then linearly extrapolated to climate model ensemble sizes smaller than five, i.e. 0.8 for an ensemble size of four, 0.6 for an ensemble size of three, 0.4 for an ensemble size of two, and 0.2 for an ensemble size of one. The robustness scores of the other five robustness criteria were divided by the maximum score per robustness criteria to obtain the weights. Per study, we obtained six weights (one for each of the six robustness criteria), from which we determined the average to obtain a single weight per study. The weights were normalized over the range 0–1 and are presented in a separate table (Supplementary Table 3).

3.3. Increased soil erosion under climate change

Soil erosion is projected to increase with 10.0% (weighted median) in the 21st century, considering all studies, periods and emission scenarios and accounting for the robustness of each study based on the methods applied (Fig. 7a). This projection is considerably lower than a recent global estimate of future soil erosion projections (+40.9 to +56.4%; Borrelli et al., 2020), not considering the change in soil erosion by land use change herein, but similar to the projections by Yang et al. (2003), which projects a 9.0% increase. There is, however, high variability among the soil erosion projections, which range between −76% and 605% (Fig. S34). Most studies project an increase in soil erosion, with the weighted interquartile range extending from −2.9% to 32.4% (for the 25th and 75th quartiles, respectively). While the average robustness considering the six robustness criteria of all studies is relatively low (average normalized weight of 0.51), the most robust studies are also found to project both an increase and a decrease in soil erosion,

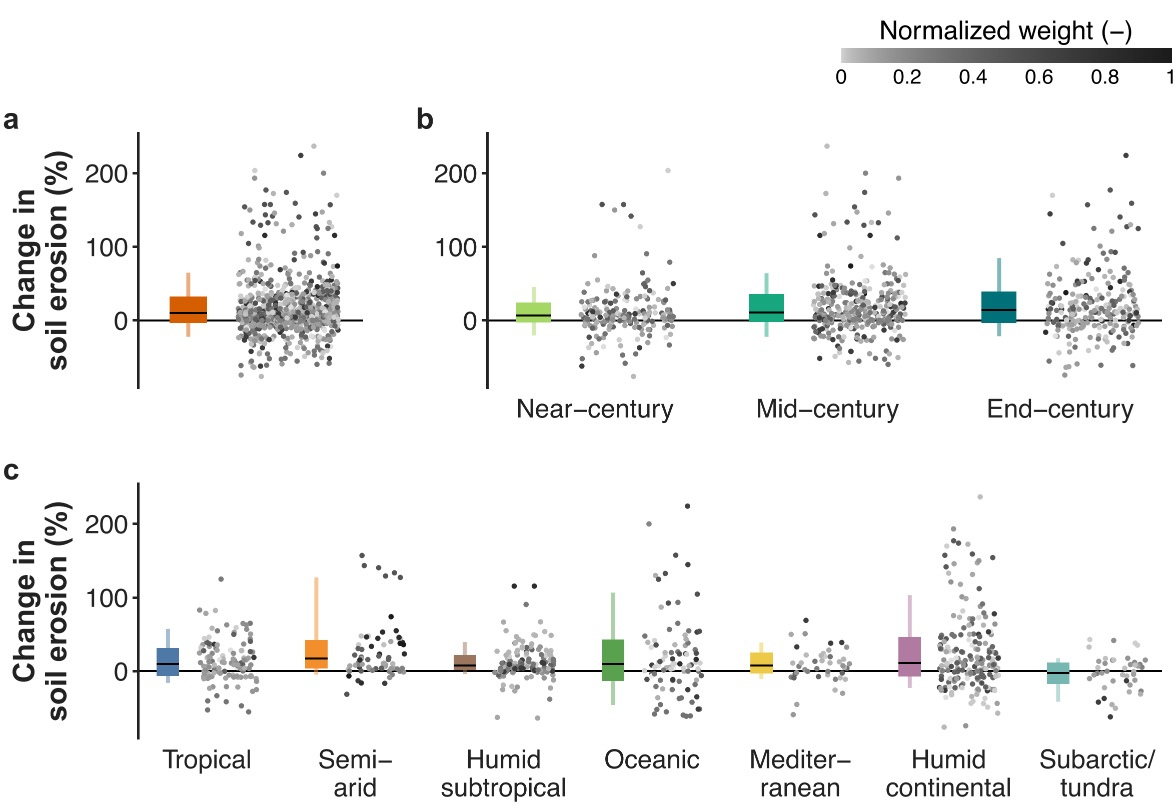

Fig. 7. Projected change in soil erosion (%) (a) considering all studies, (b) per future period, and (c) per climate zone. The colored boxes indicate the weighted interquartile range (25th and 75th percentiles), the black horizontal line the weighted median (50th percentile) and the whiskers extend to the weighted 10th and 90th percentiles. The jitter plot shows the projected change in soil erosion per study, considering the different study areas, periods and emission scenarios. The grey shades indicate the robustness of the studies, quantified with the normalized weight. For clarity, the figures are truncated at 240%, the full dataset is shown in Fig. S34-S36.

which gives further confidence in the weighted soil erosion projections.

An increasing trend in soil erosion is projected towards the end of the century (Fig. 7b), with an increase of 6.7% for the near-century to 14.2% for the end-century. Not surprisingly, the variability among the soil erosion projections also increases towards the end of the century, which is reflected by the increase in the weighted interquartile range and differences between the weighted 10th and 90th percentiles (i.e. the whiskers in Fig. 7b).

Soil erosion is projected to increase most in semi-arid climate zones (+17.3%) and is projected to slightly decrease in subarctic/tundra climate zones (−2.8%; Fig. 7c). The other climate zones project a similar increase in soil erosion, between 7.4% and 11.2%. The humid subtropical zone shows least variability among the different soil erosion projections, while the humid continental and oceanic climate zones show the largest difference within the weighted inter-quantile range. More robust studies are performed in the semi-arid climate zone (average normalized weight of 0.63). Less robust studies are performed in the subarctic/tundra climate zones (average normalized weight 0.44), where the few robust studies, that all project a decrease in soil erosion, cause the weighted median to be slightly negative.

Soil erosion is projected to increase in all continents (Fig. S37), with the largest projected increase in Australia (+21.5%). While only few studies are performed in Australia, it is the continent with relatively most robust studies (average normalized weight of 0.67). Soil erosion is projected to increase less in South America (+1.1%). While soil erosion is projected to increase in Europe (+8.6%) and North America (+6.5%), a fair share of the study areas (34.6% and 34.0%, respectively) project a decrease in soil erosion in these continents. However, in both cases, more robust studies project an increase in soil erosion.

3.4. Land use change leads to opposing trends

Land use change can either lead to a further increase of soil erosion (agricultural expansion and deforestation) or a decrease (agricultural abandonment and reforestation; Fig. 8a). Agricultural expansion under climate change leads to the largest increase of 78.6% (weighted median) with respect to the reference soil erosion without climate or land use change. In contrast, agricultural abandonment and reforestation lead to a decrease of up to −52.5% of the soil erosion in the reference period and are, therefore, often suggested as conservation measures aiming to reduce soil erosion. There is considerable variation among the results (Fig. S38), especially considering agricultural expansion, where the relative increase in soil erosion differs several orders of magnitude among the studies.

Land use change has been considered to be one of the driving forces of soil erosion under climate change (Nearing et al., 2004; Favis-Mortlock and Mullan, 2011; Mullan et al., 2012; García-Ruiz et al., 2013). Here we confirm that land use change can have a significant impact, however, not in all cases causing an additional increase of soil erosion as suggested by previous studies. Nonetheless, current global land use change trends are characterized by increasing agricultural land cover and decreasing forest cover (Winkler et al., 2021). In addition, four out of the five global land use projections from the Shared Socioeconomic Pathways (SSP) foresee a continuation of these trends (Riahi et al., 2017), which would be associated with additional increase of soil erosion. Only the sustainability pathway (SSP1) projects an opposite trend in land use change and, hence, can be expected to result in reduced soil erosion rates.

Climate change is expected to have a significant impact on vegetation development (Peñuelas and Boada, 2003; Adams et al., 2017), including plant biomass (Tietjen et al., 2017), phenology (Cleland et al., 2007), root density, and species distribution (Peñuelas and Boada, 2003). These vegetation characteristics play vital roles in soil erosion processes, such as the separation of raindrops between leaf drip and throughfall, with a low and a high impact, respectively, and the effect of vegetation on surface runoff, affecting concentrated flow erosion (Morgan and Nearing, 2010). The few soil erosion impact assessments that account for vegetation development under climate change, apply regression equations to model the response of vegetation indices, such as the Normalized Difference Vegetation Index, on changes in climatic variables, including temperature and precipitation (Park et al., 2010; Eekhout et al., 2018; Zhang et al., 2019). Climate change can have a positive or negative impact on vegetation, depending on the projected change in climate conditions and resistance of plant species for change in climate conditions (Peñuelas et al., 2018). Due to this complexity and the importance to soil erosion, more research is needed to project future changes in vegetation cover, with the aim to account for these changes in soil erosion impact assessments (Nunes et al., 2008).

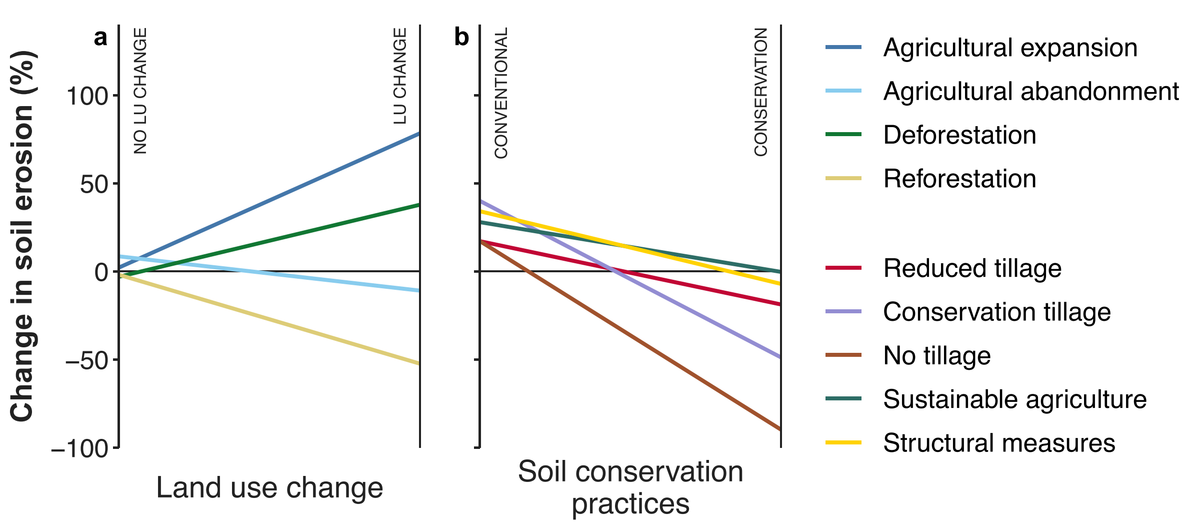

Fig. 8. Projected change in soil erosion (%) under climate change with respect to the reference period for (a) the main land use change scenarios (from no land use change to land use change) and (b) soil conservation practices (from conventional management to conservation management). Each line shows the weighted median change in soil erosion from Fig. S38 and S39.

3.5. Climate change adaptation through soil conservation

Soil conservation practices were mainly applied in studies where soil erosion is projected to increase under climate change with conventional agricultural practices (+17.2 to +40.1%), that is to say, in those studies with an identified need for climate change adaptation. All conservation practices reduce soil erosion to below the reference value without climate change (Fig. 8b). The three reduced tillage alternatives seem most effective to reduce soil erosion and show a gradient in efficiency, from reduced tillage (−18.8%), to conservation tillage (−49.0%) and no tillage (−90.0%). The other two conservation practices show a more moderate decrease, reducing soil erosion to around the reference value (i.e. 0%). Most consistent and robust results were obtained in studies that applied reduced tillage (Fig. S39). The results from the studies that applied structural measures show most variation, because of the range of conservation measures considered, which include terraces, hedgerows, and buffer strips, among others. These measures may all have a slightly different aim and implementation strategy, which affects the efficiency to reduce soil erosion under climate change. Besides, structural measures often aim to reduce the off-site impacts of soil erosion, without significantly reducing on-site hillslope erosion (e.g. Lanckriet et al., 2012).

Conservation measures not only aim to reduce soil erosion, but have additional benefits, such as increased carbon sequestration (West and Marland, 2002), and improved biological activity (Helgason et al., 2010), aggregate stability (Zotarelli et al., 2007) and overall soil quality (Almagro et al., 2016; Luján Soto et al., 2021). Currently, the relative share of conservation agriculture of total global cropland is estimated at 12.5%, with a clear increasing trend since the mid-1990s (Kassam et al., 2019). Whether this trend will persist into the future is very uncertain, where only the sustainability pathway (SSP1) of the Shared Socioeconomic Pathways explicitly assumes that sustainable agricultural practices will be implemented (O'Neill et al., 2017; Riahi et al., 2017).

3.6. The uncertainty cascade

There are multiple sources of uncertainty involved in the assessment of the impact of climate change on soil erosion, which is also known as the "uncertainty cascade" (Coulthard et al., 2012). This cascade includes emission scenarios, general circulation models, downscaling techniques, bias-correction methods, and soil erosion models (Coulthard et al., 2012; Mondal et al., 2015; Simonneaux et al., 2015; Garbrecht et al., 2016; Op de Hipt et al., 2018; Eekhout and de Vente, 2019b). While this has not yet been assessed in a soil erosion context, it is likely that a large share of the uncertainty originates from climate models and their post-processing, in a similar way as demonstrated in hydrological studies (Vetter et al., 2017). Especially the post-processing of climate model data is an important aspect of soil erosion impact assessments, due to the difference between spatial and temporal scale of General Circulation Models and the small temporal and spatial scale processes involved in soil erosion (Favis-Mortlock and Mullan, 2011; Mullan et al., 2012; de Oliveira et al., 2019).

In this systematic review, we identified and categorized ten methodological aspects related to the uncertainty cascade, from which six showed significant differences in projected change in soil erosion. Through an expert consultation we determined the relative importance of these six robustness criteria, from which four are related to the use and post-processing of climate model data. The results from the expert consultation showed that the minimum size of the climate model ensemble was suggested to be five, which is much higher than the ensemble size applied in most studies (Fig. 3). Most other variables show a gradient among their categories, from uncertain to robust, where more recent methodological advances (RCP emission scenarios, trend preserving quantile methods) and the involvement of multiple model concepts (models forced by precipitation and runoff) and post-processing methods (application of downscaling and bias correction) were valued as more robust.

From the obtained weights per study we can conclude that there is a lot of uncertainty in the methods applied, with an average normalized weight of 0.51 and without a clear trend towards more robust studies (Fig. 9). Partly this is due to the fact that more recently developed methods were considered more robust, which still lack large-scale implementation. On the contrary, the share of studies that apply a climate model ensemble smaller than five is still large, despite the fact that many studies have shown that the climate model ensemble size is one of the main sources of uncertainty in climate change impact assessments (Samaniego et al., 2017). The same holds for the delta change bias-correction method and the application of soil erosion models that only consider one forcing (i.e. precipitation or runoff), which are shown to have a significant impact on soil erosion projections (Eekhout and de Vente, 2019b, 2020). These findings suggest a large potential for improvement towards more robust soil erosion projections in climate change impact assessments.

Soil erosion models are at the end of the uncertainty cascade and their differences were considered here only by considering soil erosion model conceptualization (i.e. forced by precipitation, runoff or both). We could have used additional information from the studies to quantify the robustness of the soil erosion models. The results of model validation against observed soil erosion rates under current climate conditions would have been an ideal robustness criterion. Some studies provide this information, but many did not, and validation methods are very diverse between studies making them difficult to compare. It is also questionable if those validation results would have improved the results here, since a satisfactory model validation under current climate conditions does not guarantee consistent model performance under climate change. Eekhout and de Vente (2020) compared three soil erosion models, which gave similar results during model validation. However, when the three models were applied under climate change considerably different results were obtained from the three models, with a decrease projected by RUSLE and an increase by MUSLE and MMF. This to say, that even similar validation results do not guarantee similar response under climate change. Moreover, model validation may be obscured by the exclusion of important erosional processes, such as gully erosion and channel morphodynamics, which will affect validation results when using sediment yield data from the catchment outlet. In those cases, the model validation may be satisfactory for the wrong reasons (de Vente et al., 2013). While we do think that model validation is important, we did not account for soil erosion model validation as a robustness criterion for the assessment of the impacts of climate change, because of the absence of validation results in many studies, the validity of those results considering the impacts of climate change and the erosional processes considered by the models.

4. Conclusions

Based on a systematic review of 224 studies worldwide we conclude that soil erosion is projected to increase globally under climate change. The weighted median increase of 10% is similar to the single model global projection provided by Yang et al. (2003), but clearly lower than the single model projection by Borrelli et al. (2020). By building on the wealth of case studies worldwide and accounting for the uncertainty of the methods applied, we present findings from a large number of soil erosion projections considering the robustness of each study to account for uncertainty. An increasing trend of soil erosion is projected towards the end of the century that will lead to further land degradation, especially in semi-arid environments. The increase of soil erosion could be further aggravated by land use change characterized by agricultural expansion and deforestation. This stresses the urgent need for soil conservation and integrated land use planning aiming to reduce loss of fertile soil and related on- and off-site impacts for society. The review demonstrates that soil conservation practices, reforestation and agricultural abandonment are effective measures to reduce soil erosion

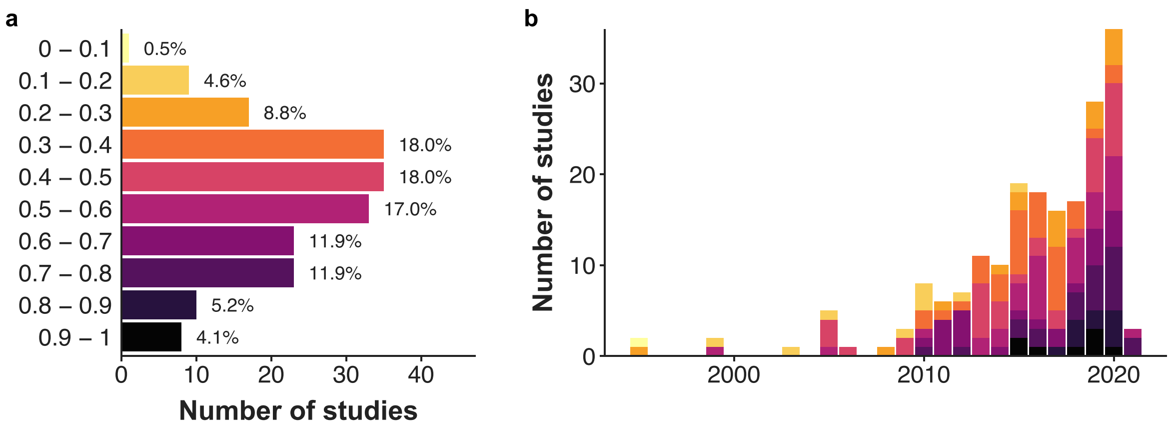

Fig. 9. (a) Number of studies per normalized weight class. (b) Yearly contribution of studies per normalized weight class.

under future climate conditions, often leading to erosion rates below reference conditions without climate change.

We identified six methodological aspects that significantly affect the assessments of climate change on soil erosion. Based on the results of a statistical analysis and an expert consultation, we recommend to consider the following methods when assessing the impact of climate change on soil erosion. A climate model ensemble of at least five climate models should be used, where the climate data originates from the latest CMIP6 climate scenarios, that provide a relatively high spatial and temporal resolution of projections, as compared to previous scenarios. The climate model data should be (dynamically or statistically) downscaled and bias correction should be applied, preferably using trend preserving quantile methods that are better suited to represent extreme events. The post-processed climate model data should be applied in a soil erosion model that is forced by both precipitation and runoff, accounting for the most relevant soil erosion processes. Considering most robust methodologies of the different aspects of the uncertainty cascade is fundamental for spatial evaluation of the impact of climate change on soil erosion and identification of most effective adaptation strategies.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.earscirev.2022.103921.

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