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Nature-based solutions' co-benefits beyond risk reduction: a review of assessment methods

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ABSTRACT

Nature-based solutions (NbS) can considerably reduce risks arising from weather extremes for society, and in addition provide multiple societal and environmental co-benefits. NbS are typically designed by the public sector, but the private sector, such as the financial sector, could also contribute to the finances needed to enable NbS uptake. However, a barrier to these investments and NbS implementation is the challenge to quantify NbS co-benefits. Through a systematic literature review, we investigate the methods available for evaluating co-benefits of NbS, beyond risk reduction. We examine their strengths and weaknesses in order to assess their applicability in the broader context of nature-based insurance and investment solutions. The review identified several (economic and non-economic) methods available that can provide a (semi-)quantitative assessment of co-benefits, with different levels of overall effort and knowledge requirements. The study showed there is no single method that is widely used to assess a specific co-benefit or NbS. Critical aspects of NbS co-benefits assessment arise from the temporal and spatial scales covered, and data availability. Previous work has been predominantly context-specific and applied to specific cases, but in principle the methods applied are replicable and scalable to different contexts. Most of the methods showed the possibility of identifying multiple co-benefits and dealing with possible disbenefits. A key limitation identified in the reviewed papers is the lack of consideration of impacts of future climate change on the NbS. We discuss challenges and advantages of the applied methods to facilitate the integration of a more comprehensive assessment of NbS co-benefits in a broader context that could help to overcome some issues and strengthen a robust evidence base for NbS performance.

1. Introduction

Nature-based solutions (NbS) can play a significant role in reducing the impacts of weather extremes and climate change on society. Thereby, NbS support adaptation strategies by providing a wide range of co-benefits, such as recreational areas, increasing social cohesion, and promoting educational and physical activities, enhancing human health and well-being [1]. NbS also support sustainable economic growth by generating employment, fostering innovation, and enhancing resource efficiency [2]. Because of their primary- and co-benefits, NbS are promoted to support transition to a sustainable and climate-resilient society in many international and European policy ambitions [3–7]. However, NbS still face sizeable challenges and barriers to their adoption and implementation. These range from limited expertise of NbS, insufficient evidence of its performance and co-benefits, social and governance challenges and institutional or structural obstacles in policies and legal frameworks, to misperception, maintenance concerns and economic and financing barriers [8]. More specifically, with regard to financing, the UNEP State of Finance of Nature report states that investments in NbS need to at least triple to meet targets for climate

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change, biodiversity, and land degradation [9].

The quantification of NbS co-benefits has potential to make NbS more attractive than traditional risk-reduction and climate change adaptation measures, such as engineering or grey approaches, including dams, levees, dikes, stormwater drainage systems, and coastal hard defences such as seawalls and breakwaters. This could help to inform decision-making processes and public sector investments in NbS. Moreover, insurance and insurance-linked investments have the potential to support NbS implementation contributing to filling the financial gap between current investment levels and the needed scale of finance identified by UNEP [10,11]. The interest of the (re)insurance industry in NbS has increased, particularly in relation to their capacity to reduce the intensity of climate-related hazards, especially frequent and small-scale events, such as heavy rainfall events or heatwaves in urban areas [12, 13]. If NbS contributes to lower natural disaster losses, then this may improve the insurability of natural disaster risk at affordable premiums. Ensuring long-term ecosystem functionality, protecting nature assets for future generations and enhancing broader socio-economic resilience could be relevant co-benefits for insurance that go beyond the immediate risk reduction value of NbS. The potential for risk reduction through NbS, coupled with their co-benefits, could make it beneficial for insurance companies to participate in NbS development in collaboration with governments.

Still, despite the growing interest and recent developments in hazard modelling and economic evaluation of NbS for climate risk [13–16], their uptake in the (re)insurance sector - such as through capital investment - remains limited [17]. There are gaps and limitations in the available methodologies for assessing NbS effectiveness and their dynamic nature over time, particularly in view of the impacts of future climate change [18]. Additional barriers to the financing and uptake of NbS likely include the relative lack of experience in implementing NbS, with limited monitoring activities of this impact and subsequently scarcity of data on costs or damage reduction. Despite the existence of frameworks and tools that provide useful guidance, such as the IUCN Global Standard for Nature-based Solutions and related self-assessment tools [19], co-benefits and disbenefits are often overlooked in studies and not always considered in the decision-making process to design, implement, or assess NbS projects. This can lead to underinvestment in NbS and distort the true environmental, social, and economic impacts and value they deliver [20,21].

In context of these obstacles, this paper explores the available methods for assessing co-benefits of NbS, in order to identify challenges and opportunities for their applicability in a broader context, including for the financial sectors. We conduct a systematic literature review to provide an overview and mapping of the methods available to assess the environmental, social, and economic co-benefits of NbS beyond disaster risk reduction, by examining the strengths and weaknesses for their usability and usefulness. In addition to improving understanding of the co-benefits of NbS, the review identifies methodological gaps and data requirements, as well as opportunities to combine assessment approaches to better capture their multidimensional value. In doing so, the paper sheds light on how co-benefit assessment can inform investment and financing schemes. This helps to align financial mechanisms with the full range of benefits and beneficiaries generated by NbS.

2. Methods

We conducted a systematic review of the peer-reviewed literature, focusing on studies evaluating NbS for climate change adaptation and disaster risk reduction. Although we acknowledge the relevance of grey literature in the context of NbS assessment, the review was restricted to peer-reviewed scientific publications to ensure transparency, replicability, and comparability in the selection and assessment of studies, and to focus on methods that have undergone academic peer review. Research on NbS and disaster risk reduction has expanded considerably in recent years [13,22,23]. In particular, there has been growing interest in improving applied flood risk modelling for the insurance sector [16, 18,21,24]. We build on the previous work and focus the scope of our review on the co-benefits of NbS in disaster risk reduction, to strengthen the evidence of NbS compared to more traditional engineering solutions, including from a financing and insurance perspective.

The review protocol for conducting the search is detailed in Staccione et al. [25]. We selected a set of keywords covering five areas: nature-based solutions, risk reduction, disasters, co-benefits, and methods. The full list of keywords is provided in the Supplementary Material (Section A). The keywords were combined in a single search query using the "AND" operator. Scopus and Web of Science were used as search databases (search field: title-abstract-keywords). We restricted the review to journal articles published in English from January 2005 to March 2026. The defined timespan refers to the initial definition of ecosystem services as the benefits that people can obtain from nature [26], and the successive development of related concepts, including nature-based solutions and co-benefits. We did not limit the scope of the review to any geographical area, spatial scale, or ecosystem type.

We searched for studies describing the design, implementation, or use of nature-based approaches primarily aimed at reducing climate-related hazards and disasters, across various scales and ecosystems (NbS for disaster risk reduction (DRR) - see Fig. 1). These can include, for instance, floodplain restoration or urban water retention measures to reduce flood risk, reforestation and urban parks to mitigate heat waves, or sustainable forest management practice to reduce wildfire. In addition, eligible studies must comprehensively assess the ancillary effects of NbS beyond risk reduction, such as improving biodiversity and habitat quality, offer recreational opportunities and enhance health and well-being, support economy and sustainable development (no DRR assessment only - see Fig. 1). These effects, whether environmental, social and economic, can be either positive (co-benefits) or negative (disbenefits). Finally, the studies should present models, methods, and metrics to quantitatively assess the effectiveness of co-benefits from an environmental, economic and social perspectives (quantitative co-benefit assessment - see Fig. 1).

From the selected papers, we extracted information on co-benefits, NbS, hazards, scales, ecosystems analysed and the methods used to assess co-benefits and/or disbenefits. Methods were grouped into eight categories: 1) field sampling and observations, i.e. methods that involve the direct collection of data, through physical samples of water, soil,

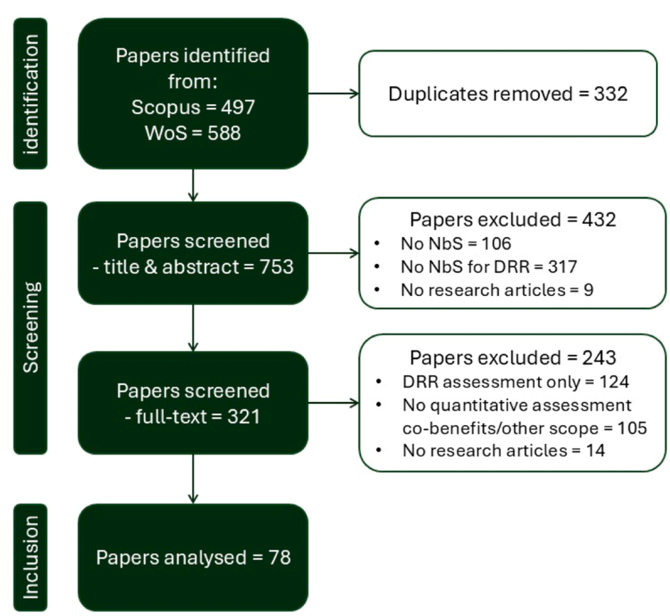

Fig. 1. Paper screening workflow applied in the systematic literature review process.

flora, fauna or their direct observation in the field (e.g. count of species), or through satellites and sensors; 2) models, i.e. methods that simulate or reproduce behaviours, status, changes and scenarios based on mathematical representation; 3) software and tools, i.e. methods based on ready-to-use software, tools or packages to analyse information, run models, simulate behaviours and scenarios; 4) statistical analysis, i.e. methods that analyse data to estimate, compare and link ecological parameters with the benefits provided; 5) stakeholder engagement, i.e. methods that engage key stakeholders (as users, decision makers, technical experts) through questionnaires, surveys, interviews and workshop; 6) multi-criteria decision analysis (MCDA), i.e. methods that use a multi-criteria decision approach, usually in combination with stakeholders engagement, to evaluate and rank solutions and benefits; 7) literature and desk review, i.e. methods that collect data and information from already existing, registered and published records and knowledge; 8) economic methods, i.e. mainly valuation methods (such as contingent evaluation, choice experiment, hedonic price, replacement cost) and cost-benefit analysis used to assess co-benefits in monetary terms.

For each category of methods, the reviewed papers were compared against five different criteria, which are overall effort and knowledge requirements, replicability and scalability in terms of scales and locations, suitability for assessing multiple co-benefits and disbenefits, inclusion of any climate change considerations (e.g. used for ex-ante and/or ex-post evaluations) or climate change scenarios. These criteria were selected to explore the broader potential of these methods, considering different perspectives, and key needs from the literature on NbS effectiveness [13,27–30]. They also align with some of the IUCN Global Standard for NbS [19]. By reading the papers, we examined how the methods were discussed and applied in relation to the evaluation of NbS co-benefits. For each method category, we extracted information on its application context and the type of co-benefits assessed. We also considered the effort required in terms of data needs, infrastructure (software, hardware, and tools), costs (time, financial, and human resources), and the level of expertise and knowledge required. Finally, we assessed spatial and temporal applicability, the ability to capture multiple co-benefits and disbenefits, and the consideration of future climate change. Based on this information, we carried out a comparative assessment of the method categories. Ratings were assigned as relative qualitative scores (low, medium, high), comparing each method category with the others included in the review, rather than as absolute performance scores. A “low” rating indicates limited applicability or relevance for a given criterion across the reviewed studies; a “medium” rating indicates moderate or context-dependent applicability; and a “high” rating indicates that the method was frequently or strongly associated with that criterion in the reviewed literature. To reduce subjectivity, the ratings were based on the evidence extracted from the reviewed papers and discussed among the authors. The assessment was further supported by consultation with multidisciplinary partners and experts within the EU project NATURANCE (www.naturance.eu), including specialists in NbS, flood modelling, finance, economics, and climate change adaptation, particularly to validate the interpretation of the methods’ practical usability and relevance for NbS financing and implementation.

3. Results

Applying the eligibility criteria, 78 papers were selected for review from the initial set of 753. The list of reviewed papers is available in the Supplementary Material (Section B).

3.1. Mapping of papers and methods

The number of papers has increased over time, with most of them being published in the last 10 years, and a significant increase since 2021. The papers cover case studies in North America (25), South and Central America (8), Europe (31), Asia and the Pacific (21) and Africa (4), with one paper focusing on global coastal areas (see Supplementary Material).

Most of the papers present case studies at the local (33%), river basin (29%) and regional scales (21%) in freshwater (33%), urban (22%) and forest (21%) ecosystems, and primarily address flood risk (54%), followed by wildfire risk (13%) (Fig. 2). Fig. 2 also provides an overview of the NbS, the co-benefits studied and the assessment method used. In line with the hazards and scales investigated, the case studies mainly analysed the implementation of natural water retention measures, such as the creation of natural ponds (14%) to collect and store rainwater runoff, the renaturation of rivers and the revegetation of riverbanks (13%), the restoration of wetlands (10%) and floodplains (5%). Secondly, we found forest fuel treatments (9%), such as forest biomass control and management, and urban nature-based solutions, including the creation of green spaces and tree planting (9%), urban retention measures (e.g. rain gardens, bioswales and permeable pavements - 9%) and green roofs and walls (6%). The co-benefits predominantly assessed are carbon sequestration (14%), biodiversity (10%) and habitat quality (8%), followed by economic and monetary benefits (7%), primary resource production (7%) and support for recreational activities (7%). Modelling approaches are the most frequently used for the assessment of co-benefits (23%), followed by stakeholders’ engagement (16%), literature/desk review (14%) and field sampling and observation (14%). Generally different methods are applied in different phases of analysis. For instance, field sampling methods are used to collect data to assess the status of an ecosystem, including before and after a nature-based intervention. These outcomes are then used to run a model to simulate future changes that can be validated in combination with stakeholders’ engagement methods.

The use of methods is spread across several world regions (Fig. 3). In Europe and South and East Asia, studies on NbS co-benefits most often apply modelling (EU 23%, Asia 18%) and stakeholder engagement (EU 20%, Asia 18%). In North America and the Caribbean, modelling (27% and 29% respectively) and literature and desk reviews (23% and 29% respectively) are the most common. In Africa, there is only one study in Kenya, that looked at the economic co-benefits of mangroves conservation for coastal flood protection [31]. Additionally, in South and East Asia statistical analysis (18%), field sampling (15%) and desk review (15%) are also widely used. Not shown on the map is the one study that focuses on global coastal areas, which evaluates mangroves conservation through the use of a global ecosystem dataset of (literature/desk review) and statistical analysis [32]. A detailed map showing the methods used per country is provided in the Supplementary Materials (Section C).

The Sankey diagram in Fig. 4 illustrates the relationships between methods (left column), co-benefits assessed (middle column) and nature-based solutions analysed (right column). Stakeholder engagement approaches are frequently applied to explore different co-benefits, especially for cultural and socio-economic benefits. Field sampling and observation are most commonly used to assess environmental benefits. But, overall, all co-benefits are assessed using multiple methods, there is no prevalent method used to assess one particular co-benefit or NbS. Similarly, there is no strict relationship between co-benefits and nature-based solutions. Each category of NbS is associated with a number of benefits, although social and cultural benefits seem to be analysed mostly in urban and river interventions (both for water quality and quantity), while habitat quality and biodiversity are more often associated with natural environments rather than urban ecosystems. It is common that different approaches are used to model the diverse and multiple co-benefits generated by similar NbS in the same city [33–35] or region [36,37]; and [38,39].

Few of the studies reviewed also included the assessment of disbenefits. These are mainly associated with urban NbS, water retention ponds and fuel treatments. In particular, they include the increase in carbon emissions associated with cutting large trees [40], the risk of

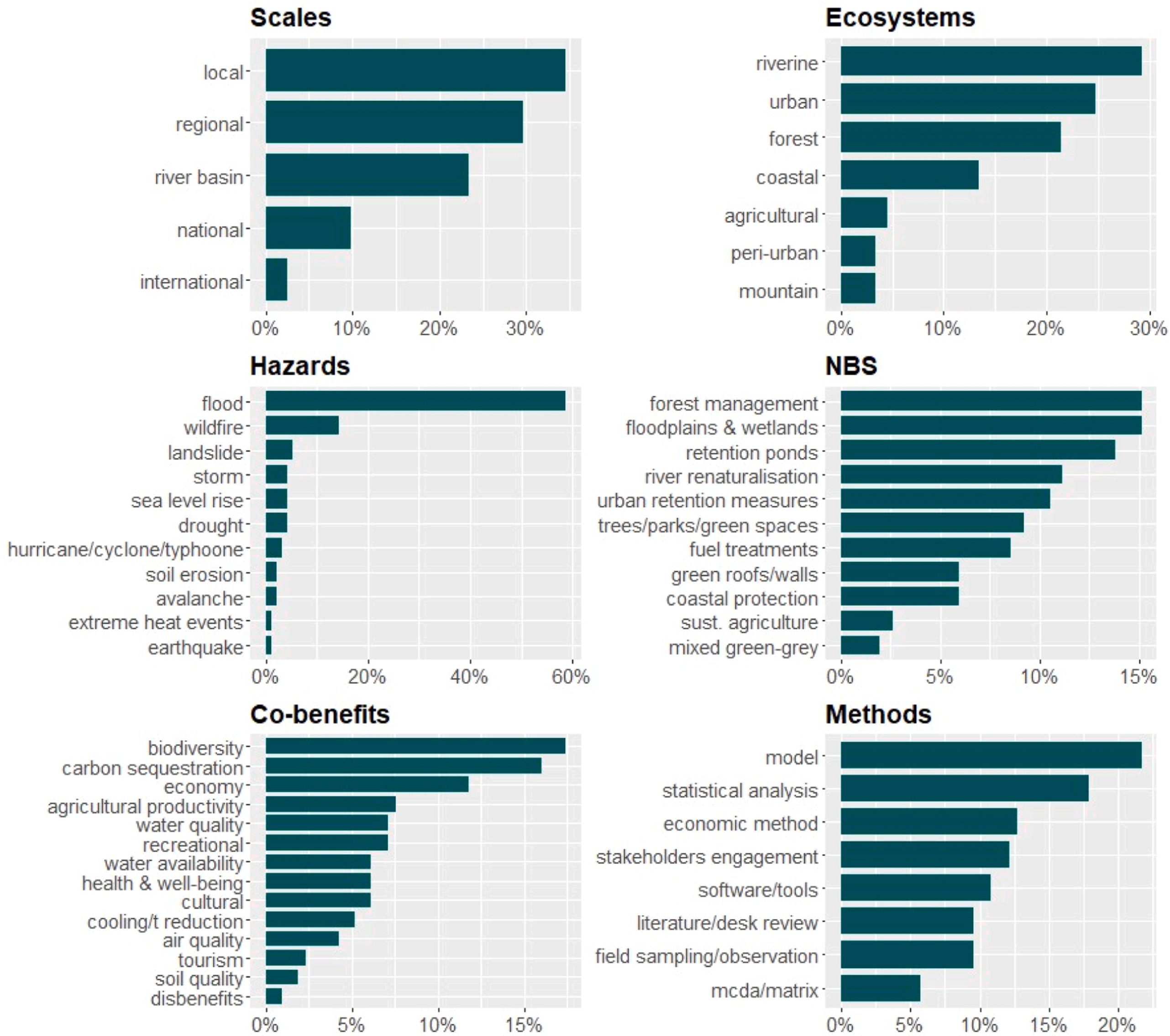

Fig. 2. Bar plots representing the percentage of cases in the reviewed of papers by spatial scale, ecosystem type, hazard addressed, NbS type, co-benefit assessed, and assessment method used.

human safety, the spread of mosquitos and allergens, the maintenance costs and efforts, the increase in housing prices, mobility issues, the loss of cultural heritage and the reduction in sustainability and resilience potentially associated with urban green interventions [41]. They are mainly assessed through modelling, desk and literature reviews, statistical analyses, and stakeholder engagement.

3.2. Methods assessment

Table 1 summarises the assessment of methods, according to the defined criteria: overall efforts and expertise required, suitability across scales and/or different locations, multiple co-benefits, disbenefits, future climate change. Each criterion aggregates multiple dimensions of information that were first assessed individually based on the evidence from the literature, and then synthesised into a single rating to enhance clarity and support the practical comparison of methods.

The criterion '*overall efforts and expertise required*' considers the higher or lower requirements in terms of input data, infrastructure (software, hardware, and tools), costs (money, time, and people), expertise and knowledge (technical skills, local and scientific knowledge about the sites and solutions studied) needed to apply the different methods. '*Suitability across scales and/or different locations*' examines the feasibility of applying the same method in different locations, ecosystems, regions or at different spatial scales (high) as opposed to defining site-specific procedures, methods and frameworks (low). The criterion '*multiple co-benefits*' and '*disbenefits*' explores the ability of methods to assess multiple co-benefits at the same time, including disaster risk reduction benefits, and the ability to capture negative or unintended effects (high) compared to assessing of a single benefit at a time (low). Finally, the '*future climate change*' criterion inspects whether the co-benefit assessment methods have been used to consider future climate change scenarios (high) or whether there is limited or no application in the literature (low).

To support the comparative assessment, the following sections provide a detailed discussion of each method category, including its main characteristics, application context, opportunities, and barriers. A summary table including a short method description and potential applications of methods for NbS co-benefits assessment can be found in the Supplementary Materials (Section C).

3.2.1. Field sampling and observations

Field sampling and observations are commonly employed to assess

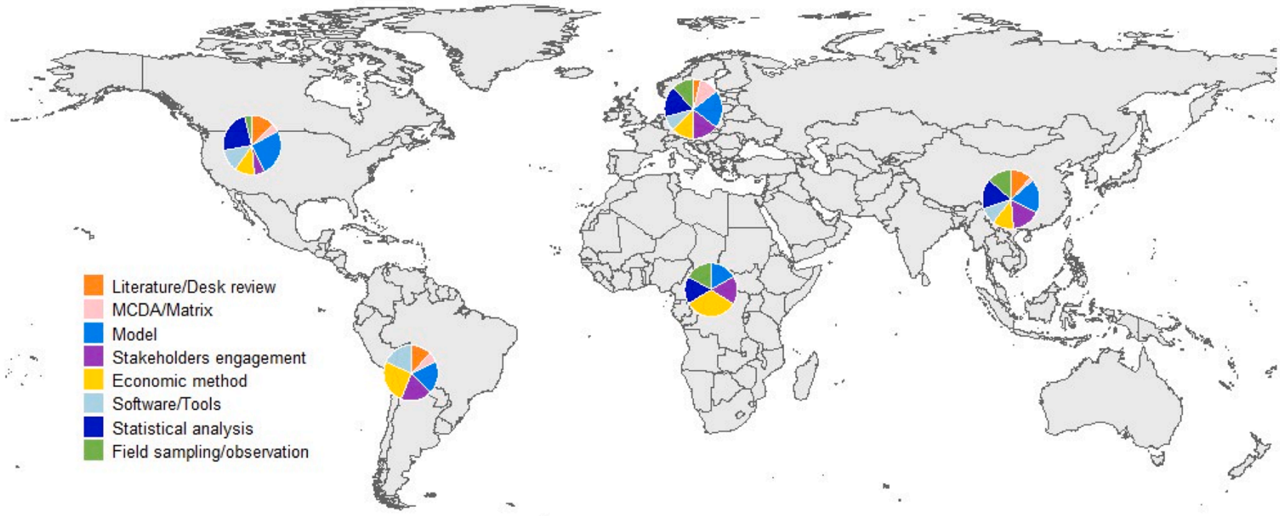

Fig. 3. Map reporting the different types of methods used to assess co-benefits in different world regions. Each pie chart reports the share of applied methods in the associated world region (North America, South and Central America, Europe, Africa, Asia and the Pacific).

environmental conditions, biophysical and biodiversity parameters before and/or after NbS interventions [42–48], or to identify indicators and proxies of ecosystem services [49–51].

To this end, field sampling and observation approaches usually need a high number of samples to be collected within the vicinity of a NbS intervention (Table 1 - *overall efforts and expertise required: medium/high)*. Sampling campaigns can last for several months and can be done randomly, stratified (e.g. by forest type, altitude, or disturbance intensity), or along transects for rapid vegetation and biodiversity assessments [42]. Amenu et al. [49], Gosch et al. [43], Kasada et al. [52], Robotham et al. [46] provide examples of this type of methodological approach, targeting for example biodiversity and soil parameters before and/or after river restoration interventions and urban conversion to sustainable agricultural land use, such as paddy fields. Kasada et al. [52] conducted a three-month campaign collecting over 200 samples across 72 transects (plants, butterflies, dragonflies, frogs), while Robotham et al. [46] collected more than 60 samples of water, sediments, and soils over one year using GPS, LiDAR, and sensors. Amenu et al. [49] reports plot-based inventories (e.g. 72 plots of 20 m × 20 m) to assess biomass and microclimate, and Gosch et al. [43] sampled zooplankton biweekly at 24 locations over four months. Sampling campaigns can last for several months or extend over one to two years to capture seasonal and inter-event variability, which can strongly influence NbS performance. For instance, Yamanaka et al. [53] gathered fish, aquatic plants, water, and bird data across multiple survey points over three months, and Murphy et al. [44] reported monitoring periods ranging from at least 12 months for microclimate assessments to up to 24 months for flood retention basins. These approaches can therefore require several instruments and infrastructure such as laboratories, making the process potentially expensive, time-consuming, and labour-intensive.

For field-observation based assessment of NbS, local expertise and knowledge can be crucial to appropriately design sampling protocols and interpret results in context of the existing risks and environmental and socio-economic conditions [47,54,55]. In NbS assessment studies, field sampling and observations are also used in combination with statistical analysis and modelling approaches. They are commonly used to validate and calibrate models and software, for example through root and stand sampling to calibrate reinforcement models for hazard risk [56] and through expert application of bio-physical models such as InVEST to assess ecosystem services like water yield [51]. This information can also feed model, software and tools to simulate future changes and impacts associated with NbS interventions (ex-ante analysis as in [52,57], to compute statistical analysis to estimate for example biomass and species richness changes [53].

Field sampling and observation are generally site- and benefit-specific. Most of the reviewed papers based solely on field measurements focus on a single benefit (Table 1 - *multiple co-benefits: medium; disbenefits: medium)*, for instance water quality [46] and biodiversity [43] in riverine ecosystems. However, recent studies show their potential for multi-benefit analysis, for example rough empirical monitoring of peak flow attenuation, water quality improvement, and pasture health in a flood detention basin [44]. When integrated with other approaches, field-based methods can further facilitate the assessment of multiple benefits using similar sets of parameters or variables, as demonstrated by forest inventories combined with bio-physical models or biomass data, microclimate monitoring, and remote sensing [44,47,48,51,54,55,57]. They can also help identify trade-offs and potential negative effects, such as nutrient retention versus phosphorus release in water detention systems [44], biodiversity gains versus reduced seeder species after prescribed burning [42], higher regulating services but lower provisioning services in forested areas [51], or mixed biodiversity outcomes after land conversion, including increased plant richness (+16%) and pond frog abundance (+25%) but reduced butterfly richness (−68%) [52].

While most of the reviewed field-observation studies focus on a single, small-scale intervention, some have demonstrated that sampling protocols can be adapted to multiple locations, enabling comparative analyses of NbS interventions (Table 1 - *suitability across scales and/or other locations: medium/low)*. Examples include river restoration studies across different river sections [43,46,54], urban water retention case studies in the UK [45], and avalanche- and landslide-related NbS assessed through common indicators in two countries [50]. Recent studies have further scaled up field approaches through landscape-level inventories and experimental designs, including stratified forest plots [49], urban field plots combined with biophysical models [51], and burned/control plots for wildfire-risk management protocols [42]. To enhance the replicability and scalability, results and sampling protocol should be archived in open-access databases, enabling broader applicability and facilitating data reuse (as shown by [32]; Straatsma and Kleinhans, 2018). Moreover, embedding sampling protocols within standardised assessment procedures and frameworks may further support their application across diverse settings [45,55], while transparent uncertainty reporting and integrated biophysical measurements can help bridge ecological science and disaster risk management practice [49].

Repeated sampling is frequently cited as necessary, particularly for

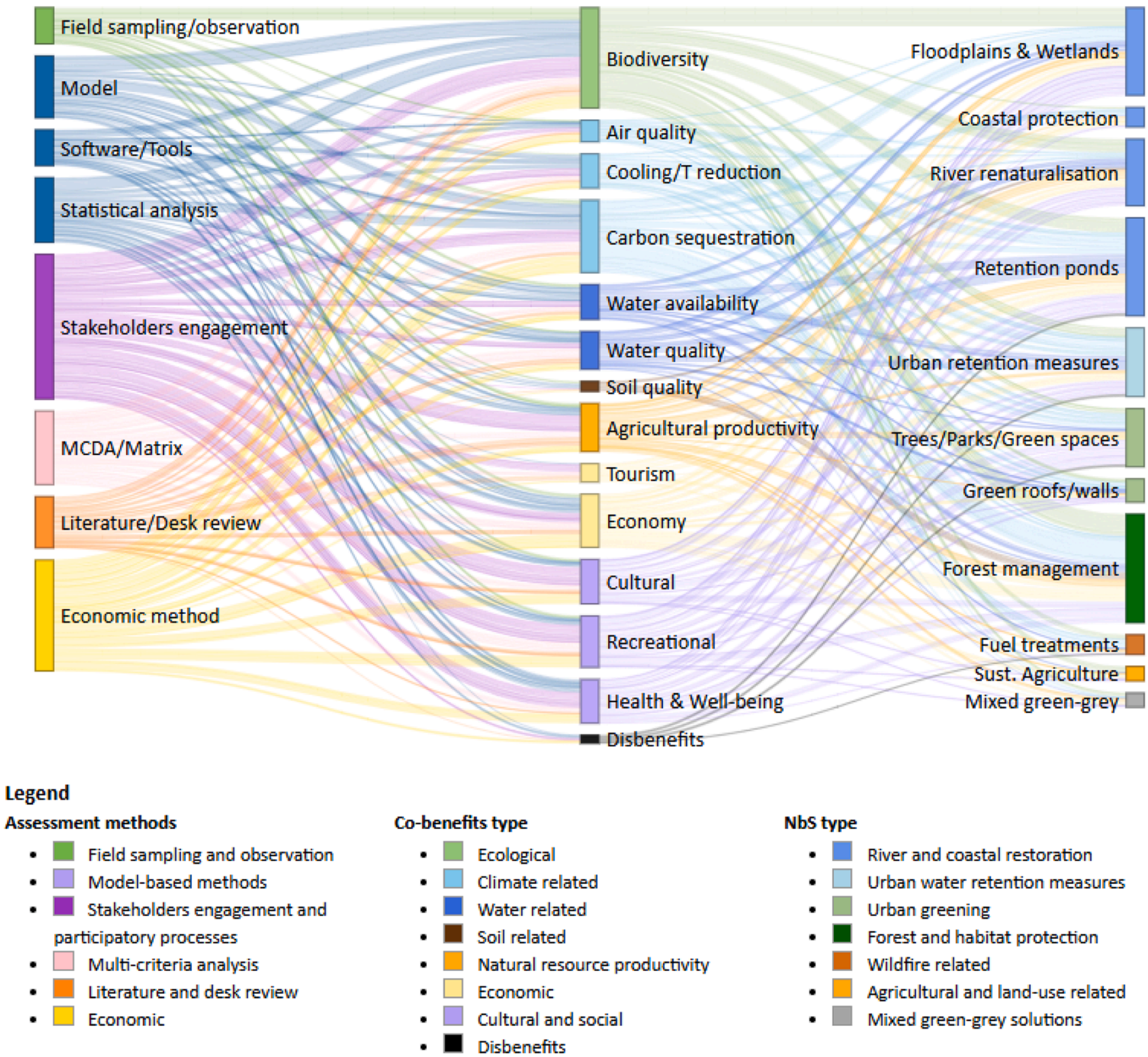

Fig. 4. Sankey diagram linking assessment methods (left column) with co-benefits assessed (central column) and nature-based solutions analysed (right column).

Table 1
Synthesis table of the potential use of methods according to different criteria. Low, medium, high levels have been used to assess each category of methods in relation to each other.

	Overall efforts and expertise required	Suitability across scales and/or other locations	Multiple Co-benefits	Disbenefits	Future climate change
Field Sampling/Observation	Medium/ High	Medium/Low	Medium	Medium	Low
Model	High	Medium/High	Medium/Low	Medium/Low	Medium
Software/Tools	Medium	Medium/High	Medium/Low	Medium/Low	Medium
Statistical Analysis	Medium	High	Medium	Medium	Medium/High
Stakeholders Engagement	Medium/High	Medium/High	High	High	Low
MCDA/Matrix	Medium/High	Medium	High	High	Low
Literature/Desk Review	Low	High	High	High	Low
Economic	High	Medium	Medium/High	Low	Medium/Low

monitoring interventions to assess their effects over time - as reported for example by [44,46,49]. Field sampling and observation techniques are mostly used to collect historical or contemporary data and to provide an ex-post assessment, including long-term forest cover analysis [49] or one-year post-intervention vegetation monitoring after prescribed burns [42]. However, these methods have limited potential of considering future climate change conditions (Table 1 - *future climate change: low)* [43,46,52,58]. Therefore, while field data provide essential biophysical baselines, they should increasingly be coupled with predictive modelling to assess how rising temperatures, altered precipitation patterns, and more severe hydrological extremes may affect NbS performance over time [44,49,51].

3.2.2. Models

Models have been used to investigate forest and vegetation growth, yield, and management and carbon sequestration capacity [36,37,40,57,59–64]; the effects of coastal restoration or conservation projects on carbon sequestration, ecosystem functioning and quality [38,39]; the effects of NbS on biodiversity [48,52,65,66] and habitat quality [56,67–69]; water yield and availability [37,45,70,71]; to assess the effectiveness of green roofs against heat stress and pervious pavement, bio-retention ponds and rain gardens against floods [72–74] or against water pollution [34,75–77]; or to compare alternative solutions against floods, including green and grey solutions, in riverine ecosystems [62,68,78].

However, in context of risk-reduction, a key shortcoming arises from models being unable to address multiple benefits simultaneously (Table 1 - *multiple co-benefits: medium/low; disbenefits: medium/low)*. They may be specifically designed to assess a single aspect, such as water quality in the case of stormwater and flood management [34,75], mangrove forests restoration linked to dike removal in coastal areas [66], or carbon emissions in the context of wildfire management [57,64], and therefore may not capture the full range of NbS co-benefits. As a result, multiple models are used to analyse different benefits, as in the case of Lee et al. [36,37]. Attempts to overcome this limitation include model integration, such as coupling hydrodynamic modelling with sediment dynamics and blue carbon assessments for mangrove restoration [63], or combining hydrological models with spatial analysis tools to prioritise NbS for joint flood mitigation and nitrate reduction at basin scale [76]. Despite this limitation, some model applications provide insights into potential positive and negative changes associated with NbS, trade-offs, and system limits. Examples include biodiversity changes linked to floodplains and river restoration [48], optimisation of urban water retention measures [78], trade-offs between water-, nature-, and people-related benefits in urban settings [35], multi-hazard analysis of urban flooding and heat stress [74], and wildfire-related carbon emission from NbS [40]. Advanced modelling further showed how short-term fire-risk reduction may undermine long-term biodiversity and carbon stability [79]. Likewise multifunctional floodplain restoration may outperform single-purpose management while reducing local agricultural production [68,70], urban models can be adopted to assess synergies between stormwater management and co-benefits such as noise reduction, pollination, and microclimate regulation [73].

Models are specific in terms of parameters and variables required, but they can be adapted and used in different locations, if information needed are available (Table 1 - *suitability across scales and/or other locations: high)*. In fact, the big advantage of modelling within the risk and NbS context is their applicability to different locations that face different conditions [40,56,57,59,76,80]. In the reviewed papers, models are used from local scales [34,35,69,71,74,75], to district and city scales [73] or multi-site analyses [72], to regional and basin scale [57,76,81] to national scales [36,37,68]. In the papers assessed different models are typically used at each scale reflecting challenges of applying models across scale, locations and contexts that arise from e.g., model resolution, represented model processes or data needs. Combining models or adopting modular approaches could overcome these shortcomings. Emerging examples include coupled hydrodynamic, sediment, and blue carbon models [63], ecosystem service models [68], high-resolution spatial datasets enabling scaling from field to basin level [76], and real-time control within hydrological models [72].

Also, model requirements can vary a lot from model to model, but are generally high in terms of data, pre-processing, parametrization and validation procedures, and computational requirements (Table 1 - *overall efforts and expertise required: high)*, as reported by Akasaka et al. [65], Calderwood et al. [70], Kok et al. [68], Shih et al. [66]. Shih et al. [66] conducted over 600 hydrodynamic simulations at 10 × 10 m resolution to assess the impact of floodplain restoration through mangrove expansion on flood risk reduction and potential ecological benefits in the Tanshuei estuary in Taiwan. Akasaka et al. [65] applied national-scale prioritisation across thousands of grid cells and over 1500 freshwater fish and macroinvertebrate species, exploring the potential of protected areas in lowland flood-prone regions for flood risk reduction and biodiversity conservation. Similarly, Calderwood et al. [70] used stochastic simulations and fine-scale meshes to address uncertainty and urban topography, while Kok et al. [68] quantified up to 13 ecosystem service indicators, requiring tools able to represent interconnected bio-physical and hydrological processes. Data availability remains a key limitation, particularly when datasets differ in spatial or temporal resolution. Complex models, such as SWMM (Storm Water Management Model), can also require substantial background information and workload, making simpler tools useful for early-stage screening, although less precise [73]. Therefore, the use of complementary information can be useful. Literature reviews are generally used to define model assumptions and settings, based on similar conditions and analysis previously done [34,40,64], but should be integrated with field surveys and observations to capture local dynamics or areas not covered by publicly available datasets [73]. In addition, models are also useful when linked with other methods, as describe in the filed samplings and observation section. They can be also combined with participatory processes and MCDA approaches to assess co-benefits produced by NbS [82], define parameters to define and assess NbS [67] or to investigate issues and potential NbS to be analysed [78], and improve comparison and decision-making transparency across ecological and social sectors [63].

Finally, according to their specific design, models have the greatest capacity to provide ex-ante evaluation, simulating future scenarios or conditions (Table 1 - *future climate change: high)*. Climate change scenarios or different climate conditions have been considered in NbS co-benefits analysis more frequently in the recent period [39,68,71,74,75,81], while other studies mainly assess long-term management options without explicitly considering climate change effects [37,38,57,64,66]. Recent examples include climate-adjusted hydrodynamic models used to assess stormwater NbS under future rainfall scenarios [71,75], forest landscape models simulating wildfire risk, carbon dynamics, and forest resilience under different climate conditions [79,81], and integrated bio-physical and hydrological models evaluating ecosystem services, blue carbon, and compound flood protection in riverine and coastal systems [63,68]. Real-time control modelling also shows improved flood-reduction performance compared with passive systems [72]. Despite remaining limitations, such as short modelling horizons and spatial-resolution uncertainties [81], modelling is moving towards adaptive frameworks where climate change is treated as a key input variable [71].

3.2.3. Software and tools

We differentiate here software and tools as a separate category (from models) that simplifies their application by user-friendly interfaces and guidelines, or ready-to-use codes [73,36,79,83,84], which can also be used to analyse input data collected with other methods, such as participatory processes (Lin et al., 2022) or field samplings [43]. In the reviewed papers we identified several tools that support the analysis of ecosystem services (InVEST - [36,83,85]; TESSA - [86]; i-Tree - [84]; GAFD - [79], trophic interactions and biomass (Ewe - [39], conservation planning (ACPF - [76], biodiversity (Primer - [43], forest resilience (WildEST - [79]; LANDIS-II - [81] root growth (MATLAB rootFORCE package - [56]; ROOT - [87], population health and social cohesion (Teeb-Stadtool - [77], recreational activities (FACTS or VGI - ref 65, and stakeholders' surveys [60].

Similarly to models, requirements vary with software and in some cases need a large amount of pre-processed input data or parametrization to be locally applicable (Table 1 - *overall efforts and expertise required: medium)*. For example, tools such as SWMM require detailed information on land cover and drainage systems, while simpler tools like GAFD (Green Area Factor for Districts) are less data-intensive and useful for early-stage design and testing of NbS alternatives [73]. User-friendly platforms can further reduce technical barriers, enabling broader application without advanced modelling expertise [79], although tools are not necessarily free to use.

In the reviewed papers, software for NbS analysis were rarely applied to assess multiple co-benefits simultaneously (Table 1 - *multiple co-benefits: medium/low; dis-benefits: medium/low)*. This is only possible when the tool includes multiple modules dedicated to different benefits, as seen in the case of InVEST, or support multi-objective analysis and trade-off evaluation (e.g. ROOT, ForSys - [79,87].

These tools can be easily applicable in different locations (Table 1 - *suitability across scales and/or other locations: medium/high)*. Use of the same software across scale can be possible, although this would possibly increase computational requirements or lower the resolution of the analysis. Deak et al. [81], Lee et al. [36], Manley et al. [79], Meraj et al. [83]; Perosa et al. [86]; Schilling et al. [76]; Schneider et al. [84] provide an example of these features. These studies applied InVEST tool to investigate two different ecosystems services in two different countries and at different scale: water yield services associated with forest restoration project at national level in Korea and sediment retention associated with forest management and protection at regional level in India, respectively. Similar scalability is observed in ACPF for watershed planning [76], LANDIS-II for landscape-scale forest dynamics [81], and ForSys for prioritising forest treatments over large areas [79].

As for models, their potential to incorporate future climate change is high (Table 1 - *future climate change: high*) as some tools can integrate climate projections to assess long-term NbS performance and support adaptive planning [60,81,85].

3.2.4. Statistical analysis of environmental and ecological parameters

Statistical analysis consists of standardized mathematical techniques employed to summarize data, test hypotheses, and support evidence-based interpretation of environmental, ecological, and socio-economic parameters. In NbS co-benefit assessment, statistical methods are primarily applied to analyse observed or modelled data rather than as standalone assessment approaches supporting informed decision-making based on quantitative evidence.

These techniques are replicable and scalable (Table 1 - *suitability across scales and/or other locations: high)*, enabling comparisons across different datasets, identification of spatial and temporal trends, and exploration of relationships between parameters and variables. Statistical analysis have been used to characterize sample populations, particularly in biodiversity analyses [43], examine distributions and correlations related to environmental conditions, interventions, or scenarios [52,53,59,88,89], compare datasets [32,45], analyse stakeholder surveys [41,90], and validate model outcomes [37]. Regression analysis is also commonly applied to define relationships between interventions and their associated benefits, particularly in the context of ecological or environmental variables [65,47], and to forecast future changes [91]. Advanced statistical techniques can further strengthen NbS assessments by supporting uncertainty analysis, identifying key drivers, isolating causal effects, comparing ecological communities, and analysing ecosystem multifunctionality [44,51,42,92,93].

They can also support model validation and feed into broader decision-support tools, such as aggregated indices and cost-benefit analysis, to assess financial viability and policy relevance [60,75,93]. Thus, statistical analyses are often integrated with other methodologies to assess various impacts and evaluate the likelihood and relationships among co-benefits or disbenefits (Table 1 - *multiple co-benefits: medium; dis-benefits: medium)*, hazards, and other influencing factors or variables, taking into account both current and projected climatic conditions based on the available data (Table 1 - *future climate change: medium/high)*.

3.2.5. Stakeholder engagement

Stakeholders engagement approaches are widely used to identify multiple co-benefits and disbenefits, even simultaneously (Table 1 - *multiple co-benefits: high; disbenefits: high)*. They mainly rely on people's perceptions and observations, for example to compare the conditions and benefits before and after NbS implementation [54,94,95]. These approaches are particularly valuable because local stakeholders can identify relevant costs, benefits, vulnerabilities, and feedback mechanisms that may be overlooked by non-participatory assessments, while improving community acceptance and participation [47,54,55,60,96,97]. Participatory processes can support the weighting, validation, and comparison of data through expert judgement [78,82,86,98], help to identify local needs and preferences [41], and evaluate the perceived benefits and impacts [20,88,90,97,99]. Qualitative interviews and tools can also reveal benefits that may be monitored and valued in the future, especially where quantitative data are limited [60,97]. They also help evaluate solution effectiveness, both for before-and-after comparisons and future planning, supporting target definition and the visualisation of trade-offs between sectoral objectives such as tourism, fisheries, and coastal protection [67,78,87,95,100]. In addition, the stakeholders engagement approach can inform the estimation of a monetary value based on stakeholders' perceptions, preferences, or willingness to pay for certain services in the NbS and risk context [101] (see Section 3.2.8).

Given that interaction with focus groups, interviews, questionnaires and workshops can require multiple iterations and a large number of people, efforts are large, both in terms of financial resources and time (Table 1 - *overall efforts and expertise required: medium/high)*. However, these iterative processes can capture aspects such as residents' well-being, community risk perception, feedback mechanisms, and local vulnerabilities, which often are overlooked by other methods, in particular quantitative ones [60]. A key challenge is ensuring representative and ethical participation, with techniques such as snowball sampling helping to identify stakeholders with specific technical or cultural knowledge, especially in less accessible communities [60,97]. Expert facilitation supports dialogue and NbS co-creation, reducing the risk of neglecting social or ecological objectives and integrating different contexts and "ways of knowing" into decision-making [87]. Appropriate communication channels, local languages, cultural knowledge, and support from translators or facilitators are also vital, especially across different geographical areas [54,55,99].

However, replicability may vary depending on the engagement process used (as face-to-face interviews or online surveys) (Table 1 - *suitability across scales and/or other locations: medium/high)*. In practice, mixed approaches combining questionnaires, semi-structured interviews, and workshops are often used within the same case, depending on the ability to involve relevant stakeholders across locations and scales (see for example [98,41,82,95]. Stakeholders engagement can be used in MCDA (see 3.2.6.) to rank impacts, compare solutions in different context and potentially inform the location and implementation of NbS [98,67,102]. Preference-based tools, such as efficiency frontiers, can help visualise trade-offs between objectives such as tourism, fisheries, and coastal risk reduction [87], while participatory approaches are crucial for identifying non-monetary benefits, including gender equity, access to education, and social justice for marginalised groups [97].

Participatory processes can also be used, sometimes in combination with other methods, for ex-ante assessment of NbS, co-benefits and value to be maintained or preserved, identification of potential future synergies and trade-offs. They can help define evidence-based, measurable, and time-bound ecosystem targets for national strategies [87], while identifying critical system components and feedback loops that non-participatory methods may overlook [60]. However, they have limited capacity to assess future NbS performance under climate change conditions (Table 1 - *future climate change: medium/low)* [41,60,67,82,96,100]. To address these limitations, multi-objective approaches can help stakeholders visualise trade-offs between competing objectives, such as tourism, fisheries, and risk reduction [87]. Finally, participatory methods are essential for capturing non-monetised benefits, including social equity, education, and health outcomes for marginalised groups, which are often underestimated by purely quantitative assessments

[97].

3.2.6. Multi criteria decision analysis

Methods based on a multi criteria decision analysis (MCDA) gather information and perceptions of people to rank and assess alternative NbS and their benefits [67]. They can use approaches based on mathematical methods (e.g. fuzzy logic approach) or system dynamic tools (e.g. causal loop diagrams or system dynamics modelling) to support complex decision-making and manage uncertainty linked to subjective information [82,96,98]. They can be also based on evaluation matrices to compare different options against criteria, assess trade-offs, rank alternatives, and identify suitable solutions [67]. Commonly, MCDA involve direct stakeholders' engagement to ensure that decisions reflect the perspectives, knowledge, and needs of the affected communities or groups [78], including in participatory settings such as Living Labs and multi-actor frameworks [103]. More advanced approaches can further combine expert judgement with spatial data to improve robustness and contextual relevance [63].

MCDA methods are thus closely linked to stakeholder engagement approaches and share similar strengths and weaknesses. The overall effort and expertise required is high (Table 1 - *overall efforts and expertise required: high)*, depending on the quality of the information collected and the ability to interpret and translate complex information into simplified quantitative values, and the understanding of cause-effect relationships among variables. MCDA require knowledge of the underlying algorithms, and skills in programming and used of technical tools, although models and software can support the analysis [63,82,86,98,104]. They are often applied in participatory settings such as Living Labs, where expert facilitation is needed to balance stakeholder perspectives, for instance between risk reduction priorities and ecosystem co-benefits [103].

MCDA is designed to deal with complexity and, therefore, can easily address benefits and disbenefits between multiple solutions or implementation scenarios (Table 1 - *multiple co-benefits: high; disbenefits: high)*. It supports multifunctional evaluations, helps prioritise criteria such as flood risk reduction, biodiversity, and socio-economic benefits, and improves understanding of complex interactions, interconnections and feedback processes between NbS, co-benefits and disbenefits [20,63,82,96,98]. Additionally, MCDA techniques can be applied in different locations, and potentially across scales, although considering that main input data comes from participatory processes and can limit the application (Table 1 - *suitability across scales and/or other locations: high)*. At the same way, their potential to consider future climate conditions is limited to that (Table 1 - *future climate change: low)*, unless combined with dynamic or process-based assessments able to represent evolving hazards and environmental conditions [63].

3.2.7. Literature and desk review

Literature review collects data and information from existing, registered and published records and knowledge. In this context, the method's strength lies in collecting historical information. It facilitates also the comparison of conditions, economic costs and benefits, and, if necessary information is published, of pre- and post- interventions' biodiversity, ecological, environmental impact [33,48,105]. As well, the information collected can be used to guide the ranking of solutions and support evidence [67,102], to inform the definition of alternative scenarios to be modelled [34,38,40,47,57] and to inform stakeholders in participatory processes and evaluations [54,55,78,95,100].

In the context of NbS and co-benefits assessment, literature and desk reviews are generally used in combination with other methods, to define context and assumptions, collect historical data, create dataset and summarise information. Most of the time, desk data and information collection is used in combination with data from field sampling to have a complete set of information for the analysis, such as flood maps and historical rainfall and groundwater information [55] and to determine model inputs and assumptions [34,38,61,74,106]. For example, Dutta et al. [34] reviewed about one hundred studies to identify pollutants, NbS for pollution control, and modelling tools to assess urban water quality under different NbS interventions, while Baustian et al. [38] collected carbon flux data for coastal NbS mitigation assessment in the coastal areas of Lousiana. Literature-based approaches also support benefit transfer, applying economic values from previous studies to new contexts, which can be refined with local data, models, and stakeholder input to better estimate ecosystem services [105]. They help to evaluate multiple benefits and disbenefits (Table 1 - *multiple co-benefits: high; disbenefits: high)*, as in the case of Bartowitz et al. [40], who based the assessment of the unintended carbon consequences associated with NbS approaches to wildfires on an extensive review of data and literature in the US. They can also serve as input to assess risk reduction, impacts, exposure, or vulnerability, mainly for a post-intervention and post-disaster evaluation [40,50,53,102]. However, their direct applicability for climate change conditions is very limited (Table 1 - *future climate change: low)*. When combined with modelling, literature-based evidence can nonetheless inform projections of future ecosystem dynamics, such as changes under sea-level rise [105]. Overall, integrating literature data with local biophysical and socio-economic information help to reduce transfer errors and ensure that assessments reflect site-specific conditions and community values.

The overall efforts and expertise requirements typically are lower in comparison to other method categories, however literature and desk review presents some challenges as well (Table 1 - *overall efforts and expertise required: low)*. Firstly, the definition of the search strategy can be challenging - the right terms and synonyms, metrics, time-frame and area of studies need to be taken into consideration. Systematic data extraction from the literature identified can also be time consuming, depending on the number of studies and the final scope of the analysis. Difficulties may arise if data are not be publicly available, and time and costs are required to obtain them. But overall, if the appropriate information is available, literature/desk review follow a standardised methodology that can be easily applied in different contexts and at different scales. Literature review can easily be applied to multiple locations, even simultaneously (Table 1 - *suitability across scales and/or other locations: high)* [40,102]. In this regard, literature reviews can also help to identify and fill information gaps. For example, meta-analysis combined with value transfer functions can estimate co-benefits where primary data are unavailable by analysing statistical relationships between NbS values and the ecosystem services they provide [107].

3.2.8. Economic methods

Economic valuation methods assign a monetary value to NbS co-benefits beyond disaster risk reduction. Among those identified in our set of papers, cost-benefit analysis is prominent, assessing NbS interventions in terms of costs, benefits and value generated. For example, Alves et al. [33], applied cost-benefit analysis to urban NbS for flood management, comparing costs and benefits with and without considering the co-benefits generated. Recent studies expand this approach through life-cycle cost-benefit analysis, which includes long-term operation and maintenance costs alongside multiple co-benefits [108]. Values are generally derived from market prices, implementation and maintenance costs, usage costs, and avoided damages or losses, and indirect benefits, such as avoided environmental contamination from protected critical infrastructure. Uncertainty can be addressed through Monte Carlo simulations, presenting results as probability distributions rather than single expected values [93]. Often used alongside other evaluation methods, cost-benefit analysis calculates net present value, benefit-cost ratio, and total economic value to compare policy interventions or investment options [108]. Nordman et al. [109] estimate the economic benefits and costs of green infrastructure for urban stormwater management using the benefit transfer method, while Bilkovic et al. [105] refined literature-derived values with local data, such as population density, ecosystem morphology, and storm exposure. Economic valuation can also rely on specialised tools to estimate ecosystem services including carbon storage, air quality regulation, urban cooling, runoff reduction, and community benefits [72,85,97,105]. Karanja and Saito [31] use avoided damage and market price approaches to estimate the total economic value of mangrove ecosystem services beyond flood risk reduction.

Other economic valuation methods include replacement cost, revealed preference approaches, such as hedonic pricing and travel cost, and stated preference approaches, such as contingent valuation and choice experiments. These methods have, for example, been applied to estimate values for habitat creation, recreation, coastal protection, and public well-being [108]. Revealed preference methods estimate ecosystem-based amenity values using real-world data, like property prices or recreational use, relying on observed behaviours and choices. Stated preference techniques assign monetary values when no direct market value is available through stakeholder engagement. Contingent valuation assesses the willingness to pay for environmental services or NbS, as in the case of Reynaud et al. [101], who conducted a contingent valuation study to assess a peri-urban park dedicated to water pollution control and flood risk reduction by estimating the value the people place on different ecosystem services and park design options. Choice experiments, instead, present cost-varied scenarios with different co-benefits. Herivaux and Le Coent [41] used this approach to analyse public perceptions of two flood risk reduction strategies in peri-urban areas with varying ecosystem preservation and green infrastructure levels, supported by different tax increases. Recent applications also use discrete choice experiments to assess stakeholder priorities, such as shoreline restoration benefits [105]. These applications require a high level of overall effort, expertise and data to define a monetary value for the benefits (*Table 1 - overall efforts and expertise required: high)*, as expert and stakeholder involvement is important to translate co-benefits into economic terms, capture locally relevant and non-monetary values, validate benefits and project objectives, and improve trade-off assessment and decision acceptance [97,108]. Participatory methods can also validate benefits and project objectives, helping avoid underestimation of NbS value and improving trade-off assessment and decision acceptance [105,108].

Overall, economic methods are used to value multiple co-benefits together (Table 1 - *multiple co-benefits: medium/high)*, ranging from energy savings, carbon sequestration, quality and availability of natural resources and temperature cooling to tourism and primary production, or recreation and biodiversity protection, avoided environmental contamination, biological control, and improvements in well-being, safety, education, and health services (see for example [33,93,97,108–111]. These assessments need indicators and proxies to define a monetary value of diverse benefits, in order to be comparable within a cost-benefit framework. This may involve different levels of uncertainty, heavily dependent on data quality. To address this, advanced tools and models, together with probabilistic approaches, can support ecosystem service valuation and decision-making under uncertainty [85,93,97,105]. Although economic methods have not been widely used to assess disbenefits (*Table 1: disbenefits: low)*, they can identify potential economic losses, such as higher costs of highly engineered NbS compared with simpler nature-based alternatives [72], negative externalities, perceived disservices, or feedback effects that reduce NbS effectiveness [93,105]. In the reviewed papers, disbenefits are explicitly considered in limited cases, such as Herivaux and Le Coent [41] who investigated the people's perception of benefits and negative effects of NbS in the analysis of choice experiments results.

Economic evaluation have mostly been used at local (as in [109]; Reynaud et al., 2017; [111] and river basin scales (as in [31,33,62,112], across continents and in various environments, including urban, peri-urban, forest, freshwater and coastal areas. Recent studies show a shift towards more spatially explicit analyses using high-resolution data to capture local variability in ecosystem service provision [108]. These methods are adaptable to different locations and potentially at different scales, although they may require modifications in experimental design (Table 1 - *suitability across scales and/or other locations: medium)*, since values such as flood risk reduction depend strongly on local factors, including population density and critical infrastructure [105].

Economic methods are used for both ex-ante and ex-post evaluation, but generally do not consider future climate change scenarios (*Table 1 - future climate change: medium/low)*. While earlier studies rarely incorporated climate change, more recent approaches increasingly integrate future scenarios, such as habitat shifts under sea-level rise or NbS performance under extreme rainfall conditions [85,113]. In ex-ante evaluations, economic methods compare NbS alternatives to identify costs and benefits, defined both in terms of market prices and indirect valuation, and to optimise management and investments [37,61,108,113], including technical enhancements such as real-time control systems [72]. Cost-benefit analysis is more frequently used to assess impacts after of NbS post-interventions or post- disaster, often in combination with physical models and software [31,33,36,78,86,109]. To support these analyses, economic assessments increasingly rely on integrated modelling tools and probabilistic approaches to quantify ecosystem services and uncertainty [93,97]. Interactive tools can also communicate economic co-benefits to stakeholders and decision-makers, improving transparency, acceptance, and policy uptake of NbS [105].

4. Discussion

4.1. Implications of findings

Multiple methods are available, which can be applied singularly or in combination, to provide a quantitative assessment of co-benefits that arise from NbS for disaster risk reduction. In principle, these methods can be used across different scales and locations and, in addition to multiple benefits, can also identify disbenefits.

Our review shows there is no specific method to assess individual co-benefits from NbS, which reflects also that what is considered a co-benefit varies with different perspectives and study context. Given the different perspectives, it seems important to collect a comprehensive and multidimensional (environmental, social, economic) value of NbS and co-benefits, which ideally requires application of several of the identified methods within the same NbS and disaster-risk-reduction context. At the moment, the heterogeneity of approaches makes the comparison of NbS effectiveness and value difficult, thus limiting their use in multiple sectors, including the insurance and financial sectors, but also in decision-making processes more broadly [27,29]. This is especially true for non-tangible and non-market benefits, such as biodiversity and well-being [30]. However, economic methods allow for estimating a monetary value of the co-benefits of NbS.

Taking a broad view of the multiple benefits ensures a more comprehensive understanding of the true value of NbS, which is expected to facilitate their uptake in financing. It is therefore encouraging that the identified methods demonstrated the potential to address multiple benefits and, potentially, disbenefits. The co-benefits assessed cover social, environmental, and economic aspects, addressing a wide range of stakeholder interests. Participatory processes and stakeholders' engagement play a key role in the design, implementation, and assessment of NbS and co-benefits (EEA, 2021). Even in a quantitative evaluation, the integration of stakeholders' knowledge, opinions and perceptions can be fundamental to valuing and quantifying NbS benefits. Many of the reviewed papers combined stakeholder engagement approaches with different quantitative assessment methods. This allows data and indicators (e.g. from modelling) to be aligned with the interests of stakeholders and the main beneficiaries of NbS [29]. The involvement of stakeholders is important to improve NbS acceptance and foster possible investments.

4.2. Limitations and opportunities

Limitations are associated with the complexity and high level of effort required to implement most of these methods. Overall, the lack of a standardised methodology, set of data and indicators is a critical shortcoming that prevents the development of a common evidence and knowledge base for NbS in contexts where multiple benefits are sought beyond disaster risk reduction alone (EEA, 2021; [30]. This is in line with previous literature that highlighted limitations of the current state of knowledge concerning NbS co-benefits, due to the confined location and climatic context of most of the studies [13,27]. Implementing effective NbS that deliver multiple benefits requires contextualisation in terms of climatic, environmental and socio-economic conditions (EEA, 2021). Given the financial and time-costs of most of the identified methods it seems prohibitive to constantly repeat efforts to assess an NbS' impact (ex post or ex ante) at different locations. Clearly, better ways to apply these methods at different scales and different locations need to be found as an important step towards the implementation of NbS as a wider strategy for climate change adaptation and disaster risk reduction beyond site-specific solution [30].

Among the many challenges, overcoming limitations associated with data needs and data availability is critical, particularly, with reference to the current mismatch between the global or large-scale datasets generally used by catastrophe models and the necessity of primary local data required for local-scale NbS projects [12,13,16]. Addressing the issue of data scarcity is possible by supplementing traditional field sampling with additional methods of data collection. Remote sensing technologies, such as high-resolution satellite imagery, or drone-based monitoring, combined with object-based image analysis, and deep learning are becoming increasingly powerful. They have been shown to e.g., enable a fine-scale, repeatable, and cost-effective evaluation of ecosystems and vegetation dynamics [114]. For instance, drones equipped with different sensors can map species composition, canopy traits and habitat structure, thereby supporting restoration projects, invasive species management and precision agriculture [115–118]. AI-based models can also help to improve classification accuracy and facilitate more efficient large-scale and long-term monitoring, as shown in seagrass conservation and forest assessments [115,119]. Integrating drones and satellite data expands monitoring from local to regional scales, supporting the analysis of biodiversity and ecosystem functions [120]. Additionally, across both European and Global South contexts, citizen participation has been showed to be an effective way of supporting flood management, urban mobility, and wetland restoration. Examples include urban mobility studies in Barcelona [121,122] and community-led flood monitoring in Indonesia and Fiji [123]. Finally, many collaborative data-sharing initiatives, including open-access environmental data portals, regional observatories, and research networks, such as the European Environment Agency, Copernicus and the UN Biodiversity Lab, are making harmonised, interoperable datasets accessible in different contexts and at different scales.

NbS can take time to become effective (for instance forest growth or re-wetting of peatlands), or to recover after extreme events, influencing also the profitability for investors in the short term (EEA, 2021). Likewise, NbS can lose effectiveness in the long term if not adequately managed. A main limitation of NbS and co-benefits assessment methods is therefore their lack of considering future climate change. Although some methods, modelling in particular, would have a high potential to do so, most studies identified here carried out an ex-post assessment of the benefits and effectiveness of NbS. When an ex-ante assessment is presented, studies explored the expected benefits of planned NbS, but rarely considered whether climate change would pose a risk to the NbS (such as forest mortality, or drying of wetlands) and whether NbS resilience to climate- and weather-related hazards will be influenced by ecosystem management and biodiversity [124]. Moreover, some NbS may need a few years to start providing an adequate level of risk reduction and other co-benefits [96]. Therefore, integrating this aspect into the assessment is necessary to support long-term planning that takes into account uncertainties about future climate change impacts and societal adaptation needs (EEA, 2021). This requires attention to be paid not only to climatic factors but also to evolving land-use patterns and socio-economic systems.

A comprehensive evaluation of NbS must consider the interconnected components of vegetation, soil, water and biodiversity, as well as their dynamic interactions. All of these components are shaped by climate, changes in land use, socio-economic development and ecological conditions [125]. To address these complexities, advanced modelling approaches can offer valuable opportunities. Process-based ecosystem models, such as dynamic global vegetation models (DGVMs) like LPJ-GUESS, simulate ecological interactions and biophysical processes, including vegetation growth, hydrology, nutrient cycling, and carbon sequestration, under different climate and land use scenarios [126,127]. They help predict shifts in ecosystem structure and function and assess the potential of NbS to mitigate climate impacts [128–130]. However, DGVMs generally operate at broad scales and are not directly applicable for detailed spatial planning or local NbS implementation. Their outputs should be interpreted in close collaboration with modelling experts and complemented by region-specific knowledge extracted and scientific literature. In parallel, agent-based models of land-use change, such as CRAFTY, simulate spatial dynamics in response to policy, climate, and socio-economic drivers [131,132]. These models support trade-off analysis and scenario testing at landscape scale. While these models have limitations, such as data requirements and computational complexity, they provide critical insights into long-term risks, co-benefits, and adaptation options. When combined with stakeholder-informed scenarios and participatory approaches, they can help to bridge the gap between scientific modelling and practical, context-specific planning for resilient and multifunctional NbS [133].

4.3. *Implications for insurance and investments*

Integrating co-benefits of NbS is essential for unlocking the total economic value of NbS. Without accounting for the different array of co-benefits provided by a particular NbS, the comparison against traditional engineered solutions is being conducted only with a fraction of its total value [134]. Public sector investors can be interested in promoting NbS that not only reduce climate risk but also increase air quality (reducing healthcare costs), create new recreation spaces or increase tourism revenue in the region. Several co-benefits can increase the quality of life in the region, leading to potentially higher political support for NbS interventions. Additionally, private sector investors can also benefit from co-benefits since, for example, the availability of green and water areas can increase property prices in a neighbourhood.

However, besides the limitations regarding the monetization of co-benefits for NbS, some co-benefits have a wider societal impact and act as a positive externality. Hence, private investors will not receive the economic revenue derived from certain NbS co-benefits. This complicates the investment case for NbS by private sector entities. A collaboration between public and private investors is suggested to overcome the challenge of coordinating climate adaptation investments that generate a diversity of benefits [135]. In such partnerships insurers and other private sector investors can contribute to part of the NbS investment cost in a way that is proportional to the private sector benefits of NbS, such as climate risk reduction. Moreover, insurance can promote investment in NbS by granting premium reductions, i.e. the reduction of amount paid for insurance coverage, in regions where these are implemented [136]. The premium reduction and co-benefits, together, may make NbS financially attractive for policyholders or local governments.

Accounting for future climate change impacts in the assessment of NbS is particularly relevant in the insurance sector, as the effectiveness of NbS on risk reduction and potential co-benefits will translate into the pricing of insurance premiums in the long-term [18]. Currently, insurance models tend to underestimate the acceleration of weather extremes and do not account for future climate change, as they are mostly based on past events and backward-looking approaches [24]. A full benefit assessment and understanding of the functioning of NbS over time is also important for the development of sustainable financial instruments, schemes, and investments, especially in the context of insurance and risk prevention. This is also a key consideration to ensure future insurability and maintain a financial buffer for insurance companies. The potential of NbS to reduce risks makes them increasingly relevant for insurers, as they can lower claims (i.e. formal request by a policyholder to an insurer for compensation or reimbursement after a loss or damage) and premiums in countries with existing coverage, and improve insurability in those without [137]. By reducing losses and stabilising premiums, NbS offer an opportunity for insurers to expand their client base while contributing to climate resilience.

Additionally, to address the heterogeneity of methods and the challenges of integrating co-benefit assessments into insurance and investment frameworks, there is a need for more standardized approaches that combine ecological, economic, and risk-reduction metrics. Existing initiatives such as the TEEB (The Economics of Ecosystems and Biodiversity) framework and the World Bank's Natural Capital Accounting system could provide a foundation. TEEB offers a structured, multi-scale methodology for valuing NbS co-benefits in both monetary and non-monetary terms, supporting the integration of ecosystem services into financial decision-making [138]. The World Bank's framework links these services to national accounts, enabling the inclusion of NbS co-benefits in public finance, planning, and investment risk analysis at both macro and project levels [139]. Both frameworks offer data-driven approaches adaptable to financial products such as green bonds or parametric insurance. They also facilitate cross-sector dialogue among governments, development banks, insurers, and investors through consistent and transparent valuation methods. Advancing these frameworks collaboratively could reduce methodological fragmentation and improve the credibility and comparability of co-benefit assessments, making NbS more actionable and attractive to the financial sector.

Increasing knowledge sharing between investors, insurers, public sector decision-makers and scientists is pivotal [18]. Linking scientific research on risk assessment methods with actuarial modelling, for example, can serve to bridge knowledge gaps between the scientific and insurance communities. This could also strengthen the development of robust evidence on NbS performance under current and future climate change. Finally, this closer collaboration could help to identify the profiles of end users and potential investors, provide more accurate and tailored values of risk reduction and co-benefits generated by NbS, and encourage their investment and implementation. This can facilitate transformative decision-making processes that take into account the broader welfare and well-being generated by NbS.

From an investment and insurance perspective, the relevance of NbS assessment methods depends on their ability to provide decision-relevant, robust, and comparable information that also holds under future conditions. In this context, the criteria used in this review (Table 1 and Tab SM.1 in Supplementary Materials) offer a useful lens to identify which methods are most suitable to support financial decision-making. Methods that can quantify multiple co-benefits and disbenefits, allow ex-ante assessment under future climate scenarios, are scalable across locations and contexts, and provide transparent and comparable outputs are more likely to inform investment decisions. However, no single method fully satisfies all these criteria. Therefore, a combination of complementary approaches is typically required: models are essential to simulate future performance and climate risks, economic valuation methods translate NbS benefits into monetary terms, stakeholder engagement and MCDA help capture non-monetised benefits and validate assumptions, while field data and statistical analysis strengthen empirical evidence and reduce uncertainty. This integrated approach can increase the credibility of NbS assessments, reduce investment risk, and improve alignment between scientific evidence and financial decision-making, ultimately making NbS more actionable and attractive for insurers and investors.

4.4. Future research

The reviewed papers clearly report the co-benefits of NbS beyond disaster risk reduction in different environments, at least at local scale and for riverine, urban and forest ecosystems. However, an notable shortcoming of the existing body of evidence is its strong geographical bias towards the Northern Hemisphere, especially the US and EU, where most NbS applications have been implemented and studied. Future research should prioritise addressing this imbalance by investigating whether and how the existing methods can be applied or adapted in tropical and developing regions. This will require targeted efforts to collect primary data in the Global South, since these regions often lack reliable datasets and existing large-scale models are typically not calibrated for local ecological and socio-economic conditions. Research should also explore appropriate methodologies for assessing and monetizing co-benefits in these contexts, including the impact on biodiversity, to ensure that NbS evaluations are globally relevant and equitable. Future reviews could also systematically incorporate grey literature, such as project reports, technical guidelines, policy documents and practitioner-led assessments. This literature may provide valuable evidence on the implementation of NbS and the evaluation of their co-benefits in underrepresented regions.

Although some of the identified challenges can be overcome using existing methods, future studies should also develop methods for collecting and integrating data. Collecting primary data through field sampling and observations, supported and combined with desk and literature reviews and local knowledge from stakeholders. This data could then be made available in open-access databases, which would be highly relevant for defining reference values. As quantitative information from different locations is being brought together, the positive and negative effects related to NbS across these different locations will emerge, providing a more robust basis for investment decisions or determine insurance values, ideally including also non-market values. In parallel, the further development of physical and economic models, statistical analyses, and stakeholder engagement approaches, that can to some degree draw on the same set of information, could promote the broader uptake of NbS by making their co-benefits more visible, measurable, and relevant across multiple policy and financial domains.

5. Conclusions

This literature review examined the range of methods available for evaluating the co-benefits of NbS, beyond risk reduction, exploring their respective strengths and weaknesses. The findings revealed that a variety of methods exist for assessing and capturing the multidimensional value of NbS, ranging from field sampling and observations to models software, tools and stakeholder engagement as well as economic valuation. However, challenges remain in guaranteeing their applicability in a variety of contexts. Enhancing data availability, improving the comparability of results and the fostering of collaboration between the scientific, policy and financial sectors are key to unlocking the full potential of NbS. Closing knowledge gaps and aligning assessment frameworks with decision-making processes will provide stakeholders with a clearer, and more practical understanding of the value of NbS. Additionally, future assessments should systematically incorporate the impact of climate change to ensure long-term effectiveness and resilience. Linking scientific evaluations with financial and policy frameworks can bridge critical gaps, support informed decision-making, and unlock new investment opportunities. Ultimately, addressing these gaps and fostering cross-sector collaboration will enable NbS to be recognised for more than just their role in reducing disaster risk, but also as sustainable, multifunctional strategies that deliver broad environmental, social, and economic benefits. This will support resilient and equitable development in diverse global contexts.

Declaration of generative AI in scientific writing

During the preparation of this work the authors used DeepL Write and ChatGPT- 4o in order to revise text for conciseness and conduct spell-checking. After using these tools, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

CRediT authorship contribution statement

Andrea Staccione: Writing – review & editing, Writing – original draft, Visualization, Methodology, Formal analysis, Data curation, Conceptualization. **G. Guillermo García Álvarez:** Writing – review & editing, Writing – original draft, Methodology, Data curation, Conceptualization. **Max Tesselaar:** Writing – review & editing, Methodology, Conceptualization. **W.J. Wouter Botzen:** Writing – review & editing, Methodology, Conceptualization. **Almut Arneth:** Writing – review & editing, Supervision, Methodology, Data curation, Conceptualization.

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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Supplementary materials

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Data availability

Data will be made available on request.

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