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Insular ecosystem services in peril: a systematic review on the impacts of climate change and other drivers

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Abstract
Islands around the world are disproportionately affected by climate change, and their adaptive capacity is generally lower than that of mainland areas. Ecosystems play a vital role in supporting the well-being of island communities; however, their response to climate change has not been thoroughly assessed. Following the PRISMA methodology, this study presents a systematic literature review that examines studies on the impacts of climate change on island ecosystem services worldwide. Our findings highlight that island ecosystem services studies are increasing over time. About 60% of studies that explicitly focused on climate impacts report adverse effects on these services, predominantly impacting marine ecosystems (including fisheries and coral reefs), with significant but less frequently studied effects on terrestrial ecosystems. Climate factors such as rising temperatures, increased sea levels, and extreme weather events are commonly associated with negative impacts on island ecosystems. These effects are intensified by the combined influence of non-climatic factors, particularly land-use changes. Although island ecosystem services hold potential for nature-based solutions towards climate mitigation, their effectiveness is limited by knowledge gaps and insufficient policy-driven adaptation strategies. Addressing these gaps is essential to support sustainable adaptation and resilience in vulnerable island communities.

Keywords Global warming · Ecosystems · Islands · Land-use changes · Policy interventions · PRISMA

1 Introduction

Human activities, primarily through emissions of greenhouse gases and extensive land-use changes, have unequivocally caused global warming of about 1.1 °C above the preindustrial levels in 2011–2020 (IPCC 2023a). This warming trend has accelerated in the most recent

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years (Urdiales-Flores et al. 2023). For instance, 2023 has been reported as the hottest year on record, following an exceptionally warm summer in the Northern Hemisphere (Esper et al. 2024). Among other impacts, climate change poses a pervasive and growing global threat to biodiversity, ecosystems and the services they provide (Weiskopf et al. 2020). Climate change is affecting ecosystems at multiple scales, ranging from individual species to ecosystem shifts in productivity, species interactions, and emergent properties (Weiskopf et al. 2020). The climate parameters that can directly impact ecosystems and their services include temperature (including air, land, and water bodies), components of the hydrological cycle (including precipitation, soil moisture, evapotranspiration and atmospheric humidity), cloud cover and radiation, mean sea level and other oceanic properties such as acidity. Due to non-linearity in climate processes induced by various feedback mechanisms, changes in these parameters are not uniformly distributed in space and time (Gu and Adler 2023; Urdiales-Flores et al. 2023; Zittis et al. 2024), while alterations in their mean state, variability, or seasonality can significantly impact ecosystems' distribution and functioning (Malhi et al. 2020; Gruber et al. 2021; Ruthrof et al. 2021). In addition, trends in climate extremes can differ from trends in the mean state (Zittis et al. 2021) and may be more likely to trigger abrupt changes in ecological systems than trends in the mean climate state (Turner et al. 2020).

At the same time, ecosystems can contribute to climate change mitigation, particularly through carbon sequestration, i.e., the uptake of carbon-containing substances (Lal et al. 2013). Established forests are major terrestrial carbon sinks as they accumulate and store more carbon for longer periods compared to non-forest ecosystems (Pan et al. 2011). Coastal ecosystems such as mangroves (Bhomia et al. 2016), salt marshes (Prahalad et al. 2020) and seagrass meadows are also important carbon sinks, sequestering and storing carbon at significantly higher rates per unit area than forests (Bertram et al. 2021). Recognition of their importance prompted the introduction of the term 'blue carbon'. In this respect, the conservation and restoration of blue carbon ecosystems is a key contribution of ocean-based activities for climate change mitigation (Duncan et al. 2016). Marine sediments are also a significant pool of organic carbon on the planet and a crucial reservoir for long-term storage (Atwood et al. 2020). As a result, the ocean is a major sink of atmospheric carbon, absorbing approximately 2.3 Pg of CO_2 from the atmosphere annually (Le Quéré et al. 2009).

Ecosystem services (ES) refer to the benefits that people obtain from ecosystems (MEA 2005). These services are fundamental to economic and social well-being (Ghaley et al. 2014). As defined by the Common International Classification of Ecosystem Services (CICES)[1] (Haines-Young and Potschin 2013), ES are the direct and indirect contributions of ecosystems to human well-being, and are structured into three primary categories: provisioning services (i.e., material or energy outputs from ecosystems, such as food, freshwater, raw materials, and medicinal resources (Hasan et al. 2020)), regulation and maintenance services (i.e., processes that moderate environmental conditions, including climate regulation (like carbon sequestration), flood control, disease mediation, and air or water quality regulation (Kremen et al. 2007; Smith et al. 2013; Ghaley et al. 2014)), and cultural services (i.e., non-material benefits, such as recreation, spiritual enrichment, and aesthetic experiences (Milcu et al. 2013)). Underlying these services are critical ecosystem processes and functions, such as soil formation, photosynthesis, pollination, and nutrient cycling. The concept of ES has been increasingly integrated into policy and environmental accounting

[1] https://cices.eu/

frameworks (Maes et al. 2013; Barton et al. 2024; United Nations 2024). Building on this, the Nature's Contributions to People (NCP) framework, advanced by the Intergovernmental Platform on Biodiversity and Ecosystem Services IPBES (Díaz et al. 2015, 2018), expands the ES approach by emphasizing the co-production of benefits through human-nature interactions. NCP recognizes that services are not solely ecological outputs but are shaped by human knowledge, practices, and interventions (e.g., sustainable farming or wetland restoration).

Island ecosystems are highly susceptible to the effects of climate change, including rising temperatures, sea level rise, and coastal flooding caused by extreme weather events (Garlati 2013; Leclerc et al. 2020; Macinnis-Ng et al. 2021). Over one-third of the global biodiversity hotspots deemed priorities for conservation are primarily or entirely composed of islands, with nearly all tropical islands located within these hotspot regions (Myers et al. 2000). Compared to the mainland, insular hotspots of biological and cultural diversity are also more vulnerable to tourism development, uncontrolled land-use changes and the consequences of financial crises (Vogiatzakis et al. 2023). For example, islands are ecologically fragile, have limited resources, and are more susceptible to natural disasters and externalities (Balzan et al. 2018; Vogiatzakis et al. 2020). Especially the smaller islands are disproportionately affected by climate change, despite contributing minimally to global greenhouse gas emissions (Tandrayen-Ragoobur et al. 2024). For instance, Small Island Developing States (SIDS) have substantially lower per capita carbon emissions, averaging 4.6 tCO_2-eq, compared to the global average of 6.9 tCO_2-eq (IPCC 2023a). Issues of inequity arise as vulnerable island populations face disproportionate consequences (Tandrayen-Ragoobur et al. 2024). Islands depend greatly on ES provided by their own, often limited, land (e.g., freshwater provisioning and pollination services) or the surrounding coastal and marine environments (e.g., coastal protection or food provision through fisheries) (Vogiatzakis et al. 2023). Ecosystems often provide vital services that benefit society beyond their boundaries, such as lifecycle maintenance, carbon sequestration, or recreation and tourism (Smale et al. 2019; Bratman et al. 2019). Thus, in terms of functional diversity or ecosystem services, islands depend on both marine and terrestrial, as well as freshwater ecosystems (Hernández-Delgado 2015; Balzan et al. 2018). Existing literature on nature-based solutions (NbS) indicates that island ecosystems can play a pivotal role in climate change mitigation and adaptation. For instance, coastal habitats such as mangroves and coral reefs act as natural barriers against storm surges and erosion, enhancing island resilience to climate impacts (Hilmi et al. 2025). Beyond coastal environments, traditional land-use practices such as agricultural drystone terraces in Mediterranean islands have gained recognition as NbS. In Cyprus, the abandonment of these practices was found to negatively affect soil organic carbon stocks (Djuma et al. 2020), while their restoration can enhance water retention and prevent soil erosion (Zoumides et al. 2017).

In addition to climate-induced factors, the functionality of ES is also influenced by various other drivers, including land-use changes, population growth and development, and the introduction of invasive species (Kumar Rai and Singh 2020; Hasan et al. 2020). Land-use changes, primarily driven by rapid urbanization and agricultural expansion, have led to widespread habitat degradation and loss. This degradation severely undermines essential ES such as carbon sequestration, biodiversity conservation, and water regulation (Hasan et al. 2020). Population growth exacerbates these pressures, particularly on islands with limited space and resources, as it intensifies land demands for infrastructure and agriculture (Marques et al. 2019). Furthermore, the introduction of invasive species (e.g., *Spartina alterniflora*) can alter ecosystem dynamics and reduce the functionality of native coastal wetlands, even in mainland habitats (Jiang et al. 2023). The small size of islands leads to smaller populations, species impoverishment and the absence of some functional groups, like top predators, creates greater vulnerability to the impacts of invasive species compared to continents (Russel et al. 2017; Barton and Fortunel 2023). Native species on islands are disproportionately vulnerable to invasives due to attributes related to behaviour, life-history and certain morphological characteristics (Tershy et al. 2015). Invasive species avoid competition either because they move into vacant niches or because of the limited ability of island species to compete (island syndrome) (Baeckens and Van Damme 2020). The interplay between these non-climate drivers and climate-induced factors is often overlooked in ES assessments. Filling this gap is vital for formulating effective conservation strategies, especially on islands where ecosystems are inherently vulnerable due to their isolation, limited resources, and high levels of endemism (Hasan et al. 2020; Vogiatzakis et al. 2023).

Although insular ecosystems are exceptionally vulnerable to climate change impacts, they remain underrepresented in global climate change assessments, with limited focus on their unique vulnerabilities and adaptive capacities (Leclerc et al. 2020; Bellard et al. 2025). Existing studies primarily assess the exposure of these ecosystems to climate threats rather than their resilience or adaptive needs (Smit and Wandel 2006; Whitney et al. 2017). Furthermore, while ES assessments are prevalent across various regions, there is a critical lack of focus on island ecosystems specifically, leaving substantial knowledge gaps regarding their response to climate and land-use changes (Aretano et al. 2013). In addition, while various uncertainties, such as modelling and data uncertainties, are inherent in ES assessments, their role in the uptake of ES assessment results in decision-making remains unclear (Walther et al. 2025). These gaps impede science-policy integration, which is essential for developing effective adaptation strategies (Cámara-Leret and Dennehy 2019).

To address these limitations and identify potential research gaps, this study systematically reviews the global scientific literature that assesses the impacts of climate change on the functioning or efficiency of ecosystem services in islands throughout the globe. Our integrated approach addresses a wide range of ecosystem services, including those of terrestrial, freshwater, coastal, and marine environments. The assessments'type and location, the chosen methodologies, the level of complexity and the consideration of uncertainties are some of the key factors explored. Thus, a core objective of this assessment is to provide a comprehensive understanding of the complex interactions between climate change and additional stressors on island ecosystems. Specifically, we aim to (i) explore the synergistic impacts of climate and non-climatic drivers—such as land-use changes, economic growth, and tourism—on ecosystem services, which are often overlooked in climate assessments; (ii) examine the potential of ecosystem services to serve as nature-based solutions for both climate change mitigation and adaptation in island contexts, and (iii) identify the role and efficacy of policy interventions in mitigating these impacts and supporting ecosystem resilience. Through this integrated approach, we seek to offer insights that support science-informed policy and sustainable adaptation strategies tailored to the unique needs of island communities.

2 Methods

2.1 Definition of islands and sea zones

In this study, we consider the international standard for the definition of what an island is, according to the United Nations Convention on the Law of the Sea.[2] Islands are defined as naturally formed areas of land, surrounded by water, which is above water at high tide. In contrast with rocks, islands can sustain human habitation or economic life of their own and have exclusive economic zones or continental shelves. An archipelago is a group of islands, including parts of islands, interconnecting waters and other natural features which are so closely interrelated that such islands, waters and other natural features form an intrinsic geographical, economic and political entity, or which historically have been regarded as such.

To facilitate the analysis and discussion, we used the United Nations Food and Agriculture Organization (FAO) Major Fishing Areas.[3] These are arbitrary areas, the boundaries of which were determined in consultation with international fishery agencies on various considerations, including (i) the boundary of natural regions and the natural divisions of oceans and seas, (ii) the boundaries of adjacent statistical fisheries bodies already established in inter-governmental conventions and treaties, (iii) existing national practices, (iv) national boundaries, (v) the longitude and latitude grid system. (vi) the distribution of the aquatic fauna, and (vii) the environmental conditions within an area. Here, we focus on the 19 major marine fishing areas that cover the waters of the Atlantic, Indian, Pacific and Southern Oceans, along with their adjacent seas, as defined in Supplementary Table 1.

2.2 Literature review methodology

Systematic reviews are a type of literature review that follows a specific set of scientific methods to limit errors, mainly by identifying, evaluating, and synthesizing all relevant studies to answer a specific question or set of questions (Petticrew and Roberts 2006). While individual studies can provide valuable insights to inform policy and practice, summarizing and analyzing a range of findings in a structured manner provides a more robust understanding of the topic at hand (Laplaza et al. 2017). By focusing on synthesizing evidence across the range of questions posed by policymakers and practitioners, systematic reviews more effectively employ existing research to develop and support evidence-based policies and decisions (Snilstveit et al. 2012). In the present study, we conducted a systematic literature review guided by the Preferred Reporting Items for Systematic Review Recommendations (PRISMA) protocol (Page et al. 2021). Specifically, we employed a three-step approach: first, systematic article identification via database searches; second, screening for excluding duplicates or irrelevant studies; and third, a review of selected articles with information extraction. This framework is informed by qualitative-oriented and synthesis-based methodologies relevant to ecosystem assessments. The three steps are presented in Fig. 1 and described in the following paragraphs.

[2] https://www.un.org/depts/los/convention_agreements/texts/unclos/unclos_e.pdf

[3] https://www.fao.org/cwp-on-fishery-statistics/handbook/general-concepts/main-water-areas/en/

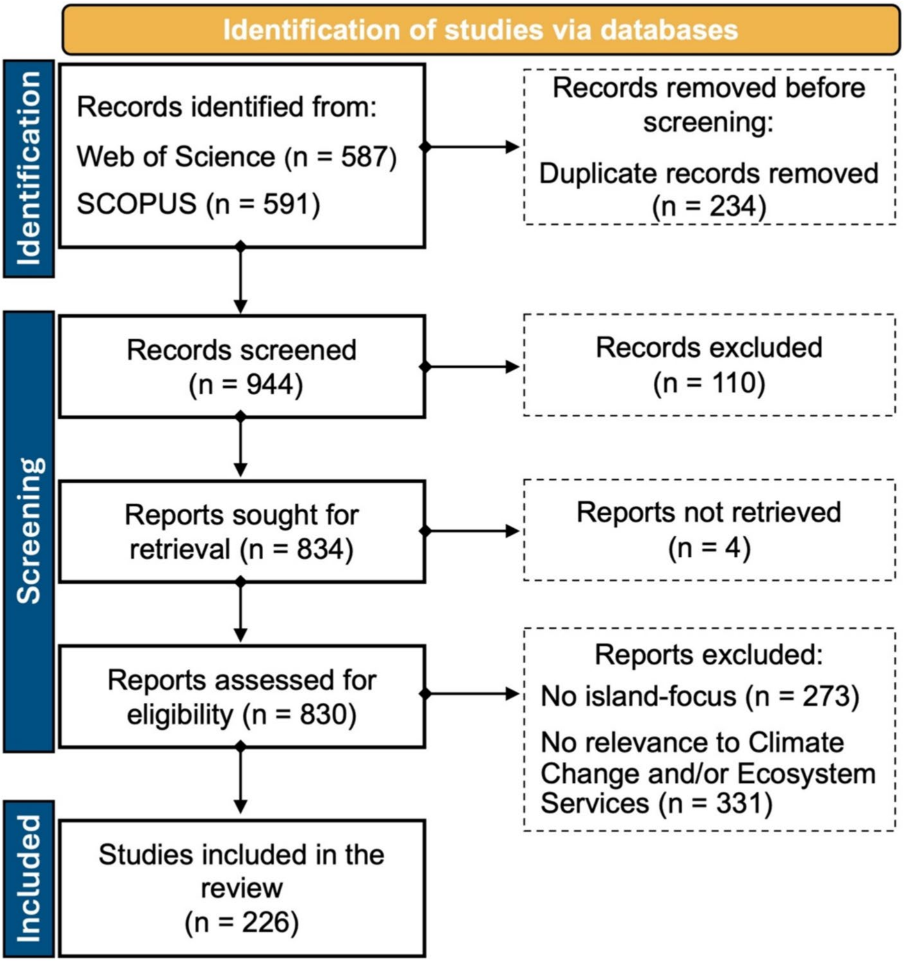

Fig. 1 Workflow of the systematic literature review, following the PRISMA framework

Search protocol and identification of studies For our literature search, we used the following terms and BOOLEAN search operators: (“ecosystem service*” OR “ecosystem good*”) AND (climat* NEAR chang*) AND (island* OR islet* OR archipelag* OR insular). These were applied on a topic search in two of the most widely used academic databases (Scopus[4] and Web of Science Core Collection[5]). We intentionally avoided using more specific terms such as ‘crops’ or ‘fisheries’ that could bias the results toward these services and return an impractical number of papers. The same applies to specific climate change phenomena (e.g., sea-level rise or global warming). The final search included studies published up to the year 2023 and was limited to peer-reviewed scientific articles written in English. Applying the search protocol resulted in a considerable volume of records (585

[4] https://www.scopus.com/

[5] https://www.webofscience.com/wos/

from Web of Science and 591 from Scopus). In this step, we also applied a pre-screening to remove 234 duplicate records.

Screening process From the 944 records, 110 were excluded because they did not refer to peer-reviewed publication types (e.g., book chapters or editorials). A total of 834 reports were sought for retrieval, but four of these could not be accessed. From the 830 reports that were assessed for eligibility, 273 were excluded because there was no apparent island focus. For example, in numerous cases, we excluded studies about ES and the "Urban Heat Island", a phenomenon that refers to urban areas being significantly warmer than their surrounding rural areas, or studies in locations with toponyms including the string "Island", that, however, were not islands according to our definition. In addition, 331 reports were excluded because the consideration of ES or climate change was superficial (e.g., these topics were merely mentioned in their abstract). This final screening yielded a total of 226 publications.

Literature review and coding This step involved the design of a questionnaire for recording the results, the literature review, and the coding of responses in a way that facilitates further analysis. The questionnaires included 31 questions that were divided into seven sections, comprising information about (i) the overall relevance, (ii) the study area, (iii) the ES assessed, (iv) the climatic drivers, (v) the non-climatic drivers, (vi) the role of decision making and policy interventions, and (vii) the overall treatment of uncertainty. The ES assessed (Supplementary Table 2) encompass provisioning services (food and nutrition provision; biotic and abiotic material provision; freshwater provision and regulation; genetic and biochemical resources), regulation and maintenance services (climate and atmospheric regulation; carbon storage and sequestration; waste and toxin mediation; soil formation and erosion control; biological control and pollination), and cultural services (physical and experiential recreation; aesthetic and inspirational value; cultural and spiritual significance). Furthermore, the study explicitly examined the impact of specific climatic drivers, including changes in temperature, shifts in precipitation patterns, sea-level rise, ocean acidification, and the increasing frequency and intensity of extreme weather events. The non-climatic drivers considered here to impact island ecosystem services are land use changes, alien species, population growth, economic growth and development, pollution, diseases and pests, resource extraction and degradation, technological advancements, and management or policy interventions. Possible responses were pre-defined for coding the outcomes in a binary form that would allow further data processing. This includes the extraction of statistics (e.g., for counting proportions of articles within certain categories) and visualizations for supporting the main findings and discussion. The questionnaire sample, including the pre-defined responses, is provided in Supplementary Table 3. Each article was reviewed once by a single author. For quality control and consistency in responses, a second round of review was conducted by the lead authors of the study.

3 Results

All studies presented and discussed in the results section were extracted from the systematic literature review. Due to the large volume of reports assessed, in this section, we provide only representative examples. This discussion is primarily organized according to the thematic sections introduced in the previous paragraph.

3.1 Geographic overview

Out of the 226 papers reviewed, the majority of knowledge regarding the impacts of climate change on insular ES comes from islands located in the Pacific Ocean (Fig. 2a). The Pacific Western Central Zone is the most studied region, represented in 47 studies (e.g., Butler et al. 2014; Kiddle et al. 2021; Hafezi et al. 2021; Agaton and Collera 2022; Al-Asif et al. 2022), followed by the Atlantic Western Central (e.g., Doughty et al. 2017; Nelson et al. 2018; Reguero et al. 2018; Powell et al. 2019), the Pacific Northwest (e.g., Jiang and Wang 2003; Kaeriyama et al. 2012; Bao and Gao 2021; Abe et al. 2022), the Pacific Eastern Central (e.g., Barbosa and Asner 2017; Bremer et al. 2018; Langle-Flores and Quijas 2020; Fezzi et al. 2023) and the Mediterranean (e.g., Milanesea et al. 2011; Lorilla et al. 2020; Grace et al. 2021; Ioannidou et al. 2021; Mateo-Ramírez et al. 2022). The latter is the smallest sea zone by area, yet it is discussed in nearly 10% of the published literature on the topic. Assessments mainly cover islands in one sea zone, while about 8% of the studies considered several sea zones or have a global coverage (e.g., Sasmito et al. 2016; Newton et al. 2018; Cook et al. 2022). Atlantic South West, Indian Ocean Antarctic and Indian Ocean Western were the least studied sea zones, followed by the Arctic and Antarctic, with virtually no peer-reviewed publications.

In terms of country coverage, relatively few studies consider more than five countries. Many of these countries are groups of small island states, mainly in the Pacific or the Caribbean (Marre and Billé 2019; Grima and Singh 2020). Thirty studies are for islands in the USA (Supplementary Figs. 1 and 2), with the majority focusing on the Hawaiian archipelago (e.g., Gibson et al. 2022; Asner et al. 2022). Islands in other countries located in the Pacific are also frequently assessed; for example, several studies focus on China, mainly on Hainan Island (e.g., Hughes et al. 2013; Wen et al. 2019; Ali et al. 2019), Vanuatu (Pedersen Zari et al. 2020; Buckwell et al. 2020a, b), and the Philippines (e.g., Duncan et al. 2016; Song et al. 2021; Agaton and Collera 2022). About a fourth of the published literature is about European countries, including overseas territories, for instance, the Canary Islands, Ascension or Saint Martin in the Caribbean. Greece, Spain and Portugal were the most studied countries in Europe (e.g., Nikolaidis 2011; Megía-Palma et al. 2020; Neves et al. 2021).

The first peer-reviewed studies that discussed the linkages between climate change and islands'ES were published around two decades ago, in 2003. (Fig. 2b). Both were about Pacific islands and, in particular, New Zealand's South Island (Schallenberg et al. 2003) and Hainan in China (Jiang and Wang 2003). Since then, the number of studies has grown significantly, with more than half of them published between 2020 and 2023. A consistent rise in research output is evident over time across all topics. However, the study of climate change impacts on island-focused ES exhibits a notably higher growth rate in relative terms (Supplementary Fig. 3). This trend, mostly evident in the last decade, underscores the novelty of the field and reflects the growing recognition within the scientific community of nature's contributions to human well-being.

3.2 Island ecosystems and their services

As anticipated, this review, which concentrates on islands, reveals that most of the examined ES services pertain to marine ecosystems (Fig. 2c), which were assessed in 69% of the studies. Such examples include seagrass habitats or coral reefs (Asch et al. 2018; Brodie et

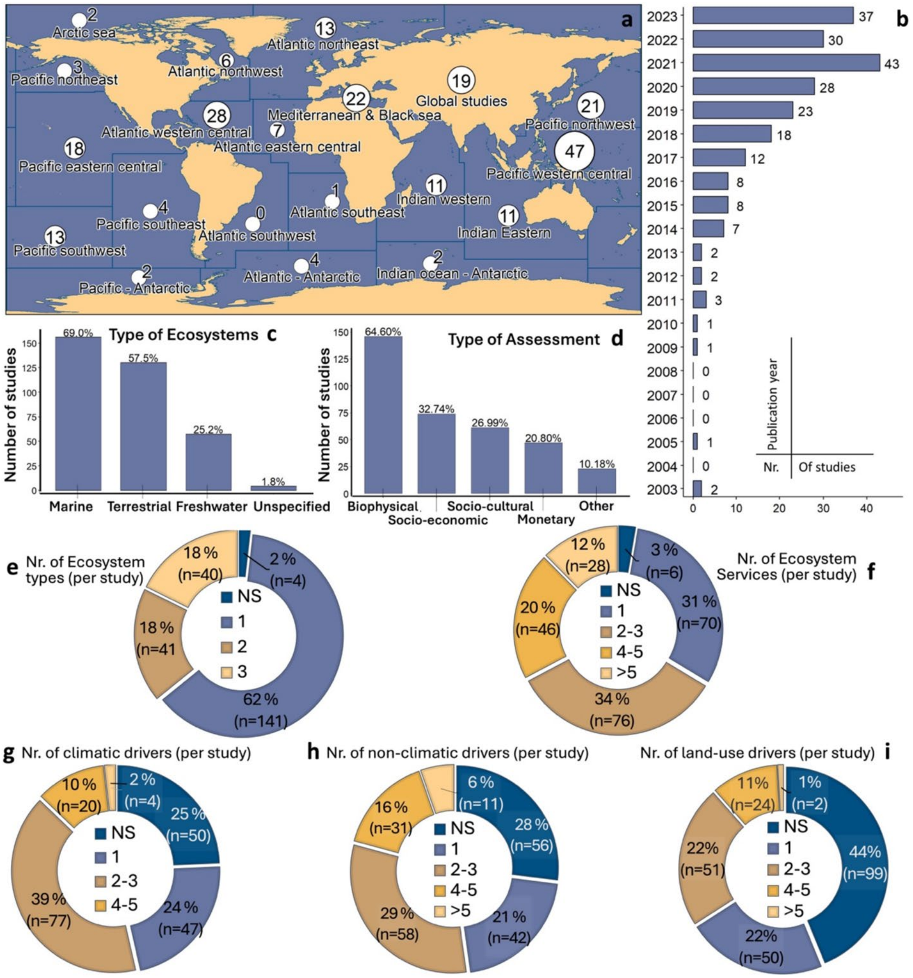

Fig. 2 Literature review summary in terms of geographic location of assessments (**a**), year of publication (**b**), type of ecosystems assessed (**c**), type of assessment (**d**), number of ecosystem types (**e**), number of ecosystem services (**f**), number of climatic drivers (**g**), non-climatic drivers (**h**), and land-use features considered per study (**i**). NS stands for not specified

al. 2020; Leiva-Dueñas et al. 2020; Al-Asif et al. 2022). Terrestrial ecosystems, e.g., tropical forests or other vegetation types, were assessed in 130 studies (e.g., Ágústsdóttir 2015; Latham et al. 2015; Nelson et al. 2018). A substantially smaller portion of publications (25.2%) studied freshwater ecosystems despite, for instance, the cruciality of freshwater supply for wildlife and farming (Kivilä et al. 2022; Wilmot et al. 2022). The majority of studies (62.4%) focus on a single ecosystem type (Fig. 2e). Relatively fewer cases considered more integrated approaches and included two (e.g., terrestrial and freshwater or marine and terrestrial) or all three types of ecosystems (Grima and Singh 2020; Wilmot et al. 2022).

Out of the 226 studies reviewed, 35% were exclusively model-based (e.g., Filgueira et al. 2014; Lillebø et al. 2019; Guyondet et al. 2022). These examples include hydrodynamic, biogeochemical, risk calculation or climate modeling tools. A similar subset (33.6%) included field measurements and ecosystem sampling (e.g., Morley et al. 2022; Steinmuller et al. 2022; Al-Asif et al. 2022), while 41 studies involved expert elicitation and stakeholder engagement as the primary methodological approaches (e.g., Singh et al. 2017; Ruiz-Frau et al. 2019; Abe et al. 2022).

Nearly two-thirds of the reports were biophysical in nature (Fig. 2d), assessing the direct response of ecosystems and their services under changing environmental conditions (e.g., Torres et al. 2021; Kivilä et al. 2022; Hapsari et al. 2022; Montero-Hidalgo et al. 2023; Meixler et al. 2023). Several studies (32.7%) performed a socio-economic assessment, and a monetary valuation was often included (e.g., Bremer et al. 2018; Newton et al. 2018; Pedersen Zari et al. 2020; Fezzi et al. 2023). Socio-cultural aspects, referring to the less tangible benefits obtained from islands' ecosystems, were assessed in 61 studies (e.g., Sangha et al. 2019; McNamara et al. 2021; Smart et al. 2021). Approximately one-third of the studies included more than one type of assessment (Pedersen Zari et al. 2020). Finally, some studies mentioned the term ecosystem services without specifying how these were assessed.

Nearly half climate change impact assessments (41.6%) focused on food and nutrition provision as the studied ES (e.g., Woodhead et al. 2021; Falardeau et al. 2022; Mayorga et al. 2022), with fisheries receiving particular attention (Fig. 3). Regulating services, such as climate and atmospheric regulation, including the moderation of extreme weather events and carbon storage and sequestration, were the focus of 89 studies (e.g., Murdiyarso et al. 2015; Trégarot et al. 2021; Steinmuller et al. 2022). Physical and experiential recreation (e.g., Banerjee et al. 2018; Abe et al. 2022) and soil formation and erosion control services were also frequently discussed (e.g., Hopkinson et al. 2018; Tourlioti et al. 2021). Other insular ES such as freshwater provision and regulation (e.g., Wilmot et al. 2022), biotic and abiotic material provision (e.g., Cook et al. 2022), services of cultural and spiritual significance (e.g., Buckwell et al. 2020b), ES of aesthetic and inspirational value (e.g., Ioannidou et al. 2021), biological control and pollination (e.g., Wyckhuys et al. 2022), waste and toxin mediation (e.g., Duijndam et al. 2020), and genetic and biochemical resources (e.g., Komugabe-Dixson et al. 2019) received less attention. At the same time, some studies mentioned ES as a general term but did not specify further. About one-third of the reviewed studies focused on services other than the ones specified here (e.g., Pouteau et al. 2018; Iwaniec et al. 2021). Regarding the variety of ES assessed, most studies (65%) only investigated either one or up to three services (Fig. 2f). Approximately one-fifth of the studies examined four or five ES, while only a few (12%) investigated five or more (e.g., Newton et al. 2018; Duncan et al. 2020).

3.3 Climate change impact on islands' ecosystem services

According to our analysis (Fig. 4), nearly half of the studies focused on the impact of temperature, mainly warming of the atmosphere or water bodies (e.g., Day et al. 2018; Crosby et al. 2018; Ochoa-Gómez et al. 2021), followed by sea-level rise (e.g., Sasmito et al. 2016; Hopkinson et al. 2018; Hapsari et al. 2022) and precipitation changes (e.g., Barbosa and Asner 2017; Nelson et al. 2018; Wen et al. 2021). Besides the mean climate conditions in terms of temperature or precipitation, about one-third of the reviewed studies discussed the effects of extreme events. Such examples include the impacts of floods in the Fiji Islands (Duncan et al. 2020) and storms in Prince Edward Island in Canada (Filgueira et al. 2014).

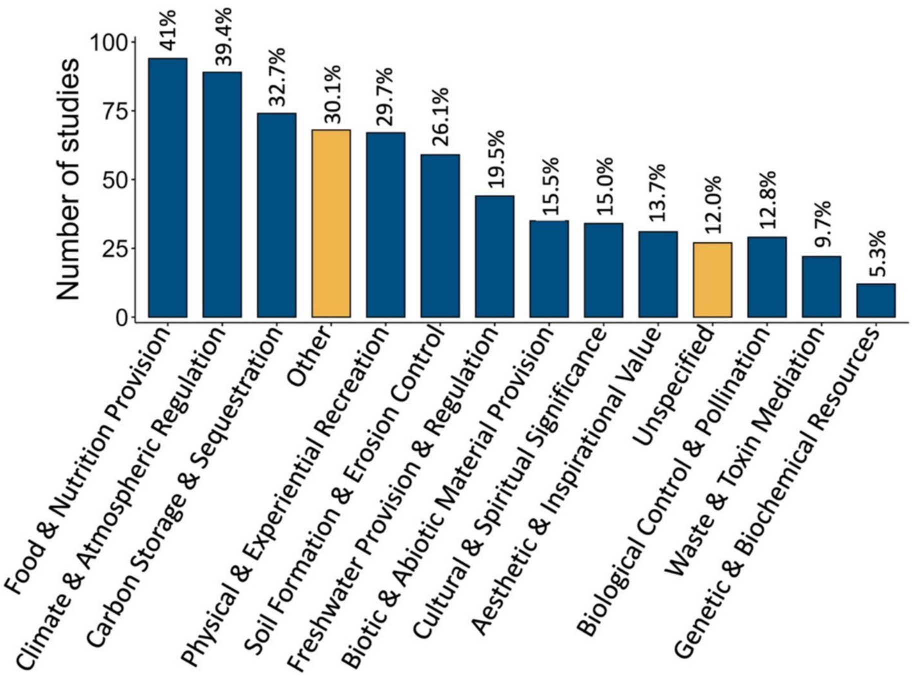

Fig. 3 Types of ecosystem services assessed in islands globally and the frequency of their assessment

Most studies discussed the impact of a single climatic driver (e.g., temperature only or sea level rise only) or the combined effect of two climate drivers, e.g., temperature and precipitation (e.g., Newton et al. 2018). Fewer studies considered several climatic drivers together, such as precipitation, extreme events, or ocean acidification, combined with the most commonly studied temperature and sea level rise (e.g., Hafezi et al. 2020). A few studies that included two or more climatic drivers also considered interactions between them. Interactions were synergistic, antagonistic or unclear. For instance, interactions between more than one type of extreme events in small tropical islands were assessed, and these interactions were found to be acting synergistically towards a negative impact (Hernández-Delgado 2015). Approximately half of the studies (45.6%) were assessments for the past or present, whereas only 18 explicitly involved future projections (e.g., Bremer et al. 2018; Tanner and Strong 2023). The remaining studies combined aspects of both past and future conditions (Sato et al. 2021).

More than half of the reviewed studies (52.2%) identified an adverse effect of climate change on the ecosystems of islands and their services (Figs. 4 and 5). This percentage rises to 60% when focusing only on studies that explicitly assessed the impacts of climate change (not shown). These are either studies that have incorporated some type of climate information, whether in the form of quantitative data (e.g., observations or climate simulations) or qualitative assessments (e.g., stakeholder perceptions). Influenced by the most frequently assessed ecosystem types, primarily marine and less often terrestrial, adverse impacts mainly refer to marine ES. Although this absolute comparison may suggest otherwise, normalizing the impact types reveals a comparable proportion of negative impacts

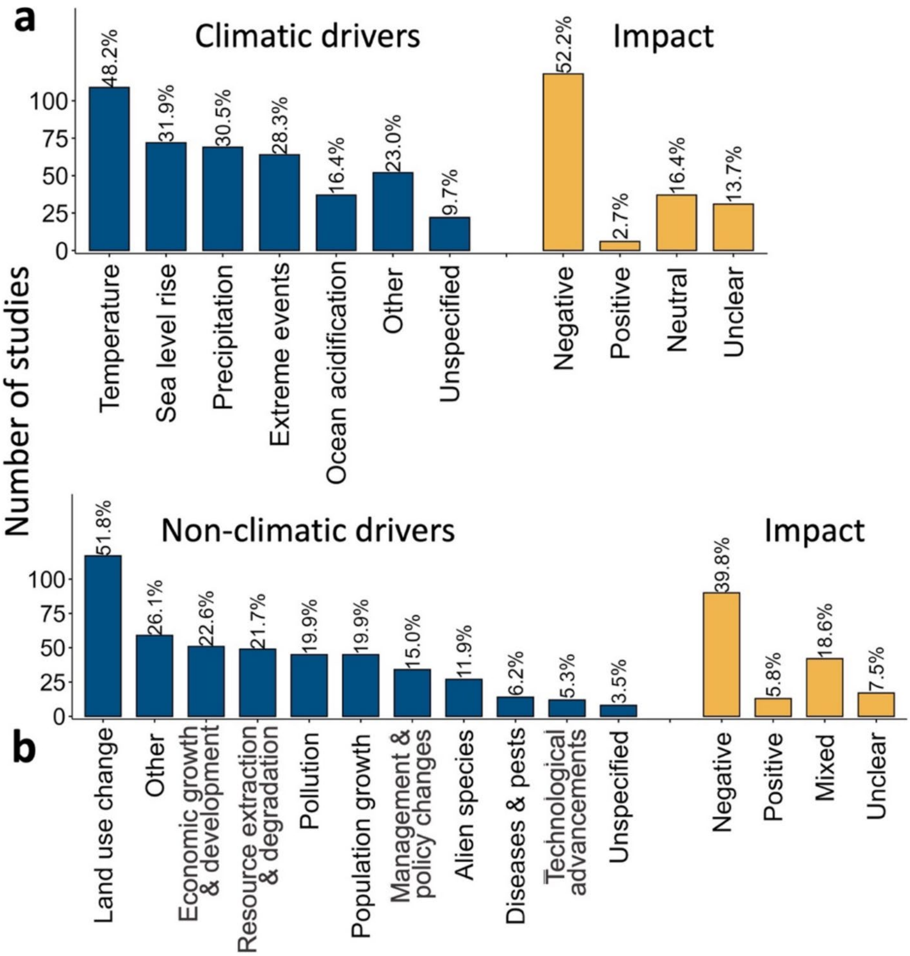

Fig. 4 Assessment frequency of (**a**) climatic and (**b**) non-climatic drivers and the effect of their impact

across all three ecosystem types (Fig. 5). Common threats include rising ocean temperatures, which are driving, for example, high-impact coral bleaching events (Fezzi et al. 2023) or can impact the productivity of fisheries (Neves et al. 2021) and, thus, food provisioning services. Other examples include impacts on coral reefs and seagrass beds through the intensification of hydrodynamic forces caused by sea level rise (e.g., James et al. 2023). Rising sea levels also impact terrestrial ES near coastal zones, for example, through the erosion of marsh edges in Plum's Island Sound estuary (Hopkinson et al. 2018). Such ecosystems provide services such as carbon dioxide sequestration and protection from coastal storms. Some studies (16.4%) identified a neutral or mixed impact, with both positive and negative effects. For example, in assessments that consider a large geographic area, changes in climate conditions might have a negative effect in one region (e.g., lower latitudes) and a positive impact in another (e.g., higher latitudes) (Sato et al. 2021). In relative terms, unclear impacts induced by climatic drivers are more evident in freshwater ES (Fig. 5). The impact was either unclear or unspecified in 31 cases, mainly because these studies mention climatic

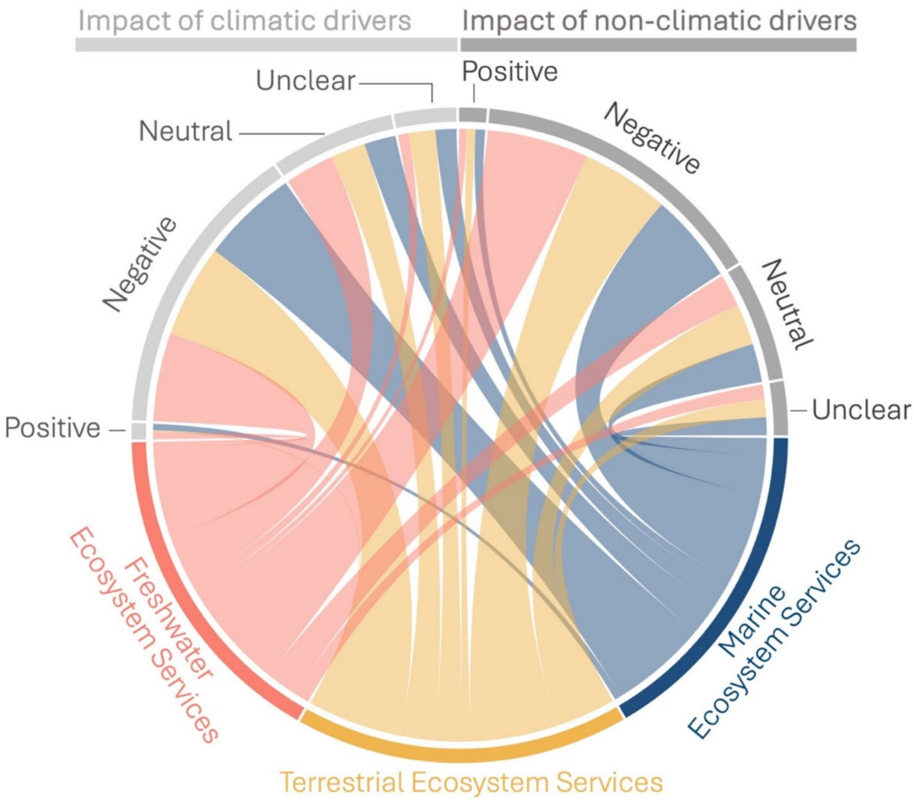

Fig. 5 Linkages between islands' ecosystem services and types of reported impacts. To facilitate an intercomparison between ecosystem types, these are normalized according to the number of studies that explicitly assess the impacts of climatic and non-climatic drivers

changes as a term but do not include any specific information about a specific climate driver. For example, studies that are mainly investigating the impacts of invasive alien species discuss their effects on ES and that these may become more pronounced under a warming climate (McCarthy et al. 2019). In such studies, climatic variables per se may not have been analyzed. Cases of positive impact were very limited (e.g., Filgueira et al. 2014; Ochoa-Gómez et al. 2021; Kivilä et al. 2022); however, both negative and positive impact cases are worth exploring further to unveil the complexity between climate and ES.

3.4 Synergies with non-climatic drivers

A substantial number of studies (72%) also considered other drivers together with climatic drivers (Barbosa and Asner 2017; Smart et al. 2021; Ondik et al. 2022). Most of the non-climatic drivers included the effect of land-use changes, which was discussed in 51.8% of the studies (Fig. 4b and Supplementary Fig. 4). Economic growth and development, resource extraction, and pollution were also often included (e.g., Singh et al. 2017; Bremer et al. 2018; Pedersen Zari et al. 2020; Fezzi et al. 2023). Human population growth, management or policy changes, as well as invasive alien species, were also included in the analysis as potential drivers of ES in islands in combination with climatic drivers. Diseases or pests, and technological advancements were only assessed in a few studies.

Out of the 163 publications that considered non-climatic drivers, 90 studies indicated a negative impact on islands' ES (e.g., Guillaume et al. 2018; van der Geest et al. 2020; Smart et al. 2021) (Fig. 4b). However, a limited number of studies also reported a positive impact. These were mainly related to habitat protection, reforestation, rewilding practices, and actions associated with policy interventions or improved management (e.g., Longley-Wood et al. 2022; Parker et al. 2023). In 42 assessments, the effect of non-climatic drivers was either mixed or unclear. The effect of non-climatic drivers was mostly synergistic or additive to the impact of climate drivers, i.e., primarily negative (e.g., Meixler et al. 2023). In much fewer studies (4.4%), this was antagonistic (e.g., Tourlioti et al. 2021), while in some cases, this was unclear (Montero-Hidalgo et al. 2023). In the cases where non-climatic drivers were included and synergistic effects were assessed, negative impacts were mostly reported. Conversely, when synergies were absent, the impacts tended to be less clear. The most common feature of land-use change is coastal zone degradation, which was discussed in 64 studies (e.g., Powell et al. 2019), followed by habitat protection (e.g., Buckwell et al. 2020b), urban expansion (e.g., Liu et al. 2021) and deforestation (e.g., Thaman 2014). Wetland modification (e.g., Doughty et al. 2017), reforestation (e.g., Atwell et al. 2018), rewilding (e.g., Magnan and Duvat 2020), and mining activities (e.g., Atwell et al. 2018) were also studied as land use change drivers impacting island ES.

3.5 Climate change mitigation through ecosystem services

Numerous studies have emphasized the crucial role of islands' ES in mitigating climate change. For example, seagrass meadows are highlighted as ecosystems that contribute significantly to carbon sequestration within the Coral Triangle in the Pacific or the Canarian archipelago in the Atlantic, with both regions severely threatened by anthropogenic activities, including climate change (Al-Asif et al. 2022; Montero-Hidalgo et al. 2023). Coral reef ecosystems are also significant carbon sinks by storing carbon in their calcium carbonate structures. Their functionality is challenged by sea-water temperature anomalies, ocean acidification, and sea-level rise. For example, in the Islas Marias archipelago located in the eastern tropical Pacific, hermatypic coral cover, carbonate production and sclerocronological characteristics showed a decrease rate, associated with thermal anomaly events (Tortolero-Langarica et al. 2022). Coastal ecosystems, such as mangroves in Indo-Pacific islands, are distinguished by high rates of tree and plant growth, coupled with anaerobic, water-logged soils that slow decomposition, resulting in large long-term Carbon storage (Murdiyarso et al. 2015). Despite their potential for mitigating climate change, extensive deforestation—often driven by aquaculture development—can result in significant CO_2 emissions. On land, peatlands are the largest natural terrestrial carbon store, storing more carbon than all other vegetation types in the world combined (Pereira et al. 2022). In island ecosystems like the Azores archipelago, the temperate climate with high precipitation and humidity levels throughout the year fosters the development of wet vegetation types, which are conducive to peat formation. Implementing restoration measures in these ecosystems can significantly enhance the carbon sequestration and buffering capacities of peatlands, providing a crucial strategy for mitigating climate change.

3.6 Ecosystem services and climate change adaptation in islands

Ecosystems can sustain social adaptation to environmental change by protecting people from climate change effects and providing options for sustaining material and non-material benefits as ecological structure and functions transform (Lavorel et al. 2020). As highlighted in nearly 40% of the studies reviewed, ES offer valuable, nature-based and cost-effective solutions for adapting to climate change, including local-scale climate regulation and the moderation of extreme weather events. This is especially crucial for islands with a lower capacity to adapt due to factors such as their distance from the mainland and limited access to either natural or financial resources. In this perspective, ecosystem-based adaptation is the use of biodiversity and ES to help people cope with the adverse effects of climate change. Common benefits of such adaptation measures include ameliorating extreme heat, mainly in urban settings, addressing the impacts of water scarcity and droughts, and protecting against sea-level rise or extreme events such as flooding (e.g., Mercer et al. 2012; Geneletti and Zardo 2016). Such measures may include restoring or conserving coastal and marine ecosystems, such as coral reefs, mangrove forests and seagrass meadows (Silver et al. 2019; Duncan et al. 2020), with less emphasis on the services provided by natural inland forests. Improved management of existing and newly established protected areas, restoration of riparian zones, urban greening, sub-urban and peri-urban home gardens, and improved agroforestry practices towards increasing resilience to changing climate conditions, and wildfires as well as enhancing food security (Pedersen et al. 2019; Mcleod et al. 2019). Over the past decades, beach nourishment has been implemented in small islands either to reduce beach erosion (e.g., in tourist areas) or to protect critical human assets (e.g., roads) that are highly exposed to storm waves. This method has been increasingly used to maintain beaches in the islands of the Maldives (Shaig 2011) and Barbados (Mycoo 2014). In the context of rising sea levels and extreme events, protecting and restoring coral reefs and coastal forests can be lower-cost, sustainable alternatives for shoreline protection. Risk reduction provided by coral reefs, mangroves, and seagrass along the entire Bahamas coast is identified as such an effective adaptation strategy (Silver et al. 2019).

3.7 Policy and management interventions

About one-third of the reviewed studies explicitly considered decisions and interventions related to policies, while a few others mentioned these aspects briefly. The majority overlooked the significant impacts of both policy and management interventions, as well as the potential consequences arising from their absence. Examples of effective policy or management interventions include more efficient irrigation practices and restoration of forests on the Island of O’ahu in Hawaii (Goldstein et al. 2012), tourists’ taxations for ecosystem conservation in Taiwan (Chen and Chen 2019), expanding protected area networks in the Pacific Islands (Kingsford and Watson 2011), or assessing and improving climate change readiness in the Seychelles (Khan and Amelie 2015). The most common approaches for determining the impact of such interventions on islands’ ES are adaptive management (Trundle 2020) and cost–benefit analysis (Buckwell et al. 2020a).

3.8 Sources of uncertainty

Uncertainty estimations in such assessments are of high essence, particularly when discussing the future impacts on ES (Runting et al. 2017). However, only a few studies (30.1%) have explicitly taken uncertainty into account, and even fewer have used quantitative approaches (e.g., Katsanevakis and Moustakas 2018). The majority of studies ignored any aspects or sources of uncertainty in their assessments. Identified sources of uncertainty were mainly related to the ES supply (e.g., Tortolero-Langarica et al. 2022) and climate information (e.g., Sasmito et al. 2016; Wilmot et al. 2022), while only in seven studies were other sources of uncertainty discussed (Langle-Flores and Quijas 2020). Common approaches used for estimating uncertainty include the development or use of future climate scenarios, for example, the representative concentration pathways (Mucova et al. 2021), the use of multi-model approaches such as ensembles of predictions or climate models (e.g., Wilmot et al. 2022), and statistical methodologies primarily associated with the sampling of ES (Lorilla et al. 2020).

4 Discussion and conclusions

The systematic review of the global peer-reviewed scientific literature on the impacts of climate change on island ES confirms a growing research interest over the past two decades, aligning with findings from other studies (Balzan et al. 2018; Vogiatzakis et al. 2023). The preparation and publication of the 6th Assessment Report of the United Nations Intergovernmental Panel on Climate Change (IPCC) may have driven this increase (IPCC 2023b). Nevertheless, this trend highlights a heightened recognition of the essential provisioning, regulating, and supporting benefits that island biodiversity and ecosystems offer to human well-being. Our review highlights that, despite extensive focus on biophysical impacts, socio-cultural assessments remain underrepresented—a gap of particular significance. The intangible cultural, recreational, and spiritual benefits provided by ecosystems are essential to island communities and often fundamentally shape their resilience to climate impacts. Addressing this gap will require innovative methodologies that capture these non-material values and clarify their role in enhancing adaptive capacity (Colloff et al. 2016; Sangha et al. 2019; Lavorel et al. 2020). Furthermore, strategies such as "Payments for Ecosystem Services" could offer promising avenues for ecosystem-based adaptation if carefully tailored to local conditions, with cultural sensitivities and social equity safeguards prioritized to ensure genuine environmental and community resilience benefits (Förster et al. 2019).

The knowledge of island ecosystems derives mainly from marine ecosystems, which is likely due to the physical geography of islands. Nevertheless, in relative terms, the negative impacts of climate change were found to be equally significant for terrestrial, marine and freshwater ES. The Western Pacific emerges as the most extensively studied region, followed by the Western Atlantic, including the Caribbean Islands. In contrast, there is limited research on island ES in the southeastern Atlantic Ocean, as well as in the Arctic and Antarctic Sea zones. As a result, the effects of climate change on the ES in these areas remain largely unexplored. The lack of research is likely attributable to their low population density and remoteness, which reduce research incentives and accessibility. This raises questions about the resilience of these less-studied zones, which in certain aspects (e.g., temperature increase) might be more impacted by climate change compared to islands in tropical or temperate zones.

The results of the systematic review indicate that the impact of climate change is predominantly negative, with rising temperatures in water bodies and the atmosphere being the primary driver. Other parameters such as increasing sea levels, changes in the hydrological cycle and extreme weather events were also found to significantly impact islands' ecosystems. Notably, fewer than half of the assessments examined the impact of multiple (i.e., more than one) climate parameters concurrently (O'Neill et al. 2017; Pouteau et al. 2018), overlooking potential synergistic effects. Complex interactions of climate change, such as a combination of regional warming and drying, could trigger positive feedback mechanisms, synergistic effects, and cascading impacts on local climate (Zittis et al. 2014; Hochman et al. 2022), and, thus, on ES. However, these dynamics have not been investigated in depth and remain largely underexplored. As a result, the adverse impacts of climatic changes on island ES are highly likely to be underestimated in the current literature.

Interestingly, the majority of assessments have focused on past or present climate conditions, while significantly fewer have addressed future climate projections. This gap may be largely due to the lack of regionalized climate information at the spatial resolution needed to capture fine-scale climate variations, particularly for smaller islands. This is also connected to addressing uncertainties regarding future climate projections, since large multi-model or multi-scenario ensembles, such as those from CORDEX—the Coordinated Regional Downscaling Experiment (Giorgi and Gutowski 2016). However, the spatial and temporal resolutions of these models are often not adequately tailored for effective assessments. This underscores the need for more precise tools and refined datasets to improve our understanding and responses to climate change.

The negative effects of climate change are often intensified by other stressors that work synergistically. Land use changes, such as coastal degradation, urban expansion, and deforestation, are commonly reported to adversely impact island ES. When interactions between climatic and non-climatic drivers are not assessed together, the effects often appear more ambiguous, suggesting a need for further investigation into these complex relationships (Louca et al. 2015). A few studies identified positive impacts of non-climatic drivers, primarily related to policy interventions, such as rewilding or reforestation practices (Longley-Wood et al. 2022; Parker et al. 2023). Nevertheless, our findings highlight that most studies have not explicitly considered the role of policy and management interventions in shaping ES outcomes. This omission is particularly critical, as policy-driven actions, including conservation initiatives, taxation mechanisms for ES, and adaptive management, can significantly influence the sustainability of ES (Kingsford and Watson 2011; Goldstein et al. 2012; Khan and Amelie 2015; Chen and Chen 2019). A key factor contributing to this oversight may be the broader challenge of uncertainty in both ecological and socioeconomic projections. As identified in our systematic review, uncertainty remains largely unaddressed, limiting the reliability of policy-relevant assessments. A forthcoming analysis (Demirel et al., in prep.) further examines how uncertainty is incorporated into ES and climate change studies on islands, revealing that uncertainty considerations are particularly scarce in policy-related evaluations. Therefore, addressing this gap requires interdisciplinary approaches that integrate environmental science with policy analysis to enhance the effectiveness of management interventions in island ecosystems.

Numerous studies emphasize the significant potential of island ES for mitigating and adapting to climate change. The proximity to marine environments, the abundance of coastal zones, and the temperate year-round conditions prevalent in many island regions, particularly those near the tropics, underscore the significant role of islands in global climate mitigation efforts, particularly towards ocean-based solutions. At the same time, island ES offer a wide range of benefits for climate change adaptation. Nature-based solutions for mitigating extreme heat or providing protection from extreme events and sea-level rise are widely recognized and discussed. This aligns with findings from broader research that is not specifically focused on islands but also identifies these services as key contributors to resilience (Donatti et al. 2020; Lavorel et al. 2020; Djuma et al. 2020; Zoumides et al. 2022; do Amaral Camara Lima et al. 2023; Kiran et al. 2023). The most commonly assessed services include food and nutrition provision, climate and atmospheric regulation, moderation of extreme events, and carbon sequestration, all of which underscore this potential. To maximise this potential, more emphasis should be placed on adaptation services, i.e., ecosystem processes or services, providing benefits to people by increasing their ability to adapt to environmental change, especially, though not exclusively, driven by climate change (Lavorel et al. 2015; Colloff et al. 2016). Such examples, also relevant to islands, include soil regulation services, microclimate regulation, provision of water for livestock and people, or mitigating storm surge, inundation and wind impacts on infrastructure. In this regard, ES should not be viewed merely as natural process outcomes but as co-produced benefits emerging from dynamic interactions between ecological and social systems (Lavorel et al. 2020). A growing body of literature on NCP emphasizes that knowledge co-production– through the weaving of scientific understanding with local and indigenous knowledge– can enhance adaptive capacity and sustainability outcomes (Tengö et al. 2017). Several of the reviewed studies explicitly highlight the role of local and traditional ecological knowledge in ES assessments and management. For example, Bremer et al. (2018) illustrate how local communities'traditional land-use knowledge in Hawaii influences land-use planning by incorporating cultural values, ES trade-offs, and scientific models. Similarly, Duncan et al. (2020) highlight the importance of community knowledge for managing multifunctional landscapes in Pacific Island countries, emphasizing that locally embedded knowledge systems shape access to resources and adaptive capacity. Additionally, Pedersen Zari et al. (2019) discuss the integration of local and indigenous knowledge into NbS to enhance resilience in Pacific urban areas, thus bridging the gaps in climate adaptation. This transformative perspective reinforces the broader relevance of integrating diverse knowledge systems into adaptation strategies, ensuring that NbS are both locally effective and context-specific (Zoumides et al. 2017; Díaz et al. 2018).

Given the complexity of these processes, a holistic approach is essential for thoroughly assessing environmental and climate changes impacting insular ES. This approach requires transdisciplinary methodologies and the active engagement of stakeholders and scientific communities with diverse expertise, including climate scientists, ecologists, biologists, and social scientists. Such collaboration is crucial for enhancing predictive accuracy regarding the impacts of climate change on island ES and for bolstering the adaptive capacity of island communities, ensuring they are better prepared for future environmental challenges.

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Declarations

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Consent for publication The Corresponding Author confirms that the present work has not been published before, it is not under consideration for publication elsewhere, and that its publication has been approved by all Co-Authors.

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