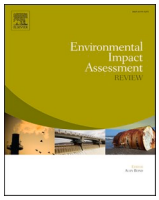
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The land use-climate change-biodiversity nexus in the perceptions of European islands stakeholders

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ABSTRACT

To promote climate adaptation and mitigation strategies, it is crucial to understand the perspectives and knowledge gaps of stakeholders involved in functions affected by or addressing land use and climate changes. A large number of stakeholders across 21 European islands were consulted regarding their views on climate change and land use change issues affecting ecosystem services on their island. Climate change characteristics perceptions included variables such as temperature, precipitation, humidity, extremes, and wind. Land use change characteristics perceptions included deforestation, coastal degradation, habitat protection, renewable energy facilities, wetlands and other variables. Other environmental and societal problem perceptions such as invasive

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species, water or energy scarcity, problems in infrastructures or austerity were also included. Climate and land use change impact perceptions were analysed with machine learning to quantify their importance on the perception outcome. For example if a stakeholder perceives that pollution, coastal degradation, deforestation, precipitation decrease, and increase of humidity are occurring on the island, and austerity is the biggest problem how likely is that the impact of climate change or land use change will be quantified by the stakeholder as negative, unclear, neutral, or positive? The predominant climatic change characteristic is related with temperature, and the predominant land use change characteristic with deforestation. Water-related problems are top priorities for stakeholders. Energy-related problems, such as energy deficiency but also wind and solar energy facilities problems, rank high as combined climate change and land use change risks. Stakeholders generally perceive climate change impacts on ecosystem services as negative, with natural habitat destruction and biodiversity loss identified as the top variables. Land use change impacts are also negative but also more complex to explain, with a higher number of explanatory variables associated with the impact outcome. Stakeholders have common perceptions regarding climate change and land use change impacts on the benefits of biodiversity despite the geographic disparity. Stakeholders differentiate between factors related to climate change impacts and land use change impacts. Water, energy, and renewable energy related issues pose serious concerns to island stakeholders and management measures are needed to address them.

1. Introduction

The rapid pace of global change, characterized mainly by climatic and land-use changes, presents significant challenges to biodiversity conservation and sustainable development (Pörtner et al., 2023; WWF, 2020). Islands make up only a small portion of the Earth's surface, yet they are home to over one-third of the global biodiversity (Pichot et al., 2024; Steibl et al., 2024). Ecosystem services, including provisioning, regulating, mediating, and cultural functions, are underpinned by essential ecosystem processes like soil formation, photosynthesis, pollination, and nutrient cycling (Elmqvist et al., 2012). These services are also heavily dependent on climate conditions, land use, and anthropogenic disturbances (Zittis et al., 2025). However, significant knowledge gaps remain regarding island ecosystem services and their response to climate and land-use changes, hindering both basic understanding as well as science to policy assessments (Mycoo and Roopnarine, 2024; Solé Figueras et al., 2024). European islands face unique challenges regarding ecosystem services, including vulnerability to climate change, habitat loss, pollution, and invasive species, all of which can impact the flow of vital services like clean water, food production, and recreation (Vogiatzakis et al., 2023). Challenges are often exacerbated by factors like tourism development, land-use changes, and resource extraction (Aretano et al., 2013). These facts and that island ecosystems are particularly vulnerable makes them valuable case studies for exploring the interplay within the land use–climate change–biodiversity nexus (Moustakas et al., 2025).

Key climatic parameters affecting ecosystems include temperature, precipitation, humidity, wind, extremes, hydrological cycle components, and oceanic properties. Climate change can also impact mental health, wellbeing, and sense of safety (Clayton and Swim, 2025) due, for example, to extreme weather events that damage both natural habitats and infrastructure (Handmer et al., 2012). These habitats and infrastructure may be critical for the island social, economic, and environmental functioning as there may be no other of the kind (Martin del Campo et al., 2023; McEvoy et al., 2024). Considering that many islands are attractive tourist destinations, climate change may be a critical factor in modulating the length and peaks of tourist season (Becken and Wilson, 2013), for example, through higher temperatures in spring and autumn or more heatwaves in summer (Hernandez et al., 2018). In addition, tourism increases the total demand for water (Becken, 2014), making it difficult to meet the needs (Falkland, 1999) already in deficit from the effects of climate change and increasing demand from farmers and primary productivity (Kourgialas, 2021).

Land use changes, including urban expansion, mining, deforestation, coastal zone degradation, and wetland modification, frequently result in habitat loss, fragmentation, and biodiversity decline (Haines-Young, 2009). These changes can undermine climate change mitigation and adaptation efforts, often interacting synergistically with climatic impacts, though such interactions are poorly understood (De Chazal and Rounsevell, 2009). While certain land-use changes, such as habitat protection, rewilding, and reforestation, can enhance biodiversity and ecosystem services, land-use change remains the primary threat to biodiversity on a global scale (IPBES, 2019; WWF, 2020, 2022). Notably, these conclusions are predominantly based on terrestrial data and fail to capture the unique dynamics of island ecosystems, where land-use pressures often concentrate in coastal zones due to high demand for housing and tourism infrastructure (Vogiatzakis et al., 2023). Seasonal energy demands further exacerbate these pressures, leading to the installation of wind and solar energy facilities (Mauger et al., 2024). Although these installations promote renewable energy, they also contribute to habitat fragmentation and biodiversity loss by occupying agricultural and natural land areas (Kuang et al., 2016). The European Commission's "renewable islands for 2030" initiative has confirmed 30 islands and groups aiming for energy independence by 2030, despite inadequate spatial planning and insufficient stakeholder consultation (Cuka, 2025).

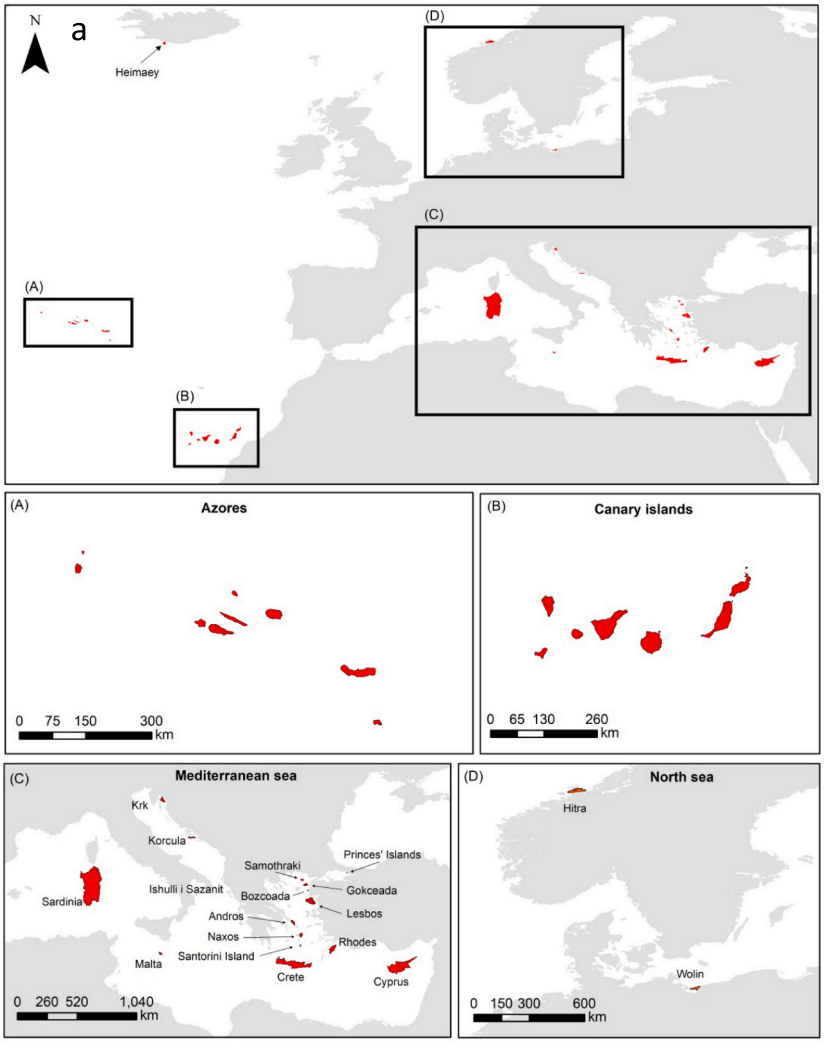
Biodiversity and ecosystem services are influenced by various additional social and economic factors (Kopnina et al., 2024). These may include demographic growth, technological advancements intensifying or relaxing natural resource exploitation, and pollution. In addition, invasive alien species, diseases, and pests can have pronounced effects on island ecosystems (Bjarnason et al., 2017; Thaman, 2002). Over-tourism generates pressure in island infrastructure such as roads and airports, housing, cost of living and waste, acting as a deterring factor for living or working in such islands stimulating debates about sustainable practices and development (Fernández et al., 2024; Kelman, 2022). Admittedly not everything can be attributed to climatic or land use changes alone. For instance, in one of the world's lowest-lying island nations (Marshall Islands) that are vulnerable to sea level rise and flooding, the majority of their population identified that education, healthcare, employment, and family visits outranked climate change and sea level rise as the main migration motive (van der Geest et al., 2020). Similar results have been recorded in other islands where financial austerity is common (Butler et al., 2014). Thus, climatic and land use factors need to be analysed in conjunction with social, financial, and other environmental factors in order to quantify their overall importance.

Perception is a subjective assessment of a concept or sensation, influenced by interests, personal growth, and the environment with profound variations between locations and individuals or groups within locations (Antronico et al., 2020; Dhar et al., 2023). In addition, the response to perception is influenced by cultural or monetary aspects and worldviews, such as the potential role of individual actions, anxiety over future climate scenarios, or the inevitability of climate change (Salas Reyes et al., 2021). Thus, an interdisciplinary approach including social, climatic, environmental, and biological sciences is needed (Balzter et al.,

2023). In addition, the scientific methods deployed need to account for the complexity of the problem investigating simultaneously several potential partly correlated variables and identifying their relevant contribution to the perception outcome (Fisher et al., 2019). Questionnaires are a popular tool in social surveys to address information about stakeholder perceptions, knowledge, and beliefs that are widely used for perception analyses, providing a heuristic function that allows information to be sorted and retrieved (Otto-Banaszak et al., 2011; Tourlioti et al., 2024).

The aim of the present study was to collect information on climate change and land use change related challenges issues from a local stakeholder perspective, and identify the main factors affecting European islands (Vogiatzakis et al., 2023). Several studies on nexus approaches explore interconnections across sectors (Authier et al., 2024; Dale et al., 2011; Newman et al., 2020; Nie et al., 2019), yet this research stands out by addressing the interplay of climate change, land use, and biodiversity benefits specifically within the climatically, biodiversity, culturally, economically, and geographically diverse context of European islands. Our research addresses the land use-climate change-biodiversity nexus by analyzing perceptions of stakeholders residing on islands. None have focused on such a broad and diverse spectrum of islands and archipelagos. This work deploys data from questionnaires distributed in over 21 European islands or groups of islands and across a large number of stakeholders in order to assess the perception of problems and associated factors regarding the land use changes-climatic changes-biodiversity nexus (Dale et al., 2011; Rasmus et al., 2024; Ruiz et al., 2023). Data were analysed with machine learning in order to simultaneously handle together a large number of variables and quantify their contribution to the perception of environmental problems in island societies (Fisher et al., 2019; Ruiz et al., 2023).

Stakeholders included are permanent inhabitants of the island studied or individuals that their primary financial activity is associated with presence on the island, from diverse backgrounds. The research questions addressed are: (1) What are the climatic variables that best quantify climate change? (2) What are the land use or land cover characteristics that best quantify land use change? (3) What are the climate- and land use change-induced problems on ecosystem services and how severe are they? (4) In addition to climatic changes and land use changes, what are the main additional environmental, societal, and economic problems and how severe are they? (5) What are the impacts of climate change on the benefits of biodiversity? Can impact perceptions outcomes be explained by climate and land use changing variables, climate change and land use change induced problems, together with the additional environmental, economical, and societal problems occurring on the island? How important is each variable on the impact outcome perception? (6) What are the impacts of land use change on the benefits of biodiversity? Can impact perceptions outcomes be explained by climate and land use changing variables, climate change and land use



b

Island	Country	Size (km²)	Stake holders
Sazan	Albania	5.70	30
Krk	Croatia	405.80	30
Korcula	Croatia	279.00	30
Cyprus	Cyprus	9,250.00	60
Crete	Greece	8,336.00	30
Andros	Greece	379.20	30
Santorini	Greece	76.19	30
Rhodes	Greece	1,400.68	30
Naxos	Greece	429.79	69
Samothraki	Greece	180.36	10
Lesvos	Greece	1,633.00	30
Heimaey	Iceland	13.40	10
Sardinia	Italy	24,090.00	91
Malta	Malta	316.00	34
Hitra	Norway	571.50	30
Wolin	Poland	265.00	31
Azores	Portugal	759.00	31
Canary Islands	Spain	7,493.00	41
Princes' Island	Turkey	10.60	30
Gokceada	Turkey	286.00	30
Bozcaada	Turkey	37.60	30

Fig. 1. a. European islands location. Each island included is depicted in red colour. **b.** Country of the island, surface area, and number of stakeholders. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

change induced problems, together with the additional environmental, economical, and societal problems occurring on the island? How important is each variable on the impact outcome perception?

2. Methods

The study included 737 stakeholders from 21 different islands or archipelagos across 12 European countries (Fig. 1). Stakeholder perceptions were recorded between February to April 2024. Stakeholders included are either permanent inhabitants of the island or individuals that their main financial activity is related with continues presence on the island. Islands were selected opportunistically based on the willingness of an academic researcher to participate in the study and collect stakeholder data on a European island that is within their expertise and research interests. Each academic researcher participating acted as mediator between the island stakeholders, was present on the study island and responsible for identifying stakeholders and contacting them.

Regarding stakeholders within each island, diverse professional groups were opportunistically contacted per island, so as to cover a wide range of professional activities including eight broad groups: (1) public authority/policy makers, (2) professionals in primary sector (agriculture, fisheries, stock raising, forestry), (3) technicians and associated

Table 1
Variables recorded and their feasible answers or scores.

Category	Var Nr	Var Name	Value				
(i) Climate change variables							
Question (i) What are the climate characteristics changing in your island?	1	Temperature	Yes/No				
	2	Precipitation	Yes/No				
	3	Wind increase/storms	Yes/No				
	4	Ocean acidification	Yes/No				
	5	Sea level rise	Yes/No				
	6	Humidity increase	Yes/No				
(ii) Land use / land cover change variables							
Question (ii) What are the observable land use / land cover changes in your island?	7	Deforestation	Yes/No				
	8	Reforestation	Yes/No				
	9	Rewilding	Yes/No				
	10	Wetland modification	Yes/No				
	11	Coastal degradation	Yes/No				
	12	Habitat protection	Yes/No				
	13	Renewable energy facility issues	Yes/No				
	14	Mining related issues	Yes/No				
	15	Urban expansion related issues	Yes/No				
(iii)Ranking overall problems	Values ranking the observed effects of problems on the island context, from 0 for Don't Know, 1 for having a small effect, 2 having a moderate effect, 3 having an important, to 4 having a very big/significant effect						
(iii) Rank the effects of these problems on your island	16	Climate change	0	1	2	3	4
	17	Land use change	0	1	2	3	4
	18	Population growth	0	1	2	3	4
	19	Economic growth	0	1	2	3	4
	20	Pollution	0	1	2	3	4
	21	Resource extraction	0	1	2	3	4
	22	Policy changes	0	1	2	3	4
	23	Nature overexploitation	0	1	2	3	4
	24	Austerity	0	1	2	3	4
(iv) Climate change & land use change problems.	Values ranking the perceived presence of each problem induced by climate change, from 0 for Don't Know, 1: Not so much, 2: Relative change yes 3: Yes, observable change to 4: Yes, very much climate -induced change.						
Question (iv) How would you assess the main climate and land use change induced problems in your island? (0-4)	25	Tourism	0	1	2	3	4
	26	Damages in habitats, protected areas or monuments etc	0	1	2	3	4
	27	Primary sector (Agriculture, fisheries etc)	0	1	2	3	4
	28	Ecosystem Destruction/Biodiversity loss	0	1	2	3	4
	29	Changes in urban environment	0	1	2	3	4
	30	New diseases	0	1	2	3	4
	31	Invasive species	0	1	2	3	4
	32	Carbon sequestration	0	1	2	3	4
	33	Pollination	0	1	2	3	4
	34	Energy related issues	0	1	2	3	4
	35	Soil erosion	0	1	2	3	4
	36	Water related issues	0	1	2	3	4
	37	Ecosystem recreation	0	1	2	3	4
	38	Infrastructure damages	0	1	2	3	4
Climate change impact on the benefits of biodiversity.	39	Climate change impact on ecosystem services	Negative	Unclear	Neutral	Positive	
Land use change impact on the benefits of biodiversity	40	Land use change impact on ecosystem services	Negative	Unclear	Neutral	Positive	

professionals, (4) professionals in the food industry, (5) professionals in the financial sector, (6) academics/researchers, (7) professionals in tourism, or (8) other, including among others house working individuals, students residing on the island, or unemployed. Sampling across professions incorporates heterogeneity in the perceptions and ecosystem services of interest. Call for participation was conducted via the online platforms and dissemination tools of the research program that funds this research. This aimed mainly at academic stakeholders residing on the island (other than the academic collecting the data for the island). In addition the questionnaires were emailed on mailing lists, posted on social media web pages, and official email addresses of various professional island groups, and authorities. This was achieved by sending them an excel file or a link to an online Google form with the questions and feasible scores (Table 1). In addition, face-to-face questionnaire completion with stakeholders was conducted. Online answers accounted for 42 % of stakeholders, while completed in person accounted for 58 % of stakeholders.

Prior to filling in a questionnaire from each stakeholder, a basic definition of "Ecosystem Services" was provided to be on a safe side that the concept is understood. Ecosystem services were defined as "the benefits that humans derive from biodiversity and ecosystems, including both the goods and services that nature provides. These services, which are essential for human well-being and economic activity, range from the production of food and clean water to the regulation of climate and disease". Some practical examples followed. Stakeholders were asked to indicate their perceptions on a binary and some on a five-point 'Likert-type' scale (Feliciano et al., 2017) allowing for ranking observed effects of climate change for example (with 0 counting for Don't know). The application of ranking for assessing level of perceived significance and the relevant answer options provided are described in Table 1.

2.1. Questionnaire design

The questionnaire consisted of pre-defined, close-ended questions designed to quantify island stakeholders' perceptions of the land use change–climate change–biodiversity benefits nexus (Otto-Banaszak et al., 2011; Tourlioti et al., 2024). Responses were either binary (YES/NO) or based on ranking problems on a 0–4 scale (0 = N/A, 4 = highest intensity). The survey was conducted in twelve languages (English, Spanish, Italian, Greek, Albanian, Turkish, Croatian, Portuguese, Norwegian, Polish, Maltese, and Icelandic). Participation was voluntary and anonymous, and all respondents were adults (>18 years). A minimum of 30 participants per island was targeted; however, only 10 were recruited in Heimaey and Samothraki (Fig. 1). Even in those islands a heterogenous sample regarding professions of stakeholders was achieved.

2.2. Climate change characteristics

Binary questions (0 = No, 1 = Yes) captured perceptions of changes in: (1) temperature (increase, decrease, extreme events, heat island effects), (2) precipitation (increase, decrease, variability/extremes), (3) wind (increase/storms), (4) ocean acidification, (5) sea level rise, and (6) humidity (Table 1). Multiple responses were permitted with examples provided in the questionnaire.

2.3. Land use change characteristics

Binary questions (0 = No, 1 = Yes) assessed perceived changes in: (1) deforestation (e.g., fire, tourist infrastructure, agriculture), (2) reforestation, (3) rewilding, (4) wetland modification, (5) coastal zone degradation, (6) habitat protection, (7) wind/solar energy facilities, (8) mining, and (9) urban expansion (Table 1). Multiple responses were permitted, with examples provided in the questionnaire.

2.4. Climate and land use change problems

Stakeholders ranked 14 potential problems (0–4 scale; 0 = N/A, 1: Not so much, 2: Relatively yes 3: Yes, observable change to 4: Yes, very much climate -induced change), including changes in tourist destinations, damage to landmarks, food risks, ecosystem destruction, urban changes, new diseases, invasive species, carbon sequestration, pollination, overconsumption, soil erosion, water issues, ecosystem recreation, and infrastructure damage (Table 1). Examples were provided to ensure participants understand the question in a similar way and can interpret it in similar way when answering (eg. For water issues, we mentioned water security, salinity levels, pollution etc. and for 'ecosystem recreation' we provided explanation in the form of benefits from visiting nature and enjoying activities outdoors).

2.5. Overall problems

A second ranking question (0–4 scale; 0 for Don't Know, 1 for having a small effect, 2 having a moderate effect, 3 having an important, to 4 having a very big/significant effect) evaluated overall perceived problems, including separate scores for climate change, land use change, population growth, economic growth, pollution, resource extraction and degradation, policy changes, biodiversity overexploitation, and financial problems (Table 1). This allowed us to capture residents' participants observed effects while assigning them a relative level of presence on each island context.

2.6. Impacts on ecosystem services

Stakeholders evaluated the impact of (a) climate change and (b) land use change on biodiversity-related ecosystem services using four options: negative (1), unclear (2), neutral (3), or positive (4). To ensure participants understand the meaning of ecosystem services, we provided a common explanation to the term services, as the benefits stemming from ecosystems and their use for supporting human and planetary wellbeing. Responses were mutually exclusive and treated as ordinal values, with lower scores reflecting stronger negative impacts.

2.7. Impact analysis on ecosystem services

We sought to explain what drives perceptions (negative, unclear, neutral, or positive) regarding the impact of climate change on the benefits of biodiversity. To do so we combined all data regarding climate characteristics changing, land use characteristics changing, problems related with climate change and land use change, and overall societal, economic, and other environmental problems occurring as perceived by the stakeholders. Perceptions of island stakeholders analysed here derive from diverse stakeholder backgrounds, islands, countries, isolation factors, climate & land use characteristics and other societal, economic, and environmental problems. The data involves a large number of variables and perceptions potentially correlated across stakeholders' background, island geography, or country. For the analysis of impact perceptions, we used Random Forest (RF) classifiers, a machine learning technique (Breiman, 2001). RFs are among the most efficient analytic tools for extracting information in noisy, complex, potentially correlated, and high-dimensional datasets such as the one deployed here and have been applied to a wide range of environmental topics (Daliakopoulos et al., 2017; Fisher et al., 2024; Moustakas and Davlias, 2021).

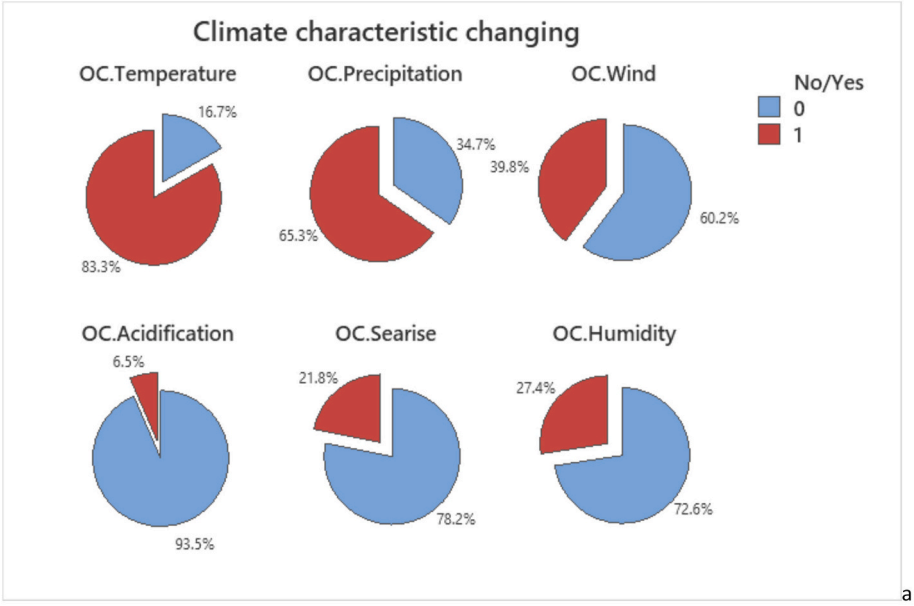
In order to quantify stakeholder perceptions regarding climate change impacts on the benefits of biodiversity, the dependent variable included climate change impact on ecosystem services (variable 39, feasible scores 'negative = 1', 'unknown = 2', 'neutral = 3', or 'positive = 4'.). RFs were fit with independent explanatory variables that included (i) the climate change characteristics (variables 1–6), (ii) land use / land cover change characteristics (variables (7–15), (iii) climate

change and land use change problems (variables 18–24; variables 16–17 not used), and (iv) overall problems (variables 25–38) as independent variables.

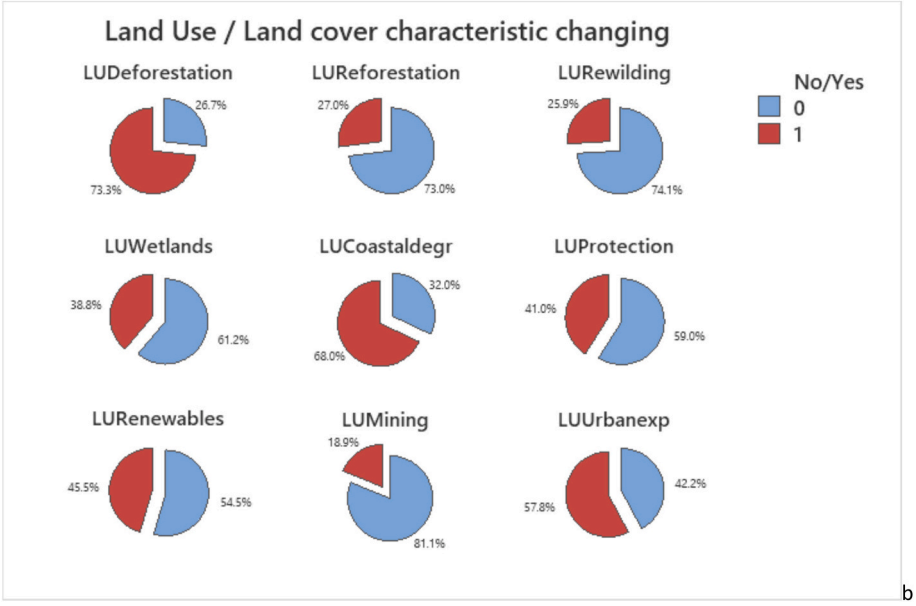
The analysis was replicated with the same independent explanatory variables as above (variables 1–38 excluding variables 16–17), and as dependent variable, land use change impacts on ecosystem services (variable 40, feasible scores also 'negative = 1', 'unknown = 2', 'neutral = 3', or 'positive = 4').

We trained and tested RF classifiers, using 10 different random states. All binary variables (variables 1–15) were treated as categorical predictors, while variables 18–38 as continuous predictors. The data split partitioning approach explored included a random partition of 70 % of stakeholders for training and 30 % for testing model outputs (Alif and Fahrudin, 2024). Sensitivity analysis performed by changing the training to testing data partition (Moreno-Alcayde et al., 2024) by up to 10 % resulted in similar or almost identical results. We did not employ multiple machine learning methods simultaneously, ensemble learning, and compare their accuracy (Sakti et al., 2024) as the objective of this study is to explicate rather than predict in novel circumstances, or to evaluate the most effective predictive tools and their accuracy.

The accuracy is defined as the number of correct bin classifications divided by the total number of instances in the dataset. In order to quantify the relative importance of each factor in the impact assessment outcome a relative variable importance chart was deployed (Venkateswarlu and Anmala, 2024). The relative variable importance chart depicts the predictors in descending order of their impact on model enhancement from all the basis functions for a predictor. The relative variable importance is used to standardize the importance values for easier interpretation (Venkateswarlu and Anmala, 2024). Relative importance is defined as the percentage improvement relative to the most important predictor, which has an importance of 100 %. The relative importance is calculated by dividing each variable's importance score by the largest value of the variables, then multiplying by 100 %.

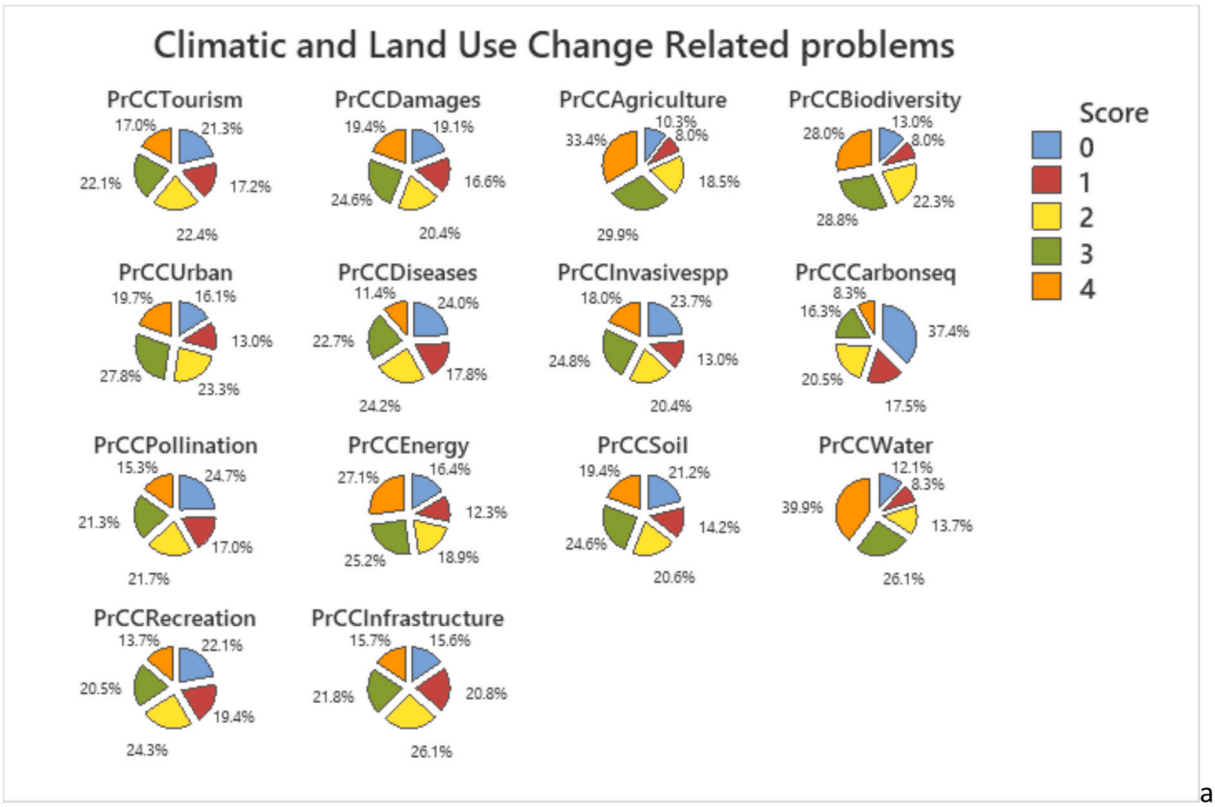


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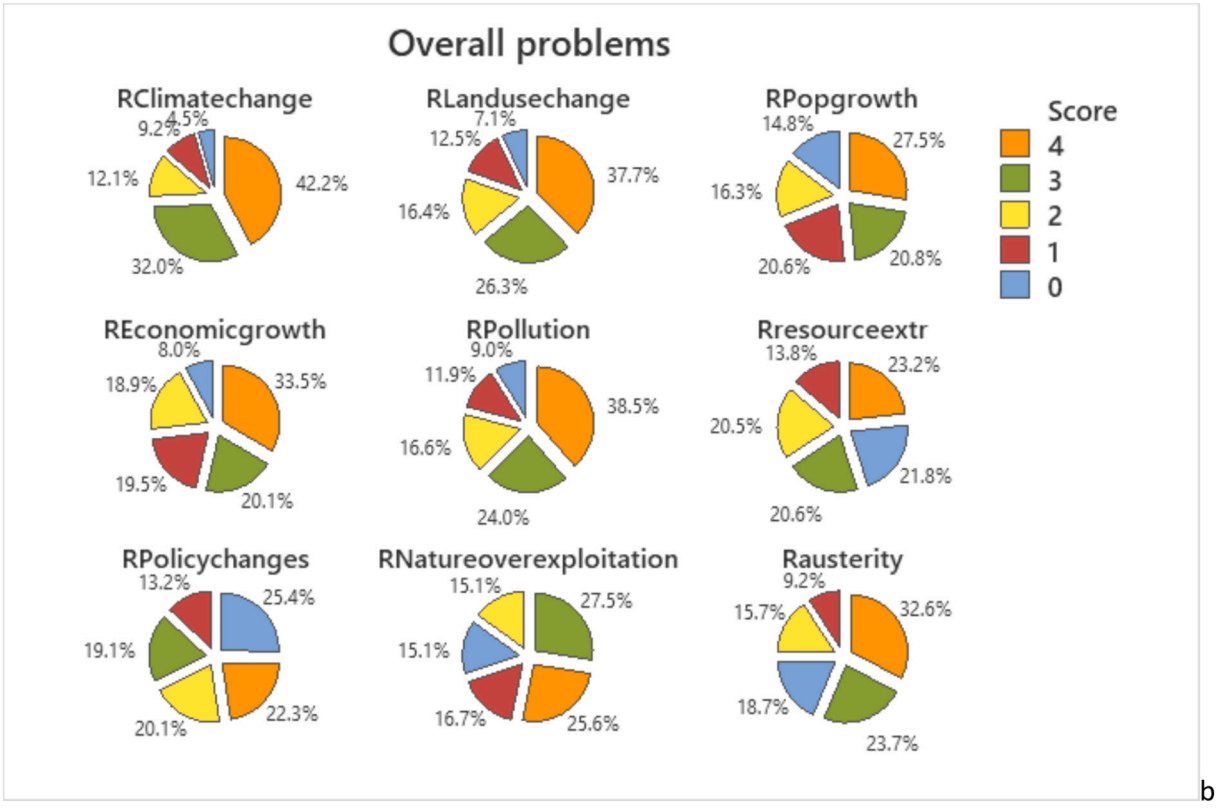


b

Fig. 2. a. Climate variables and reciprocal stakeholder perception of their change. **b.** Land use variables and reciprocal stakeholder perception of their change. In both cases answers were binary (Yes = 1 or No = 0) for each variable and allowed for multiple variables that may be changing.



a



b

Fig. 3. Stakeholder problem perception and problem severity. Higher scores indicate a more severe problem. **a.** Climate change and land use change combined problem severity ranking. **b.** Overall problem combining climate change, land use change, other environmental, and social or economic factors ranking. **c.** Mean score of climate change and land use change combined problem severity indicated in panel a. **d.** Mean score of overall combined problem severity indicated in panel b.

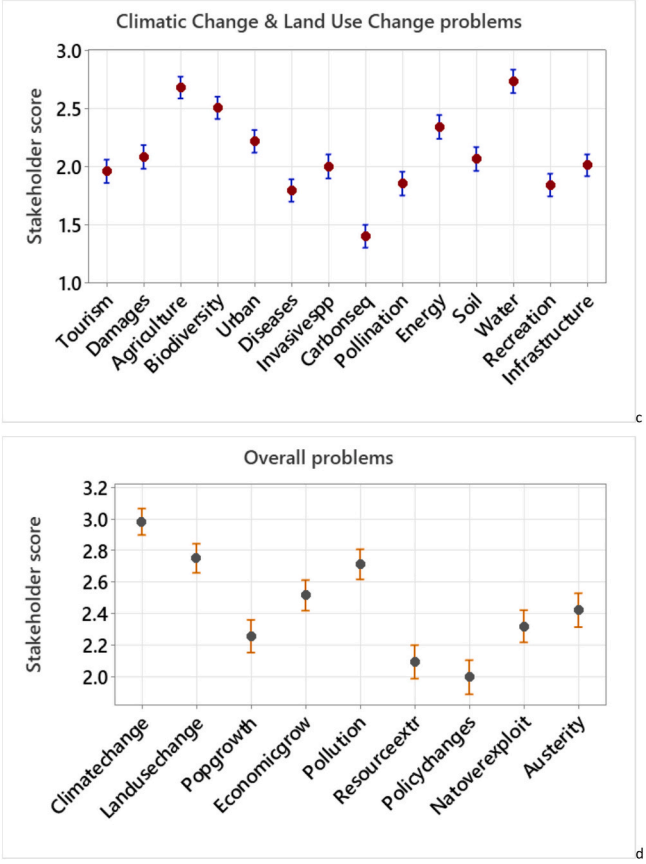


Fig. 3. (*continued*).

3. Results

3.1. Climate change characteristics

Most stakeholders identified temperature, followed by precipitation, wind, and humidity as the most predominant climate characteristics under change on their island (Fig. 2a). Acidification and sea level rise were reported least frequently in the European islands investigated (Fig. 2a).

3.2. Land use change characteristics

Stakeholders ranked deforestation as the most common land-use change process, followed by coastal degradation and urban expansion (Fig. 2b). Renewable energy facilities (solar and wind) were the fourth most reported issue, with insufficient habitat protection ranked fifth (Fig. 2b). Rewilding or reforestation was also considered a concern (Fig. 2b).

3.3. Climate change and land use change problems

Stakeholders ranked water related issues as the most severe problem, with the most common severe score (4) and the highest mean problem score (Fig. 3a, b). Primary production sector was the second-highest problem, followed by biodiversity loss (Fig. 3a, b). Renewable energy facilities ranked fourth (Fig. 3a, b). Urban expansion, habitat destruction, and soil erosion were also significant problems (Fig. 3a, b). Infrastructure damage, invasive species, and tourism posed moderate problems, while the lowest problems were associated with carbon sequestration, diseases, pollination, and recreation (Fig. 3a, b).

3.4. Overall problems

Climate change was perceived as the highest overall problem, followed by land-use changes and pollution (Fig. 3c, d). Economic growth and austerity ranked next, while nature overexploitation, population growth, and resource extraction were considered minor problems (Fig. 3c, d). Policy changes ranked as the lowest overall problem (Fig. 3c, d).

3.5. Climate change and land use change impacts on ecosystem services

Responses showed that 62.8 % of stakeholders perceived climate change impacts on ecosystem services as negative, 19.4 % as unknown, 14.4 % as neutral, and 3.4 % as positive impacts (Fig. 4a). For land-use changes, 54.4 % indicated negative impacts, 21.4 % as unknown, 21.4 % as neutral, and 2.7 % as positive impacts (Fig. 4b).

3.6. Climate change impact analysis

Machine learning analysis showed that stakeholders associated negative climate change impacts on ecosystem services primarily with habitat destruction and biodiversity loss, followed by invasive species, overexploitation, water issues, and urban expansion. Agriculture, soil degradation, pollination, and coastal degradation were also significant factors. Classification accuracy was 66.8 % (Table 2a). Stakeholders that reported unclear climate change impacts on the benefits of biodiversity were most linked to biodiversity loss, habitat destruction, and water related issues. Additional factors included carbon sequestration, recreation, invasive species, agriculture, urban expansion, soil degradation, and energy-related problems, with a classification accuracy of 61.9 % (Fig. 5b, Table 2b). Neutral perceptions of climate change impacts on the benefits of biodiversity were primarily tied to overexploitation and

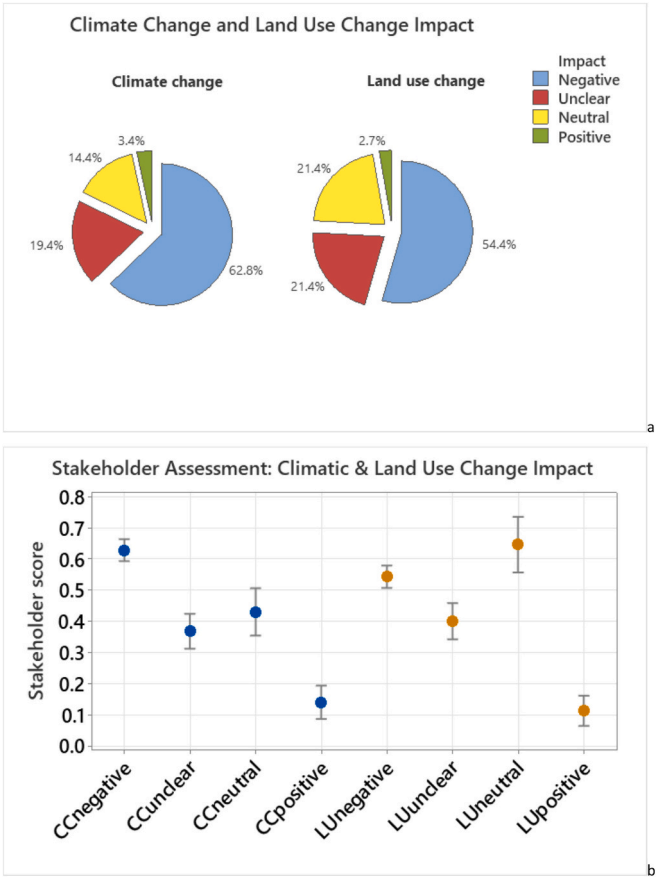


Fig. 4. Climate change and land use change impacts on ecosystem services. Impact perceptions were quantified as negative, unknown, neutral, or positive. **a.** Climate change and land use change impact assessment ranking. **b.** Mean score of climate change and land use change impact assessment indicated in panel a. Score derived by assigning values of negative = 1, unknown = 2, neutral = 3, and positive = 4.

invasive species, followed by carbon sequestration, pollination, resource extraction, and pollution. Soil degradation, austerity, policy changes, and biodiversity loss were also contributing factors. The classification accuracy for neutral impacts was 59.3 % (Fig. 5c, Table 2c). There were insufficient stakeholder responses to derive meaningful model coefficients for positive climate change impacts.

3.7. Land use change impact analysis

Machine learning analysis showed that stakeholders associated negative impacts of land use changes on ecosystem services mainly with coastal degradation, biodiversity loss, pollution, and infrastructure damage. Other contributors included invasive species, economic growth, deforestation, and recreation-related issues, alongside resource extraction, financial austerity, overexploitation, and water scarcity. The classification accuracy for these findings was 62.8 % (Fig. 6a, Table 2d). Unclear stakeholder perceptions of land use change impacts on the benefits of biodiversity were most associated with rewilding, urban expansion, and austerity, followed by recreation, policy changes, and wetland problems. The model achieved a classification accuracy of 68.6 % (Fig. 6b, Table 2e). Neutral land use change impacts were primarily linked to pollution, overexploitation, and resource extraction, with coastal degradation, invasive species, and diseases also playing significant roles. Factors like water, economic growth, rewilding, and soil-related problems contributed less but reached up to 20 % importance. The classification accuracy for neutral impacts was 71.7 % (Fig. 6c, Table 2f). Due to limited data entries, the analysis could not effectively model positive land use change impacts.

4. Discussion

4.1. Take home findings

Stakeholders perceive temperature change as the most pressing climatic issue and deforestation as the predominant land use change, highlighting the direct ways in which climate and human activities are altering island environments. Water-related problems were consistently ranked as top priorities, reflecting the central role of freshwater resources for island communities and the sensitivity of water systems to both climatic and land use pressures. Energy concerns, including both supply deficiencies and the challenges posed by renewable energy facilities such as wind and solar, were also identified as significant problems, pointing to the interconnectedness of climate, land use, and energy security in shaping stakeholder perceptions.

Stakeholders generally viewed the impacts of climate change on ecosystem services as negative, particularly through biodiversity loss and natural habitat destruction. Land use change impacts were also seen as negative but appeared to be shaped by a wider range of explanatory factors, reflecting the more complex drivers of land cover transformation. Despite geographical differences among islands, perceptions were broadly consistent, suggesting that island stakeholders share common concerns regarding the benefits biodiversity provides. At the same time, the distinction made between climate- and land use-driven impacts demonstrates that stakeholders are able to differentiate between these pressures, emphasizing the importance of addressing them through both targeted and integrated management measures.

4.2. Temperature

Results indicate that temperature is the climate characteristic that is perceived most affected by climate change, followed by precipitation. Island stakeholders often perceive temperature and precipitation as the most affected climate characteristic by climate change, in agreement with other island studies (Alcantara et al., 2023) as well as in the mainland (Rankoana, 2018). Altered rainfall patterns are also quantified as the second changing climate characteristics in other island studies (Alcantara et al., 2023). Sea-level rise is a concern, but its frequency is comparably lower in European islands. Perceptions of islanders regarding climate change impacts can be influenced by factors such as occupation, environmental engagement, and access to information about climate change (Assis et al., 2023a). Perceptions regarding climate change via temperature changes ranks higher than precipitation in spite of water related problems that are linked with precipitation (Koutroulis et al., 2013). Warmer temperatures are recorded among several European islands and thus climate change is more expressed via temperature related issues (Meco et al., 2002; Pla-Rabes et al., 2024; Zittis et al., 2025). It is also important to note that climate perceptions of stakeholders residing on islands do not necessarily coincide with actual data and scientific evidence (Assis et al., 2023b). Perceptions of traditional populations may focus on smaller temporal and spatial scale visions (Assis et al., 2023b). Potential ways to account for temperature-related problems includes nature-based solutions (De Montis et al., 2025).

4.3. De- and reforestation

Deforestation was the most indicated land use change related factor in islands. Lack of reforestation was also highlighted. Deforestation in European islands is a result of a combination of natural and human activities, including agricultural expansion, urban development, tourism growth, and logging practices (Marathianou et al., 2000; Morales et al., 2009; Kefalas et al., 2019). The growth of tourism has led to the development of new roads, hotels, and recreational areas, encroaching

Table 2
Model accuracy in the training (70 %) and testing (30 %) of the data for (a) negative, (b) unclear, and (c) neutral impacts of climate change on ecosystem services respectively. Accuracy is presented using the model outputs against the testing data not used for model training. Panels d, e, and f indicate model accuracy in the training (70 %) and testing (30 %) of the data for negative, unclear, and neutral land use change impacts on ecosystem services respectively.

a

Confusion Matrix

	Predicted Class (Training)				Predicted Class (Test)			
Actual Class	Count	1	0	% Correct	Count	1	0	% Correct
1 (Event)	317	197	120	62.1	147	94	53	63.9
0	194	60	134	69.1	79	22	57	72.2
All	511	257	254	64.8	226	116	110	66.8
Statistics	**Training (%)**	**Test (%)**						
True positive rate (sensitivity or power)	62.1	63.9						
False positive rate (type I error)	30.9	27.8						
False negative rate (type II error)	37.9	36.1						
True negative rate (specificity)	69.1	72.2						

b

Confusion Matrix

	Predicted Class (Training)				Predicted Class (Test)			
Actual Class	Count	2	0	% Correct	Count	2	0	% Correct
2 (Event)	94	60	34	63.8	42	27	15	64.3
0	417	161	256	61.4	184	71	113	61.4
All	511	221	290	61.8	226	98	128	61.9
Statistics	**Training (%)**	**Test (%)**						
True positive rate (sensitivity or power)	63.8	64.3						
False positive rate (type I error)	38.6	38.6						
False negative rate (type II error)	36.2	35.7						
True negative rate (specificity)	61.4	61.4						

c

Confusion Matrix

	Predicted Class (Training)				Predicted Class (Test)			
Actual Class	Count	3	0	% Correct	Count	3	0	% Correct
3 (Event)	76	59	17	77.6	30	22	8	73.3
0	435	180	255	58.6	196	84	112	57.1
All	511	239	272	61.4	226	106	120	59.3
Statistics	**Training (%)**	**Test (%)**						
True positive rate (sensitivity or power)	77.6	73.3						
False positive rate (type I error)	41.4	42.9						
False negative rate (type II error)	22.4	26.7						
True negative rate (specificity)	58.6	57.1						

d

Confusion Matrix

	Predicted Class (Training)				Predicted Class (Test)			
Actual Class	Count	1	0	% Correct	Count	1	0	% Correct
1 (Event)	268	213	55	79.5	133	88	45	66.2
0	243	46	197	81.1	93	39	54	58.1
All	511	259	252	80.2	226	127	99	62.8
Statistics	**Training (%)**	**Test (%)**						
True positive rate (sensitivity or power)	79.5	66.2						
False positive rate (type I error)	18.9	41.9						
False negative rate (type II error)	20.5	33.8						
True negative rate (specificity)	81.1	58.1						

e

Confusion Matrix

	Predicted Class (Training)				Predicted Class (Test)			
Actual Class	Count	2	0	% Correct	Count	2	0	% Correct

(*continued on next page*)

Table 2 (*continued*)

e

Confusion Matrix

	Predicted Class (Training)				Predicted Class (Test)			
Actual Class	Count	2	0	% Correct	Count	2	0	% Correct
2 (Event)	105	60	45	57.1	43	25	18	58.1
0	406	122	284	70	183	53	130	71
All	511	182	329	67.3	226	78	148	68.6
Statistics	**Training (%)**	**Test (%)**						
True positive rate (sensitivity or power)	57.1	58.1						
False positive rate (type I error)	30	29						
False negative rate (type II error)	42.9	41.9						
True negative rate (specificity)	70	71						

f

Confusion Matrix

	Predicted Class (Training)				Predicted Class (Test)			
Actual Class	Count	3	0	% Correct	Count	3	0	% Correct
3 (Event)	117	89	28	76.1	42	26	16	61.9
0	394	104	290	73.6	184	48	136	73.9
All	511	193	318	74.2	226	74	152	71.7
Statistics	**Training (%)**	**Test (%)**						
True positive rate (sensitivity or power)	76.1	61.9						
False positive rate (type I error)	26.4	26.1						
False negative rate (type II error)	23.9	38.1						
True negative rate (specificity)	73.6	73.9						

on natural landscapes (McElroy, 2003; Otto et al., 2007). Agricultural activities, such as crop cultivation and livestock raising, often lead to forest clearing, reducing biodiversity and disrupting ecosystems. Logging, both legal and illegal, also contributes to deforestation rates (Marathianou et al., 2000; Morales et al., 2009; Kefalas et al., 2019). Climate change, including rising temperatures and erratic rainfall patterns, weakens forests, making them more vulnerable to pests and fires. In Mediterranean islands like Sardinia and Crete, wildfires are becoming more frequent and devastating, threatening wildlife habitats and local communities (Bacciu et al., 2021). Solutions include protecting remaining forests, establishing nature reserves, national parks, and protected zones, and promoting sustainable tourism through legislation and reforestation projects. Balancing development with conservation is crucial to prevent long-term damage and maintain ecological health (Connell, 2018). In water-scarce and often shallow soil European islands, there is potential for planting or maintaining trees which have also a significant role as biocultural heritage (Camarda and Brundu, 2021). In addition the EU Biodiversity Strategy for 2030 favours reforestation (EuropeanCommission 2024).

4.4. Water

Water-related challenges are topping the list of stakeholders as a problem related with climate and land use changes. Interestingly, in the machine learning analysis accounting for all factors together, it is not topping the list of variables with high explanatory power in explaining climate change or land use change impacts. Thus, when seen together with all other factors, our analysis indicates that stakeholders may perceive water-related problems rather as a matter of bad management (Atay and Saladié, 2022) than as a climate change driven impact. Indeed, in the Mediterranean at least, long term precipitation records indicate that precipitation variability is the rule and no trend is identified (Vicente-Serrano et al., 2025). In general problems related to water are often severe, both in terms of scarcity or extreme precipitation events and public interest is high in general (Santín et al., 2023) and in islands (Ricart et al., 2024) but how it is determined by climate change is less clear.

Water is a precious resource, and addressing water-related issues is crucial for a sustainable future. A cross-scale water management system is needed spanning from the island to the local and individual unit level, to address the future water shortages (Atay and Saladié, 2022; Hophmayer-Tokich and Kadiman, 2006). Authorities should develop water management plans using desalination units, waste recycling, underground resources, and rainwater collection (Angelakis et al., 2025; Cuka, 2025). Agriculture heavily uses water resources as well as greenhouse gases (Yu et al., 2025), and climate-smart agriculture using drip irrigation can reduce freshwater demand (Kourgialas, 2021). Revisiting ethical and legal requirements for swimming pools and launching information campaigns to address tourists' higher water volume needs is crucial (Hof and Schmitt, 2011; Doménech-Sánchez et al., 2021). Incorporating water related problems of islands in the EU Water Framework Directive is key to a consistent improvement.

4.5. Energy

Energy-related problems ranked fourth in terms of combined climate change and land use change problems, while wind and solar energy facilities also ranked as the fourth most important land use problem; nearly half of the stakeholders indicated that the conversion of agricultural land to renewable energy facilities are a land use change problem on their island. Indeed, wind energy facilities induce land take and habitat fragmentation (Kati et al., 2021). In addition, they can pose a threat to biodiversity by inducing avian species loss that are important for the ecosystem functioning (Rebolo-Ifrán et al., 2025). This problem may be more pronounced in islands that their area is more restricted than mainland locations and islands are often part of migration routes providing food and shelter (Assandri et al., 2024). There are several societal barriers on the development of renewable energy facilities on islands (Oikonomou et al., 2009). Island communities may prioritize local benefits and credible mechanisms for managing intra-community conflicts in engagement processes regarding renewable energy facilities (Kallis et al., 2021).

The European Commission's "renewable islands for 2030" initiative has confirmed 30 islands and island groups aiming for energy

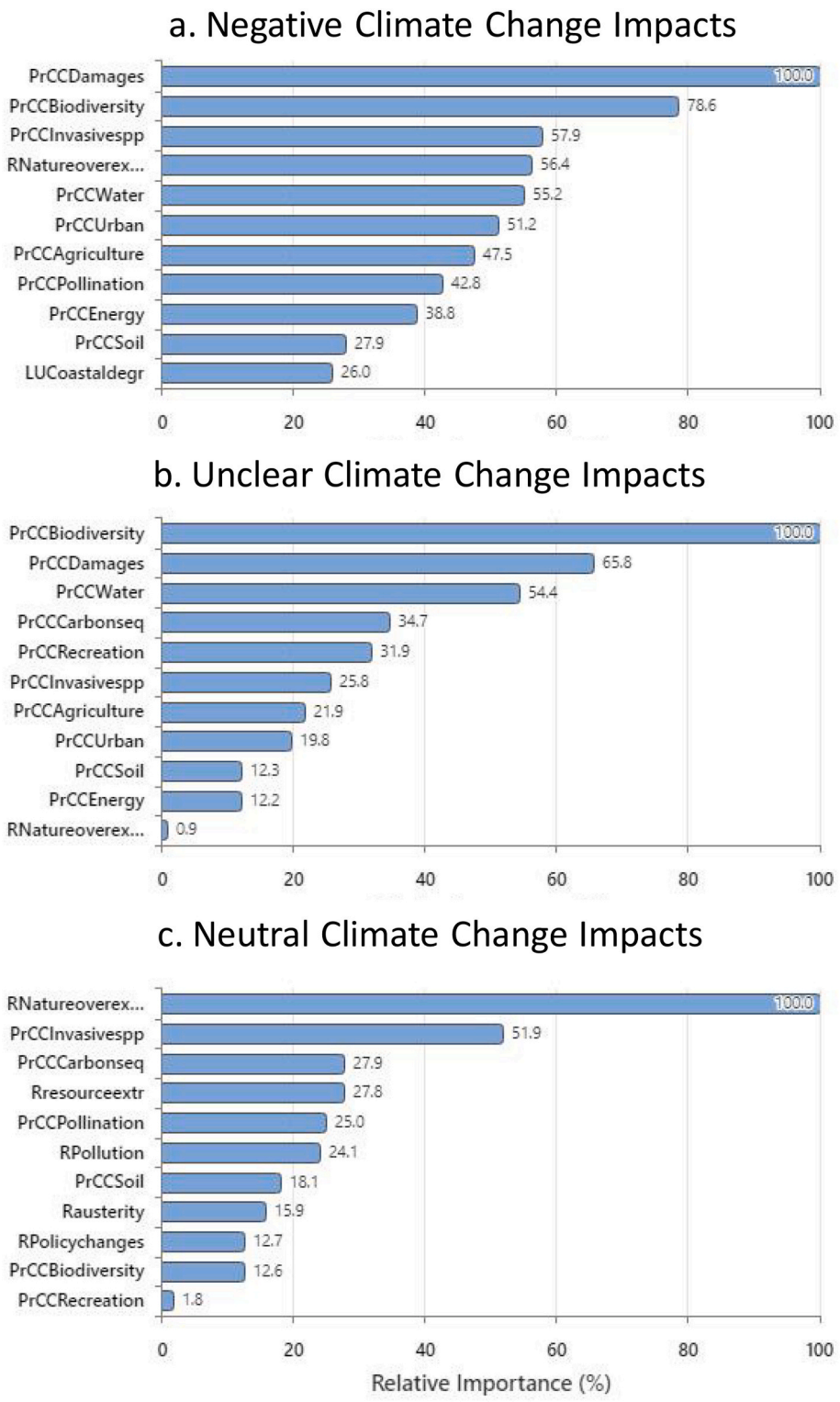


Fig. 5. Relative importance of Climate change impact assessment by island stakeholders quantified by Random Forests machine learning analysis. a. Variable importance of negative climate change impacts stakeholder perceptions. b. Variable importance of unclear climate change impacts stakeholder perceptions. c. Variable importance of neutral climate change impacts stakeholder perceptions.

independence by 2030 using wind and solar facilities. The islands will move towards their own path to climate-neutrality and receive comprehensive assistance. However, spatial planning is often not conducted locally or regionally, stakeholders are insufficiently consulted, and investors decide locations based on investment criteria (Chassot et al., 2014; Kirkegaard et al., 2023) without sufficient environmental risk assessment (Cavallaro and Ciraolo, 2005). Our results show that despite energy being an issue of concern for island stakeholders, current implementation of renewables generates a problem of negative environmental impacts. We are thus facing the two crises, biodiversity loss and climate change, as two separate crises (Pörtner et al., 2023). Climate change is a major driver of biodiversity change, but ecosystem

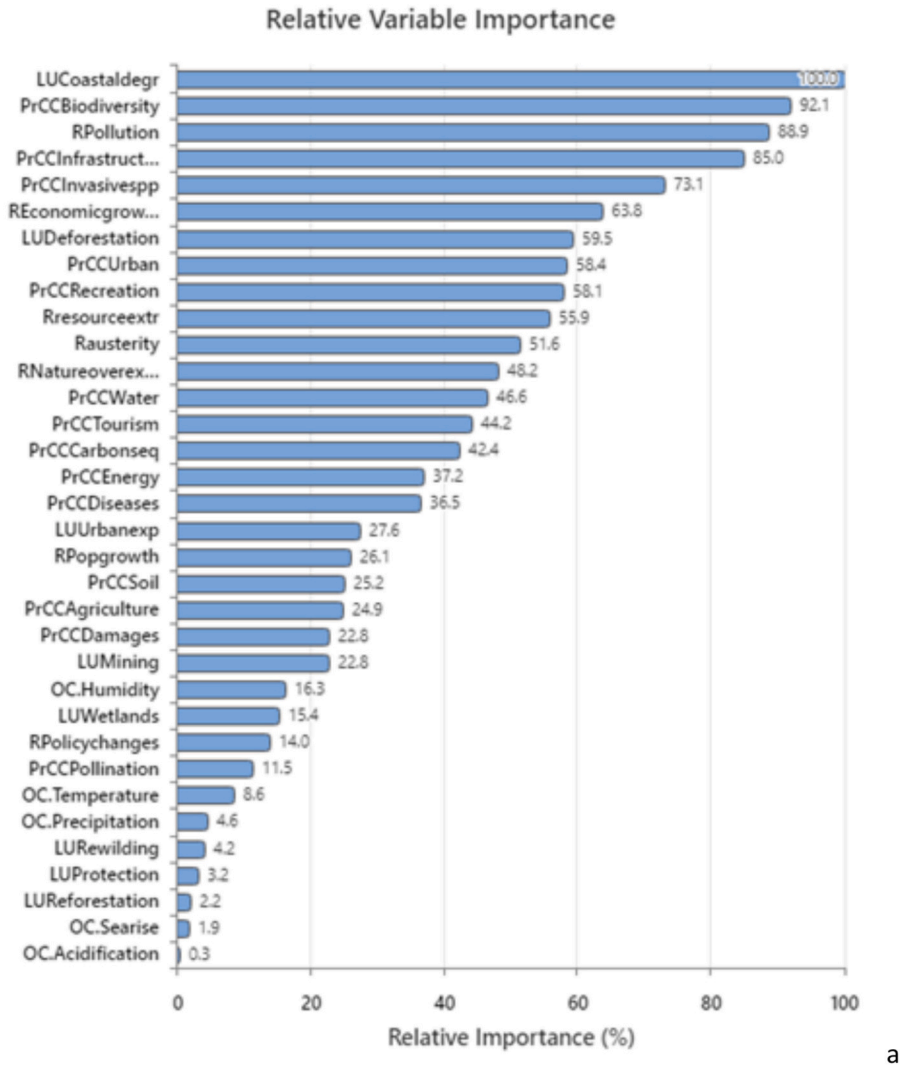


Fig. 6. Relative importance of Land Use change impact assessment by island stakeholders quantified by Random Forests machine learning analysis. a. Variable importance of negative climate change impacts stakeholder perceptions. b. Variable importance of unclear climate change impacts stakeholder perceptions. c. Variable importance of neutral climate change impacts stakeholder perceptions.

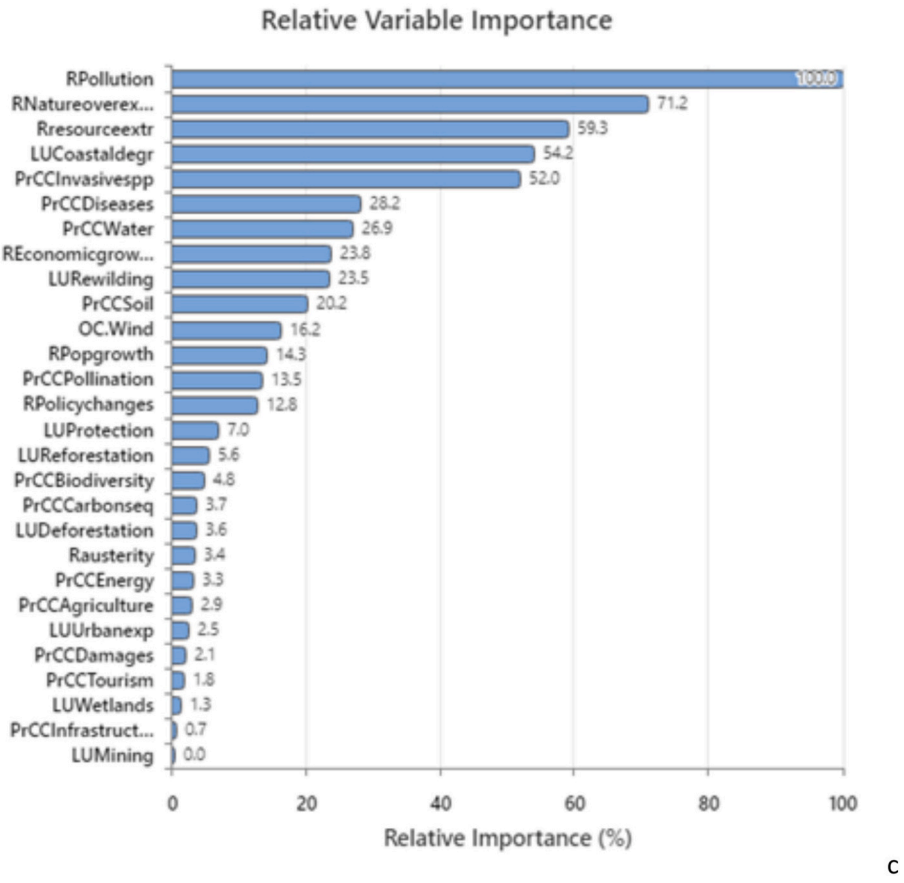


Fig. 6. (*continued*).

destruction undermines nature's ability to regulate emissions and protect against extreme weather (Seddon, 2022). Islands contribute proportionately less to climate change and carbon emissions than reciprocal mainland areas (Nurse et al., 2014). It is thus paradoxical to target complete energy autonomy derived by wind and solar energy, by the ones that actually contribute less to carbon emissions but have limited space and are more fragile to environmental changes. Policies must address these issues together with a stakeholder engagement and consensus (Kallis et al., 2021).

4.6. Impact assessment

The majority of stakeholders indicated negative climate change impacts on island ecosystem services, followed by unclear and neutral impacts. Very few stakeholders indicated positive climate change impacts on ecosystem services. There is a consensus regarding the main problems of climate change on ecosystem services for stakeholders with negative or unclear impacts views, ranking natural habitat destruction and biodiversity loss as the top problems. Stakeholders with negative perceptions of land use change impacts on ecosystem services identified also biodiversity loss as the main problem. Profiling of stakeholders with neutral climate change impacts on ecosystem services indicates that they believe that it is rather human and other environmental actions impacting ecosystem services via nature over-exploitation, invasive alien species, insufficient carbon sequestration, resources extraction (Tebboth et al., 2020) and not climate change directly. In general, neutral climate change or land use change impact perceptions are poorly linked with biodiversity (Santos et al., 2021; Watt, 2020). Land use change unclear or neutral impact perceptions are generally related with coastal degradation and pollution. Coasts are the most impacted environments, especially due to tourism growth and consequent urbanization and the main plant extinctions are reported around the coast (Fois et al., 2018). Notably policy is not a highly ranked variable regarding climate change or land use change impact, indicating that stakeholders are either unaware of related policies or that their opinion is that they have a low overall influence on the output. This can derive either by a lack of trust in policy makers (Kulin and Johansson, 2019) or environmental policies are perceived as paying more in prices and taxes rather than enacting pro-environmental laws despite being agreeable to accepting cuts on living standards (Yousefpour et al., 2020). Nevertheless, land use change policies are critical for the conversion of natural and agricultural land to artificial land cover (Guo et al., 2023; Zeng et al., 2025)

Land use change impacts are more complex to explain than climate change impacts as a higher number of explanatory variables is associated with the impact outcome. Both climate change and land use change impacts are just about equally predictable in terms of model predictive accuracy of the impact in all cases around 60 % to 70 %. Given the large number of stakeholders, islands, geographic disparity and associated variance, it appears that stakeholders have sufficiently common perceptions regarding climate change and land use change impacts on biodiversity to achieve this explanatory power. In addition, stakeholders substantially differentiate between factors related with climate change impacts and land use change impacts. Globally land use changes have been associated with several-fold higher negative impacts to biodiversity (IPBES, 2019; WWF, 2020, 2022). In the islands examined here stakeholders expressed the view that climate change has overall more negative impact than land use changes. A worldwide review on impacts of climatic changes and land use changes on ecosystem services indicated that land use changes have more pronounced effects on ecosystem services and that their synergies are key for understanding the impact (Moustakas et al., 2025). This study may not differentiate between

perceptions of problems or impacts and facts - i.e. are climate change impacts on biodiversity more pronounced in the study islands than land use changes? Land use changes are in general noteworthy less linked with biodiversity than climate change in the views of stakeholders. However, the most profoundly identified climate change negative impact, habitat destruction, is resulting in a land use change.

4.7. Limitations and future research

Factors such as the location of the island may have significant effects on the climate change or land use change problem perception and impact as they are correlated with climate and weather patterns (Nambima et al., 2024). In addition, island size may well play a role both on the impacts and problems (Vogiatzakis et al., 2016) together with access to resources to deal with challenges. Stakeholder's profession and reciprocal social or financial status may also influence the way they respond or prioritize locally observable challenges (Sivonen and Koivula, 2024). The ecosystem type (marine, terrestrial, freshwater) that the stakeholder is professionally or personally more related to, may also be impacted differently (Scholze et al., 2006). Ultimately mapping perceptions of problems and impacts based on the island, country, or geographic location may provide novel insights into initially quantifying and understanding climate and land use change perceptions and impacts (Palla et al., 2024) as experienced by residents. Stakeholders' perceptions regarding policy efficacy spanning from local, regional, national, and European level can provide novel insights in communicating or adapting policy to the citizens' needs and lived experience of changes (Nguyen et al., 2024). Incorporating open-ended questions into surveys and living labs experience may provide additional insights (Mason and Neumann, 2024; Marselis et al., 2024; Song et al., 2021).

5. Conclusions

To the best of our knowledge this is the first study which investigates the interplay of climate changes, land use changes, biodiversity and stakeholders' opinions on islands. This is further pronounced by the geographical scale of the study including a large number of islands under a common policy and legislative framework at a larger scale (i.e. EU administration). Yet these islands experience a different national, regional or local administration, expanding also in seas with very different characteristics (ecological and socio-economic) and different climate change impacts according to future model predictions (Moustakas et al., 2025; Pathirana, 2025). Most of these islands are moreover popular tourist destinations in an era of escalating tourism impact, and thus facing increasing challenges managing their vulnerable natural and cultural ecosystems (Bahçekapılı and Yalçıntan, 2024; Cadima Ribeiro et al., 2025; Leka et al., 2025; Loftsdóttir and Mixa, 2025).

The topic of environmental change, including mainly climate and land use changes, is intricate and varied, with significant effects on biodiversity, economy, and society (WWF, 2020, 2022). It can be challenging to increase public awareness and comprehension of its causes and effects. In order to pursue successful climate adaptation or mitigation strategies and promote climate resilience, it is important to understand the perspectives and knowledge gaps of stakeholders involved in functions that are affected by or address land use and climate change (Ruiz et al., 2023). Combining climate change with land use change (Louca et al., 2015) as well as other socioeconomic and environmental factors is critical for assessing the stakeholder perceptions and ranking problems and impacts (Ratnayake et al., 2024).

The majority of stakeholders indicated negative impacts of climate change on island ecosystem services, with natural habitat destruction and biodiversity loss being the top problems. Stakeholders with neutral perceptions believe that human and environmental actions, such as nature over-exploitation and invasive species, are causing ecosystem services to be negatively impacted. Land use change impacts are more complex to explain than climate change impacts, with both being equally predictable in terms of model predictive accuracy. However, land use changes are generally less linked with biodiversity than climate change in the views of stakeholders. The most profoundly identified climate change negative impact, habitat destruction, is resulting from land use change. Policy is not a highly ranked variable regarding climate change or land use change impacts, suggesting that stakeholders may be unaware of related policies or have a low overall influence on the output. Water, energy, and renewable energy related issues pose serious concerns to island stakeholders and management and policy measures are needed to address those issues. Temperature related problems need to be accounted for. Island-specific European policies may be necessary to address these issues.

Authors' statement

The work presented here, including all figures, has not been published or submitted elsewhere, nor has it been uploaded anywhere online. All authors have read and approved the manuscript, and we declare no conflicts of interest. No AI tools were used throughout the manuscript including text writing, or figures.

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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Data availability

Data will be made available on request.

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