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ORIGINAL ARTICLE

Activities and impacts in wetlands: challenges for Sardinia

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Abstract

Wetlands play a crucial role in climate regulation, water cycling, biodiversity conservation, and human well-being. Yet, they have faced centuries of degradation. This study aimed to analyze the relationship between human activities and their impacts across various wetland typologies, identify the most vulnerable systems, and investigate the main drivers of degradation. The focus was on Sardinian wetlands, located on the second-largest island in the Mediterranean. Our analysis revealed significant spatial co-occurrences between human activities and ecological impacts. The most frequent impacts included vegetation and habitat degradation, pollution, and hydrological alterations. Activities such as mining, urbanization, transportation, and tourism were particularly associated with these negative effects. While management practices yielded mixed outcomes—showing both positive and negative aspects—the extent of degradation was more closely linked to wetland size and ownership structure than to typology alone. In particular, larger wetlands and those with mixed ownership were more affected, suggesting that conventional inland vs. coastal classifications may no longer be sufficient to capture vulnerability patterns. Freshwater wetlands—often associated with small-scale agricultural use—showed lower levels of impact, highlighting the potential compatibility of traditional practices with conservation. Overall, our findings underscore the strong, often detrimental, connections between specific human activities and wetland degradation, while also pointing to the promising role of well-targeted management and conservation actions in supporting ecological resilience.

Keywords Conservation · Management · Coastal and inland wetlands · Human activities · Protected areas · Wetland degradation

Introduction

Wetlands play an irreplaceable role in regulating the global climate, maintaining the global hydrological cycle, protecting the ecosystem diversity, and safeguarding human welfare (Hu et al. 2017). Since most of the services provided by wetland ecosystems have not been traded in the economic market, the value of wetland ecosystems continues to be neglected or underestimated by stakeholders, government, and the public (Xu et al. 2019). In fact, in past centuries, instead of recognizing the importance of wetlands, humans regarded wetlands as a harbour of mosquitoes, carriers of disease, and new lands for urbanization or agriculture (Davidson 2014). Due to the dual effects of human activities and natural factors, wetlands around the world continue to decline and their quality continues to deteriorate (Finlayson 2012; Davidson 2014; Gardner et al. 2015; Gardner and Finlayson 2018; Xu et al. 2019). About half of the global loss of wetlands can be attributed to human activities and natural disturbances (Yu et al. 2020). Accordingly, concern for these habitats has led to increased research on wetland modification (e.g. Wang et al. 2020; Stein et al. 2020), health monitoring (e.g. Chen et al. 2019), and risk assessment (e.g. Ghosh and Das 2020; Zhang et al. 2017). Despite the increase in public knowledge of the importance of wetlands, there is no real understanding of the sensitivity and fragility of these vital ecosystems (Taylor et al. 2021). Accordingly, in this study, we aimed to examine challenges facing wetland ecosystems as the first step to suggest conservation solutions on the island of Sardinia.

Sardinia can be used as a representative study case in the Mediterranean biogeographic region, being the second-largest island after Sicily and hosting 2567 lentic wetlands,

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nearly equally distributed among natural, artificial, coastal, and inland ones (Fois et al. 2024). A growing literature (around 400 articles since 1900) has addressed different aspects of Sardinian wetlands (Cuena-Lombraña et al. 2021; Fois et al. 2021). Some of them have dealt with activities (e.g. economic production) or problems (e.g. pollution and diseases). However, about 90% of Sardinian wetlands have never been the subject of a pre-review paper (Fois et al. 2021). This paper comprehensively examines human activities and their consequences on Sardinian wetlands throughout the island, encompassing various typologies, in order to (1) analyze the spectrum of human activities and their resultant impacts across diverse wetlands and (2) identify the most vulnerable wetland typologies, assessing the underlying causes of wetland degradation.

Materials and methods

Wetlands definition and data sampling

The Ramsar Convention defines wetlands as "areas of marsh, fen, peatland or water, whether natural or artificial, permanent or temporary, with water that is static or flowing, fresh, brackish or salt, including areas of marine water the depth of which at low tide does not exceed six meters" (Ramsar Convention Secretariat 2013). This study followed this definition but excluded (i) streams, rivers, and other running water and (ii) wetlands with a surface area of less than 0.1 ha. The cartographic inventory was created in 2020 and continuously updated in Quantum GIS version 1.7.4 by digitizing the monitored wetlands on high-resolution satellite images from Google Earth (http://www.google.com/earth). Following Perennou et al. (2018), where uncertainty existed in the definition of the area of a wetland due to seasonal fluctuations in inundation and vegetation cover, we chose the largest potential polygon observed in Google Earth imagery time series and other available products, such as the Water and Wetness status (https://www.eea.europa.eu/publications/state-of-water) or the cartographic material available at the Sardinia Geoportal (https://www.sardegnageoportale.it). This approach avoids underestimating flooded areas that might be only temporarily inundated or masked by dense aquatic vegetation. Whenever possible, each wetland was classified according to the typology in the pan-Mediterranean wetland inventory module (Tomàs-Vives 2008), a hierarchical classification of the common types of Mediterranean wetlands within three mutually exclusive macro-categories: coastal, inland, and artificial.

In total, we mapped 2567 wetlands in Sardinia, covering an area of 501.4 km^2 (2.08% of the Sardinian territory; Fig. 1). Approximately 10% of wetlands' records are included in protected areas (i.e. regional and national parks, Ramsar and Natura 2000 sites). However, these data change

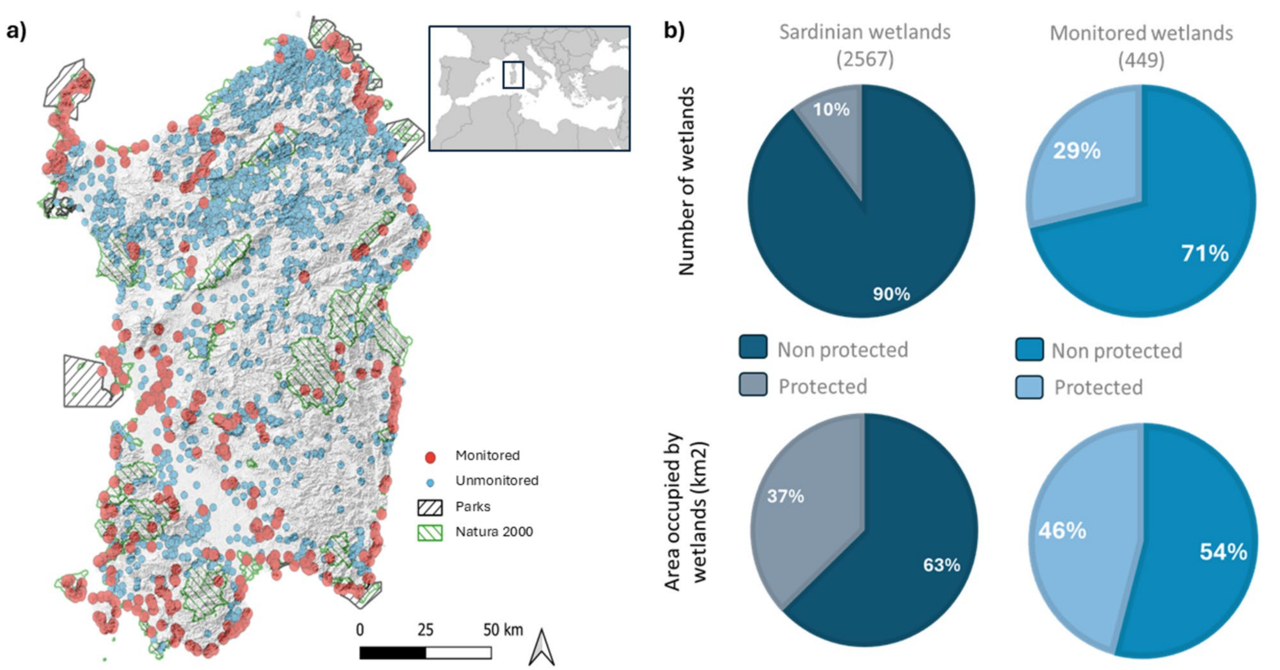

Fig. 1 **a** Distribution of Sardinian wetlands (blue points) from https://italiaiswet.it/, highlighting the wetlands included in this study (red points) and protected areas. **b** Summary of wetlands in Sardinia, including total wetland and monitored ones inside protected areas (Parks or Natura 2000 sites) or not, with respective measurements given in number and area (km^2)

significantly when considering the surface occupied by these protected wetlands: more than half of the surface occupied by wetlands (59.04%) is under protection, with the largest wetland systems mostly protected. The complete dataset is available online under the Mediterranean Island Wetland project (ItIsWet 2019).

For the field monitoring, we followed the "Rapid Assessment" protocol, the scheme denominated "Inventory, assessment and monitoring of Mediterranean wetlands" (Tomàs-Vives 2008) which introduces a Mediterranean-wide system based on the MedWet Web Information System (MedWet/WIS), a database providing a Mediterranean wetland databank. This protocol includes general information on each wetland (for more details, see Table 1). A total of 449 wetlands across Sardinia were here investigated (Fig. 1). For each wetland, human activities and impacts (inside or closed outside; for further details, see Appendix A, Table S1) were recorded using the numeric and alphabetic codes of Appendixes P and Q, respectively, of the Natura Impact Statement (Natura 2000 list; for further details, see https://medwet.org/codde/APPENDICES.pdf).

Analysis of activities and impacts co-occurrence

First, we developed a presence-absence matrix with the number of activities and impacts of all monitored wetlands to determine which associations were significant (i.e. non-random). We used the probabilistic modeling approach developed by Veech (2013), which calculates the expected frequency of co-occurrence between each pair of factors (activities and impacts) based on the distribution of one factor being independent of the second one. It then compares the expected frequency to the observed frequency and returns the probability that a lower or higher value of co-occurrence could have been obtained by chance. This matrix co-occurrence analysis was carried out using the function "*cooccur*" in the cooccur R package (Griffith et al. 2016). Starting from community data organized in activities by impacts matrix, the function returns a list containing pairwise variables (i.e. activities and impacts) co-occurrence results. The package returns a probability of co-occurrence, which can be interpreted as a *p*-value, and classifies variable pairs into categories of negative or positive associations. In this case, significant probabilities of co-occurrence were retained upon a threshold of 0.05 (Royan et al. 2016). Subsequently, utilizing the acquired co-occurrence matrix of impacts and activities, we calculated all network metrics using the package "*bipartite*" (Dormann et al. 2009).

Factors affecting activities and impacts across the island

To analyze and assess the effect of different variables on the number of activities and impacts, we first check for collinearity. This involved calculating pairwise correlations using Pearson's correlation coefficients and by excluding those significant ($p < 0.05$) and strong ($|r| > 0.7$; Nathans et al. 2012). After resolving any collinearity concerns, we proceed with Generalized Linear Models (GLMs), using Poisson regression to model the effects of predictors on the number of impacts on each wetland. We included as predictors all variables reported in Table 1. If overdispersion was detected (checked using a dispersion test), we adjusted the model by switching to a Negative Binomial regression. Finally, we

Table 1 General information for each wetland considered

Field parameters	Brief description
Typology	Classification of the wetland using the following options: (1) marine/coastal (includes estuaries, deltas, and coastal lagoons), (2) inland (includes rivers, marshes, and peatlands), and (3) artificial—when the wetland is created or modified by human activity (includes ponds, wastewater treatment areas, salt exploration sites, and aquacultures)
Presence of water	Characterization of the water residence in the wetland site as: (1) permanent—the habitat is permanently flooded, (2) seasonal—the habitat is seasonally or periodically flooded, and (3) temporary—the flooding period does not follow a seasonal or regular pattern
Dominant salinity	Characterization of the dominant salinity class during summer: (0) no available information, (1) fresh (< 0.5 g/l), (2) fresh/brackish (0.5–5.0 g/l), (3) brackish (> 5.0–18.0 g/l), (4) brackish/salty (> 18.0–30.0 g/l), and (5) salty (> 30.0 g/l)
Wetland area	Surface area of the site, in hectares (Ha)
Geographic location	Site coordinates: specify the site's latitude and longitude, expressed in degrees, minutes, and seconds (WGS 84 system). The coordinates pinpoint the central point of the wetland site
Conservation status	Indication of the conservation status of the site about its natural (undisturbed) state, using one of the following options: (1) untouched no signs of man/made changes), (2) original habitats/landforms still predominant > 50%, (3) original habitats/landform partially modified (10–50% untouched), (4) original habitats/landforms highly modified (< 10% untouched), and (5) original habitats/landform totally changed
Protection status	List the site designation codes indicating its protection status, as granted at national or international level, using one of the following options: "Natura 2000" or "Park", in this last category are included both typologies national and regional
Ownership	Classification of the wetland area as "public", "private", "mixed" (i.e. both public and private lands) or "unknown"

evaluated the model fit through summary statistics and compared model performance using AIC values to choose the best approach. Wetland area was normalized by converting each value into a *z*-score. This standardization was achieved by subtracting the mean of the area from each value and then dividing by the standard deviation of the area. This transformation centres the variable around zero and scales it to have a standard deviation of one, making it more suitable for comparison with other variables. Finally, we presented the results graphically using the "*coefplot*" function in the "coefplot" R package (Lander 2018). All statistical procedures were performed in R software version 4.3.2.

Results

Co-occurrence of activities and impacts

Main human activities found in the 449 Sardinian wetlands under study (Fig. 2) were related to Agriculture & forestry (192 wet areas), Leisure & tourism (151), Urbanization & industrialization (113), Transportation & communication (85), Human-induced change in hydraulic conditions (82), Management & conservation (75), Fishing & hunting (70), other human activities (61), and Mining (45). Principal human impacts found in Sardinian wetlands were related to the Degradation of the vegetation (208 wet areas), Pollution (159), Habitat degradation (124), Hydrological impacts (113), Decrease in wetland benefits (102), Enhancement (98), Loss of aesthetic value(s) (94), Faunal change (89) and Soil/Land impacts (66).

The co-occurrence matrix of activities and impacts (Fig. 2) shows that from the 81 possible pair co-occur combinations, 38 (46.91% of the total) were showing a significant probability of co-occurrence (p-values < 0.05, Table S2 Appendix B).

The analysis revealed significant co-occurrences between various human activities and environmental impacts, where the observed co-occurrences (obs) were notably higher than the expected ones (exp) based on chance (Table S2). For

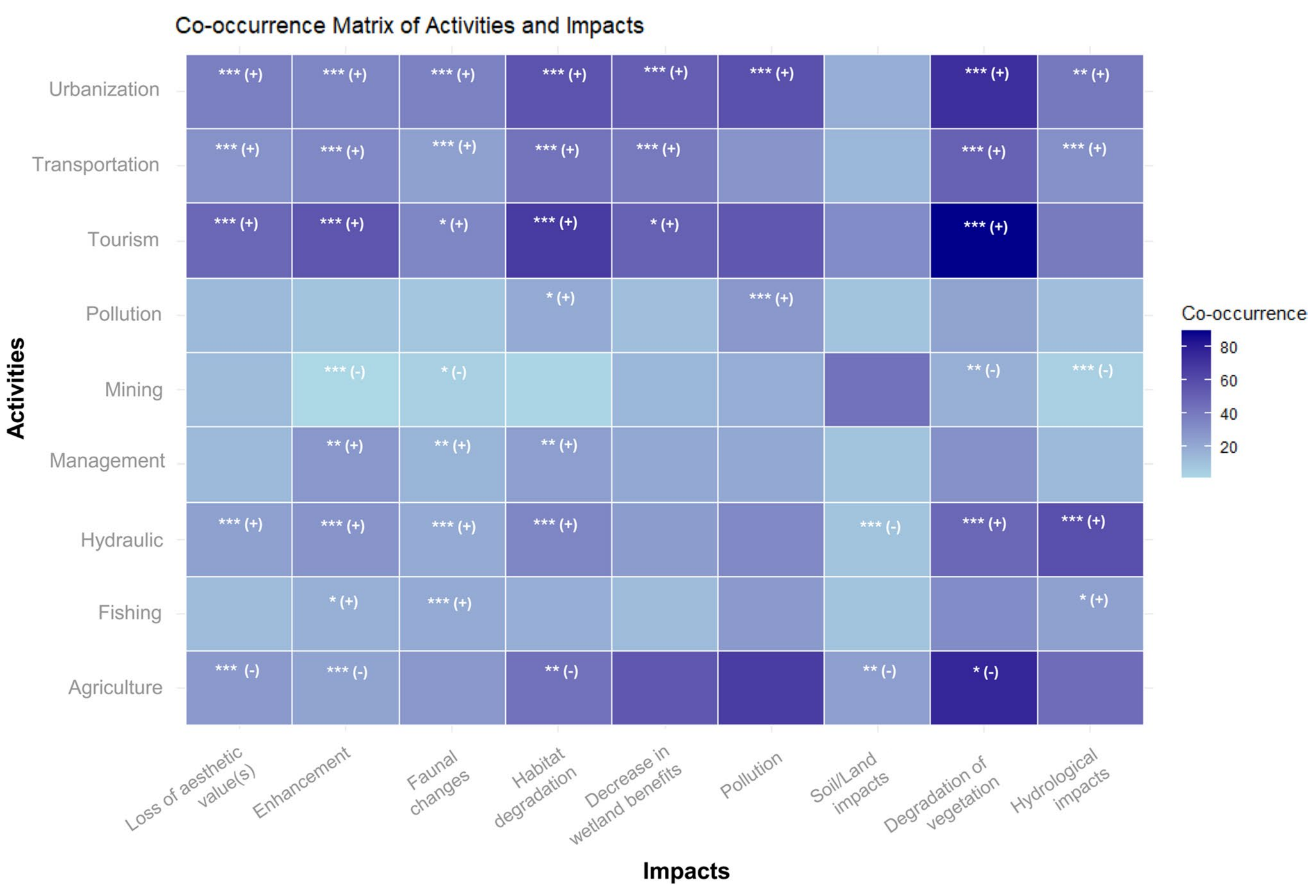

Fig. 2 Co-occurrence matrix of impacts and activities in Sardinian wetlands. ***$p < 0.001$, **$p < 0.01$, and *$p < 0.05$. (-) indicate whether the observed co-occurrence is significantly lower and (+) higher than expected. Some activities were abbreviated as follows: Urbanization (Urbanization & industrialization), Transportation (Transportation & communication), Tourism (Leisure & tourism), Management (Management & conservation), Hydraulic (Human-induced change in hydraulic conditions), Fishing (Fishing & hunting), Agriculture (Agriculture & forestry). For further details, see Table S2 Appendix B

example, “Mining and extraction of materials” co-occurs with “Soil/Land impacts” 43 times compared to the expected 11.7 ($p < 0.001$), showing a strong correlation between these activities and soil degradation. Similarly, “Urbanization & industrialization” showed elevated co-occurrences with a range of impacts, including “Loss of aesthetic value” (obs = 37, exp = 24, $p < 0.001$), “Habitat degradation” (obs = 56, exp = 33.7, $p < 0.001$), and “Degradation of vegetation” (obs = 72, exp = 49.8, $p < 0.001$). “Transportation and communication” also showed heightened co-occurrences with several impacts, such as “Habitat degradation” (obs = 42, exp = 25.3, $p < 0.001$) and “Degradation of vegetation” (obs = 50, exp = 37.4, $p = 0.002$). Additionally, “Leisure & tourism” is linked to significant faunal and habitat impacts, highlighting the environmental strain from these activities.

The results also showed that “Human-induced changes in hydraulic conditions” co-occur significantly more often than expected, with several environmental impacts. This activity is strongly linked to both positive and negative outcomes, as indicated by the higher observed co-occurrences and low p-values (Table S2). For instance, the association between “Hydraulic changes” and "Enhancement" (obs = 28, exp = 15.2, $p < 0.001$) indicates that such changes can sometimes lead to improvements or benefits, mainly in terms of infrastructure, flood control, or water management. However, the same activity “Human-induced changes in hydraulic conditions” also showed strong associations with negative impacts such as “Habitat degradation” (obs = 34, exp = 24.4, $p = 0.009$), “Degradation of vegetation” (obs = 47, exp = 36.1, $p = 0.006$), and particularly “Hydrological impacts” (obs = 58, exp = 20.8, $p < 0.001$).

The results demonstrated the co-occurrences between “Management & conservation” activities and various environmental impacts. Most observed co-occurrences were close to or slightly above the expected co-occurrences, with few statistically significant deviations. In particular, “Management & conservation” activities showed a significant positive association with “Enhancement” (obs = 27, exp = 10.6, p-values < 0.05), indicating that conservation efforts were linked to beneficial outcomes or improvements.

On the other hand, “Agriculture and forestry” shows a significant co-occurrence with “Loss of aesthetic value” (obs = 26, exp = 40.9, $p < 0.001$) and “Habitat degradation” (obs = 43, exp = 57.2, $p = 0.002$). The analysis also showed a strong association between this activity and the degradation of vegetation (obs = 76, exp = 84.6, $p = 0.063$).

Factors affecting the number of impacts across the island

No collinearity problems were detected by the pairwise correlation, apart from a high correlation between the two response variables (number of activities and number of impacts; Fig. S1 Appendix B). Accordingly, we only present the number of impacts, assuming the same patterns for the number of activities (Fig. 3). The most statistically significant variables were “normalized area” ($p < 0.010$, Fig. 3 and Table S3 Appendix B), indicating that large wetlands and wetland systems suffer more impacts than smaller ones, and “ownership” ($p < 0.010$, Fig. 3 and Table S3). In this case, wetlands with mixed public/private ownership experienced significantly more impacts ($p = 0.007$). Although typology (marine/coastal) was not a significant variable, freshwater wetlands showed a lower number of impacts than brackish and salty wetlands ($p = 0.017$). Other variables such as protection (Natura 2000 or parks) and the presence of water were not statistically significant predictors in our results.

On a landscape scale, human activities and their associated impacts are similarly distributed across the island, regardless of the protection status of wetlands or their character (natural or artificial). Although visual inspection suggests that coastal wetlands experience more impacts than inland wetlands—even among those with low to medium numbers of activities (Fig. 4), this pattern was not supported by the GLM analysis.

Discussion

Evidences of co-occurrence of activities and impacts

Human activities have profoundly influenced natural ecosystems, especially wetlands (Sheng et al. 2012). A spatial perspective is necessary for understanding human impacts on natural ecosystems for both scientific and management purposes (Goudie 2006). Generally, it is rather difficult to characterize the influences of human activities and their impacts at a landscape scale, especially since these activities are diverse and occur across a wide range of wetland types (Sheng et al. 2012). In addition, other difficulties must be considered, such as the fact that direct observations are not (always) possible due to the complexity of human-environmental interactions. Our study demonstrated the correlation between activities conducted and impacts found in a diverse and representative set of 449 wetlands (including different typologies), suggesting strong associations between human activities and their environmental consequences. While several studies have addressed the impacts of specific activities (e.g. Zorrilla-Miras et al. 2014; Gaglio et al. 2017; Nazari et al. 2024), fewer have comprehensively examined the broad spectrum of impacts determined by different activities (Borgwardt et al. 2019). Interactions between human activities and impacts need to be identified and prioritized for a fully integrated management (Sullivan and Fisher 2011). The number of impacts and how they are connected are important

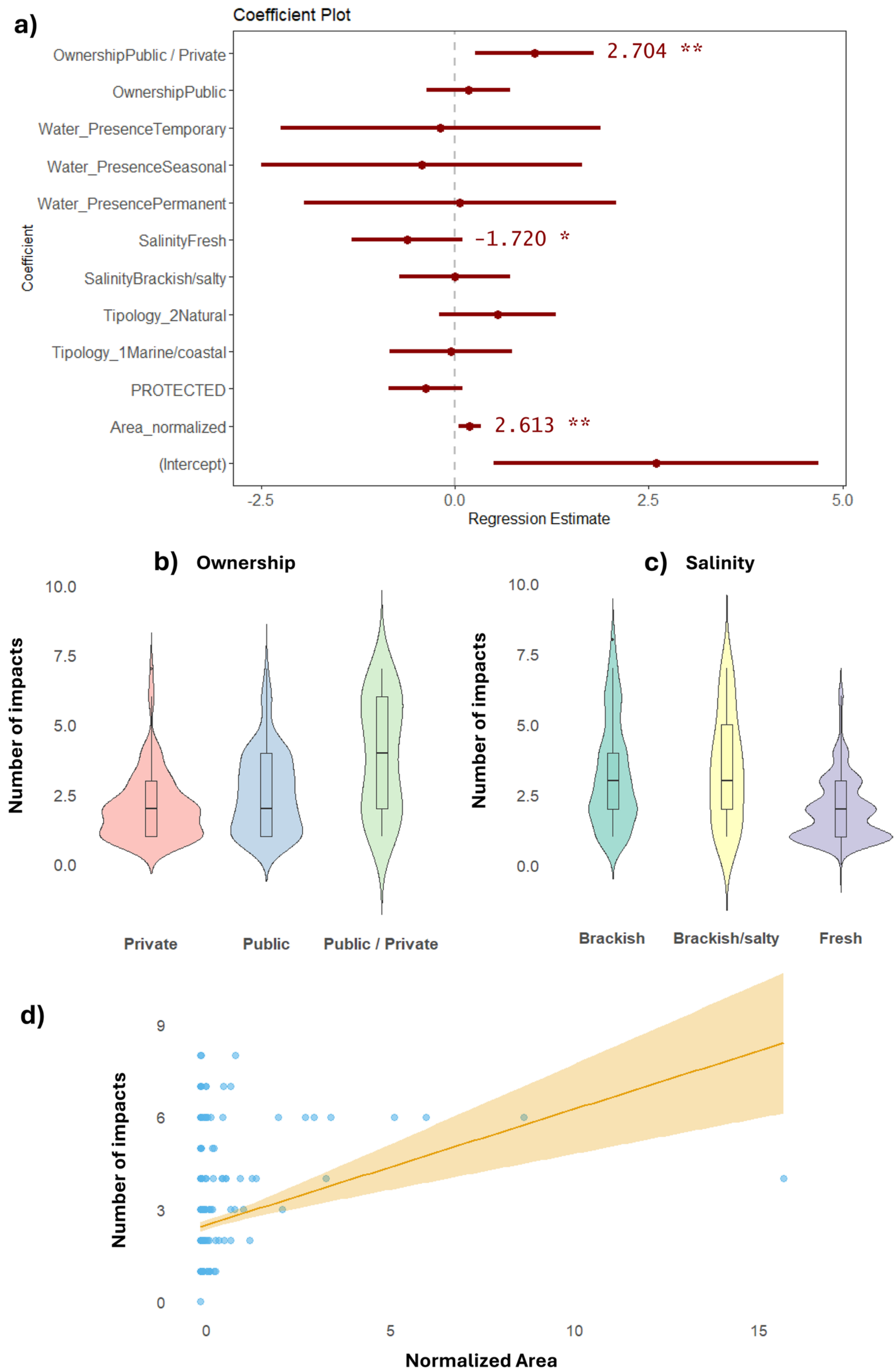

Fig. 3 **a** Coefficient plots illustrate the factors influencing the impacts across the island. Each dot represents the coefficient estimates derived from the linear model, while whiskers indicate the associated standard error around each estimate. Statistical significance is indicated by asterisks (*$p<0.1$; **$p<0.05$; ***$p<0.001$). For variables with statistical significance, the figure contains box plots for **b** ownership, **c** salinity, and **d** linear regression for the normalized area

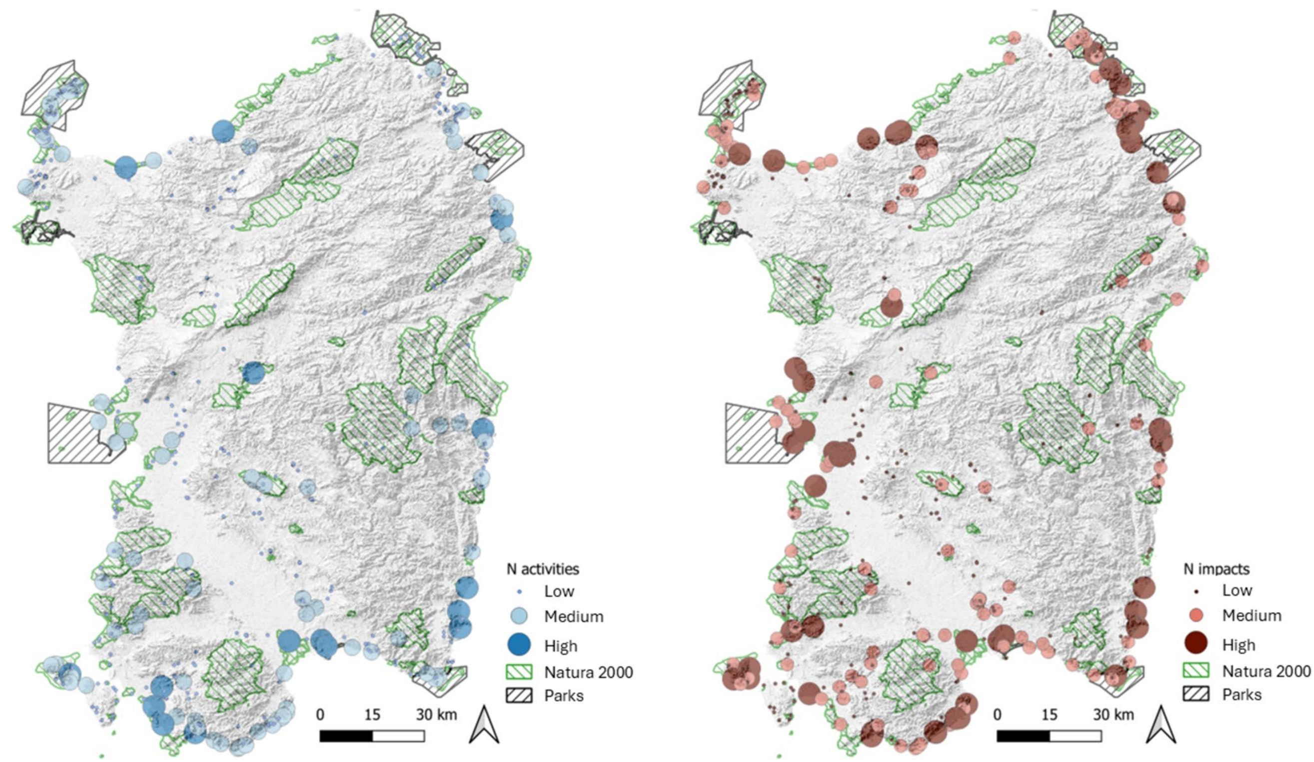

Fig. 4 Number of activities and impacts on wetlands across the island. Low values indicate numbers from 0 to 2, medium values from 3 to 5, and high values from 6 to 8

descriptors of the relationship between social and ecological systems (Borgwardt et al. 2019). It is also important to consider the fact that most activities that have a negative impact on wetlands, such as urbanization or tourism, occur mainly outside them. Consequently, future conservation actions should consider the complex cause-effect networks, even over long distances. Understanding the correlation between activities and impacts can help to optimize efforts. For example, if a decline in wetland benefits is observed, our results suggest that the initial investigation should focus on urbanization and transport activities. Among the activities, Agriculture & forestry was the most detected one, followed by Leisure & tourism and Urbanization & industrialization. Agricultural activities are considered a major threat in most of Mediterranean countries (Gerakis and Kalburtji 1998). For example, in Spain's Ebro Delta, agricultural expansion through intensive rice farming has caused habitat degradation and reduction in biodiversity, particularly of aquatic species and migratory birds (Ibáñez et al. 2010). Similarly, in Doñana (Spain) and the Camargue (France), agricultural runoff has disrupted natural hydrological processes, causing salinization of soils and degradation of both plant and animal habitats (Garcia-Murillo et al. 2025; Tourenq et al. 2001). Differently, in our study, one of the more surprising findings was that agriculture, despite its widespread presence, showed lower-than-expected negative impacts on wetlands. Indeed, both pollution and hydrological impacts were not significantly associated with agricultural activities, even though a significant incidence of agriculture on other impacts, like habitat degradation, loss of aesthetic value persists. Similar results have been observed in France, where agro-environmental schemes designed to promote sustainable farming practices have reduced the detrimental effects of agriculture on wetland ecosystems (Garnier et al. 2019). This raises interesting questions about whether Sardinian agricultural practices are more ecologically integrated, and whether the impact of agriculture is managed to minimize damage to wetlands, or whether the impact of small-scale farming is difficult to detect at this scale. At the state of the art, our results suggest that the maintenance of these small-farming practices, such as sheep farming, and the cultivation of wheat, vineyards, olive groves, and artichokes are advisable from the perspective of sustainable land use. However, there are some exceptions to the rule, particularly along the western boundary of the Oristano Gulf, where approximately 60 km^2 of the alluvial plain is occupied by the Arborea farming district with a high nitrate pollution (Schäfer et al. 2024). This irrigated plain is characterized by over 200 intensive farms, which manage around 30,000 dairy cattle and several agricultural products (Demurtas et al. 2016).

As elsewhere in the Mediterranean (e.g. Krabokoukis and Polyzos 2024), tourism is, with agriculture, the most important industry in Sardinia. While it is unquestionable that tourism plays a crucial role in the economic development of the Mediterranean Basin, it is also true that its continuous growth will exert increasing impacts on the environmental resources, mainly coastal zones. The massive fluxes of tourists, which often concentrate in relatively small areas and periods, may have a huge environmental impact on Mediterranean ecosystems and their functionality, intensifying and cumulating with other human impacts of the local population's activities (e.g. waste, water consumption, and pollution) (Drius et al. 2019). A similar pattern was found in Sardinia, where the activity of Leisure & tourism contributed significantly to habitat degradation and faunal changes, but not to pollution and other expected impacts. Similarly, following the extensive restoration of the mine spill in 1998 in the Doñana wetland system (Spain), urbanization and tourism were identified as key drivers of habitat degradation and biodiversity loss (Zorrilla-Miras et al. 2014; Paredes et al. 2021). This suggests that the recent tourist development was successfully controlled by regulations related to water use and pollution, such as the European Water Framework Directive (2000/60/EC), while less efficient are likely other conservation measures to biodiversity, like the "Habitats" Directive (92/43/EEC) or the institution of nine Ramsar sites in facing tourism-related issues in the island. Slow tourism can be promoted to dilute the human impacts now concentrated along the coast and for a few months in the summer (Balletto et al. 2020). Our results confirm the concerns already expressed that the protection status (mainly Natura 2000 network) in Sardinia is still inefficient, despite covering about 18% of the land surface, mainly due to the high biodiversity that is also present outside the protected areas or the inefficiency of 'diffuse protection' when high economic interests insist (Pranzini et al. 2015; Ferrarini et al. 2023).

Similar patterns have been observed in urbanization and industrialization, as these activities are partly driven by tourism, requiring expanded housing and services to support it (Marignani et al. 2017). Our results further highlight the growing interrelationship between tourism and urbanization, as both have been found to negatively affect the aesthetic value and thus probably the appreciation of tourists. Moreover, urbanization and industrialization are concentrated on the coast and plains like tourism and further overlap in terms of impacts on the environment and geographic space, especially in the Mediterranean area (Marignani et al. 2017).

Otherwise, the island's industry sector in Sardinia has seen a significant decline in its share of the labor force in the last decades. In 1998, it employed 22.6% of the workforce, compared to Italy's 32.0% at the time (Hospers 2003). By 2023, this percentage had dropped to 12.31%, while Italy's industrial sector remained relatively stable at 32.95% of total employment (ISTAT 2023; Sardinian Region 2024). Sardinia's industry sector is neither well-developed nor diversified, as it is still highly specialized in heavy industries with large sunk costs (e.g. petrochemicals) and in the construction industry (Hospers 2003). Considering such results is crucial to focus on a renewed landscape plan that concentrates on wetlands and the conservation and restoration of their habitats, to fulfil the global targets of the Millennium Goals and the European Nature Restoration Law.

Other less frequent activities are also worthy of discussion. For instance, the association between transportation infrastructures and vegetation degradation is not a new finding. In wetlands of the Great Lakes in the USA, road construction has been found to cause substantial habitat fragmentation, disrupting plant communities (Saunders et al. 2002). In other cases, the influence of roads is related, as in our study, to the degradation of vegetation, which facilitates the spread of invasive species (LeBlanc et al. 2010). This suggests that infrastructure development is a critical issue for wetland management, where the trade-offs between connectivity and conservation must be carefully balanced.

Our results showed significant co-occurrences between hydraulic interventions and both positive (enhancement) and negative impacts (hydrological disruptions), reflecting the challenge of finding an equilibrium between human utility and ecosystem functioning, lately correlated with biodiversity. Water management interventions, although crucial for flood prevention, often result in unintended ecological consequences, particularly in wetland areas (Verhoeven and Setter 2010). There are mutual interactions among biodiversity changes, ecosystem functioning, and abiotic factors. Integrating these interactions into a single, unified picture, both theoretically and experimentally, and across ecosystem types and processes, is a major challenge that may help bring about a true synthesis of community and ecosystem ecology (Loreau et al. 2001).

Last, we found Mining and extraction of materials affecting soil degradation. This confirms the high influence of quarries and mining in Sardinia, which have been a focus for restoration efforts and measures to mitigate their effects on waters, biodiversity, and human health (Cidu et al. 2009; 2012; Fois et al. 2023). Assisted or unassisted revegetation of soils degraded by excavation activities has been proposed as the most effective solution for soil stabilization (Fois et al. 2025), either through simple planting of native flora (Boi et al. 2023 and references therein) or with phytoremediation assisted by bioaugmentation (Tamburini et al. 2017). The highest detected impact found was the degradation of the vegetation. In this case, we must consider that wetland vegetation plays a critical role in maintaining the health and functioning of the entire wetland ecosystem (Thullen et al. 2005). Therefore, large-scale vegetation reduction and changes in the structure/abundance or species richness are a particularly noteworthy threat to wetlands (Spieles 2005). Furthermore, declines in local plant diversity, which are far more common than global extinctions, often decrease ecosystem functioning and services (Isbell et al. 2011; Fois et al. 2025). Concerning the various drivers of landscape heterogeneity, effective wetland conservation requires not only precisely locating the areas where vegetation is reduced, but also assessing the spatial differentiation in the magnitude of local vegetation changes with human activities. For wetland managers, identifying the areas that are most susceptible to vegetation reduction should be a primary concern.

Factors affecting activities and impacts across the island

Conservation management in Sardinia has not shown a generally positive association with environmental improvement. This is consistent with the findings of Lai et al. (2017), who highlighted that processes of degradation and simplification characterize both Natura 2000 sites and natural protected areas on the island. Their assessment emphasized the need for a greater focus on effective management strategies for protected areas, especially for coastal wetlands, where economic growth is high. Similarly, recent studies by Bricca et al. (2024) indicated that habitat quality, measured through typical species richness, did not increase consistently with levels of protection in the Mediterranean region. Public management of protected areas, including wetlands, needs to strike a balance between implementing measures to conserve biodiversity and addressing the economic, social, and cultural drivers of land-use impacts. In contrast, there are successful examples from the UK where conservation efforts have led to measurable improvements in wetland biodiversity and water quality (Maltby 2022). However, like in our study, these conservation efforts sometimes fall short in preventing habitat degradation, particularly when external impacts such as agriculture and urban development are prevalent. This is also in support of what was previously mentioned about the effectiveness of protected areas and highlights that while conservation efforts can help mitigate certain impacts, they need to be complemented by broader landscape-scale interventions to tackle the underlying causes of degradation (Comín et al. 2004). Improvement of wetlands within protected areas can start from a solid baseline, as these areas are more investigated than those without protection (Fois et al. 2021). All the significant drivers (i.e. wetland area and ownership) found in this study were in support of the same conservation planning improvement. First, larger wetlands were more impacted than smaller ones, supporting the idea that managing large protected areas is difficult due to the increase in overall issues and their complexity, despite being theoretically optimal for limiting impacts from outside (Fahrig et al. 2022; Fois et al. 2021). Such increased complexity in large areas is confirmed by the fact that wetlands mixed with both private and public landowners are more impacted.

In many parts of the world, large areas of wetlands are under the control of private owners (Sullivan and Fisher 2011). That is why legislation is needed to control what owners can do to ensure that they recognize the importance of wetlands as crucial functional ecosystems. The explicit inclusion of wetlands in all forms of water legislation is an essential step towards effective and sustainable management.

Potential solutions in this context include land acquisition strategies, not limited to wetlands themselves but extending to upstream areas within the watershed where many of the impacts-inducing activities originate. However, such measures are generally more feasible in inland regions, where high-impact drivers such as tourism and urbanization are less prevalent (Fois et al. 2019). Alternatively, or in synergy, the promotion of sustainable tourism remains the most viable option. While wetland typology (marine/coastal versus inland) was not identified as a significant variable, the findings present an interesting perspective. By incorporating key covariates such as normalized wetland area and ownership type, the analysis revealed that the apparent differences between coastal and inland wetlands are likely confounded by these factors. Specifically, larger wetlands and those with mixed ownership experienced more impacts, overshadowing the direct effect of typology alone. This highlights the importance of considering multiple interacting variables to accurately discern the drivers of human impacts. Consequently, our modeling approach provides a more comprehensive and ecologically meaningful understanding of the factors influencing impact distribution across Sardinian wetlands than analyses focusing solely on wetland typology.

Rather than inland or marine/coastal typology, we found differences of freshwaters against the rest, widening the spectrum of more impacted wetlands to all transitional environments.

The fact that freshwater wetlands are the least impacted suggests both good and bad news. The downside is again that brackish and salt wetlands are confirmed to be severely impacted, as also found elsewhere (e.g. El Mahrad et al. 2020; Orro and Cabana 2021); the upside is that freshwater wetlands, which are critical for wildlife survival and human well-being, are likely to be less impacted by humans due to geographical isolation, limited agriculture, and lower urban density. However, Paredes et al. (2021) demonstrated in the Doñana coastal wetland system that pollution is predominantly driven by inputs from anthropogenic sources via tributary streams and other freshwater wetlands. This highlights the predominant influence of upstream land use on the health of connected coastal wetlands, but especially in continental contexts such as the Iberian Peninsula, where watersheds are generally more extensive. Moreover, the impact of natural factors on freshwater wetlands, such as decreasing precipitation regimes due to global warming, must also be considered (Comín et al. 2004; Bagella 2023; André et al. 2024). Due to their lower economic value, combined with inland abandonment (Fois et al. 2019; Todde et al. 2024), land acquisition around freshwater inland wetlands is more feasible than around coastal sites. Slow tourism, sustainable agriculture, animal husbandry, and other sustainable economic development policies can be integrated into a multifaceted landscape plan for these inland areas.

Conclusions and wetland management suggestions

In conclusion, the main suggestions raised by our findings are:

1. Larger wetlands and those with mixed ownership were more affected, while conventional inland vs. coastal classifications may no longer be sufficient to capture vulnerability patterns.
2. Freshwater wetlands are the least impacted. This suggests that small-scale farming, which is widely practiced around Sardinian inland freshwater wetlands, has a smaller impact than other activities, such as tourism and urbanization, which are more frequent around brackish/salt waters. However, caution is needed, as downstream wetlands (often brackish) accumulate small, fragmented, and, possibly, less detectable impacts occurring throughout the entire catchment area.
3. Activities not only in the wetland but also in the watershed or "zone of influence", such as those related to tourism and scattered urbanization, are increasingly inappropriate and could seriously threaten wetlands and their functionality. Policies are urgently needed to mitigate impacts, plan and promote sustainable activities.
4. The protection of wetlands does not have a significant effect on the prevention of degradation of fauna and vegetation. This suggests a necessary improvement in their management, possibly in combination with the promotion of sustainable economic development policies.
5. The complex web of activities and their impacts can only be sufficiently represented and disentangled if many aspects are considered together including economic, environmental, cultural, and social issues. An integrated landscape approach is therefore the most effective tool to support the conservation and improvement of wetlands status.

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Data availability The dataset with impacts and activities is available on the Zenodo open-access repository: https://doi.org/10.5281/zenodo.17192999.

Declarations

Competing interests The authors declare no competing interests.

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