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Research article

Ecosystem services modelling to analyse the isolation of protected areas from a social-ecological perspective

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ABSTRACT

Biodiversity loss continues to increase globally despite conservation strategies such as the designation of protected areas and the implementation of environmental management practices. Land use changes often exacerbate the spatial isolation of protected areas, undermining their biodiversity conservation goals and the provision of ecosystem services. To address this issue, the present study investigates how a social-ecological approach, incorporating ecosystem services modelling, can address protected areas isolation and enhance habitat connectivity, using Egmont National Park in Aotearoa New Zealand as a case study. The analysis focuses on five ecosystem services including carbon sequestration, habitat quality, timber production, pasture production, and outdoor recreation. Findings highlight significant synergies and trade-offs, particularly between regulating services within the park and provisioning services in the surrounding grasslands, revealing critical social-ecological conflicts. In particular, the contrast between the indigenous forest within the park, which supports high habitat quality and carbon storage, and the surrounding grasslands, which are highly productive for pasture, underscores the challenges of balancing conservation goals with agricultural activities. This study develops social-ecological units to inform integrated environmental management strategies, aiming to reduce isolation, improve connectivity, and align biodiversity conservation with human well-being. These findings provide actionable insights for shifting trade-offs to synergies and supporting sustainable management practices.

1. Introduction

The implementation of protected areas has been the main conservation strategy used for mitigating the impacts of land use change on habitat quality and biodiversity (DeFries et al., 2005; Geldmann et al., 2024; Tesfaw et al., 2018). However, despite extensive global efforts in designing protected areas and implementing sustainable management practices, the rate of biodiversity loss continues to increase (Hill et al., 2015; Laurance et al., 2012; Rada et al., 2019). In particular, in situ conservation efforts may lead to impacts being transferred elsewhere. For example, protecting biodiversity in one area may inadvertently transfer environmental impacts to surrounding regions by inducing land use changes, and potentially isolating protected areas from other habitats (Ewers and Rodrigues, 2008; González-García et al., 2020). As a result, the isolation of protected areas has become a common issue that threatens biodiversity and related ecosystem services (ESs) -all the benefits that humans can obtain from ecosystems (Costanza et al., 1997)- because it reduces connectivity between habitats, therefore jeopardizing their objectives and leading to additional biodiversity losses (Haddad et al., 2015; Matteucci and Camino, 2012; Saura et al., 2017). Addressing this issue is a challenging task as it requires the creation and enhancement of ecological networks of protected areas, along with ensuring their effective conservation and management (Cook et al., 2019; Saura et al., 2017). Hence, better understanding the interactions between protected areas and their surroundings is paramount for achieving long-term biodiversity conservation and avoiding further losses (Palomo et al., 2014).

Furthermore, protected areas become significantly more effective in preserving biodiversity when integrated into an ecological network coupled with other unprotected natural habitats (Hilty et al., ; Keeley et al., 2021). These networks include corridors, buffer zones and other structural and functional elements that connect protected areas, especially in fragmented landscapes (Creamer et al., 2016; Najihah et al., 2017). Corridors, in particular, are species-specific, meaning that their

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design must consider the ecological requirements of particular species, as well as the variability in land cover structure, which can influence species movement and habitat suitability (Silveira et al., 2014). Because their primary focus is on ecological connectivity, these networks effectively address habitat fragmentation and biodiversity loss (Samways and Pryke, 2016). Several studies have examined protected areas isolation and their impact on habitat connectivity using different methods and approaches. These include measuring isolation with metrics such as contagion metric of spatiotemporal NDVI values (Seiferling, 2010), structural and functional connectivity metrics (Keeley et al., 2021; Najihah et al., 2017; Theobald et al., 2022), fragmentation metrics (Clerici et al., 2007; García et al., 2005; Haddad et al., 2015; Matteucci and Camino, 2012; Tapia-Armijos et al., 2015), and landscape isolation metrics (Lin et al., 2013; Rodríguez-Rodríguez and Martínez-Vega, 2019). Two common approaches applied in most studies are ecological networks that link protected areas through corridors (Mathur and Sinha, 2008), and landscape approaches that examine protected areas within their broader landscape context (Nath Sharma et al., 2021). However, both approaches may have limitations in long-term conservation of biodiversity and ESs as they overlook the social dimension and the connection between society and protected areas (Palomo et al., 2014). While the development of highly connected protected area networks is considered a valuable strategy for biodiversity conservation, landscapes significantly altered by land use changes require a broader perspective on connectivity, integrating both ecological connectivity and a social-ecological approach (Liang et al., 2023).

Social–ecological systems are interconnected systems of people and nature, where humans influence ecosystems and rely on them for essential services (Fischer et al., 2015). A social-ecological approach builds on this interconnectedness by integrating ecological and social dimensions in protected areas management to address both conservation goals and human needs (Ban et al., 2015; González-García et al., 2022a, b). This perspective highlights the critical links between ecological and social systems, especially through the delivery of ESs and the benefits they provide (Cumming and Allen, 2017; Niedziałkowski et al., 2022). In particular, ESs as part of this approach can expand conservation efforts beyond protected area boundaries by considering the flow of benefits from ES providers to beneficiaries, and by addressing the connection between these providers and beneficiaries, which could help reduce the issue of isolation (Lin et al., 2017; Palomo et al., 2014). While the potential of an ESs approach to address protected areas isolation has been recognized, there are limited studies that explore its effectiveness in identifying and balancing social-ecological conflicts to achieve both biodiversity conservation and human wellbeing. Some have incorporated the ESs concept into protected areas management. For example, Lin et al. (2017) calculated habitat quality and other ESs through the Integrated Valuation of Ecosystem Services and Trade-offs (InVEST) to design reserve networks that protect biodiversity and multiple ESs. Similarly, Zhang et al. (2020a,b) applied an ES approach using biophysical metrics to identify hotspots of water, soil, and biodiversity conservation to expand protected areas network, providing insights for ecological conservation and sustainable development. Additionally, González-García et al. (2022a,b) quantified biodiversity and ESs supply-demand to assess the utility of this approach in informing integrated territorial planning beyond the administrative boundaries of protected areas. Their aim was to achieve long-term conservation of protected areas, biodiversity, and ecological networks while also considering social preferences and human wellbeing.

While previous research has integrated ESs into protected areas design and management, there is a gap in adopting a social-ecological approach that considers ESs provision and interactions within the broader social-ecological context of protected areas, especially to help reduce habitat isolation. These include interactions between local communities, land use practices, cultural values, economic activities and management policies which influence ecological processes (Ghoddousi et al., 2022). To this end, this paper aims to investigate how a social-ecological approach, using ESs modelling as the tool, can address protected areas isolation and enhance habitat connectivity within the context of Aotearoa New Zealand. Specifically, the paper seeks to answer the following research questions: i) Can targeted environmental interventions based on an ESs approach help manage protected areas isolation and associated biodiversity loss?; ii) How can the analyses of synergies and trade-offs among ESs inform environmental interventions aimed at reducing protected areas isolation?; and, iii) How can ESs zoning through clustering analysis serve as a strategic planning tool to enhance the spatial management of protected areas? To achieve this, the paper explores how various ESs, including carbon sequestration, timber production, pasture production, habitat quality and outdoor recreation affect isolation of protected areas using Egmont National Park as a case study. The paper quantifies and maps five selected ESs to explore the contribution of ESs modelling in analysing the isolation of protected areas from a social-ecological perspective based on the spatial distribution of these services. To identify social-ecological conflicts within the study area, the paper analyses spatial synergies and trade-offs among ESs and delineates distinct ESs zones using quantifying methods. These social-ecological units are utilized to identify priority strategies aimed at addressing the social-ecological conflicts. Findings provide insights into how this approach can inform targeted environmental interventions to reduce protected areas isolation and enhance their management practices.

2. Materials and methods

2.1. Study area

Egmont National Park was chosen as the focus of this study because it is a good example of a protected area with a long history of protection within a highly altered landscape (see Fig. 1). The park is located on the western coast of Aotearoa New Zealand's North Island, covering approximately 33,500 ha (Efford, 2012). Egmont National Park was initially designated as a Forest Reserve in 1881 and subsequently established as a National Park in 1900 (Davidson, 2022). While the park's protection has effectively preserved its natural vegetation, it is surrounded by a highly altered landscape dominated by pastures on all sides, isolating it from other natural areas. This issue has compromised the effectiveness of this protected area (Ewers and Rodrigues, 2008). The prominent landmark within the park is Mount Taranaki, renowned as one of the world's most symmetrical mountains, standing at 2518 m (Turner et al., 2008). The park's unique circular shape results from its first protection in 1881, which designated a forest reserve extending 9.6 km from the summit of Mt. Taranaki (NASA Earth Observatory, 2024). The geographical location of Egmont National Park along with its rapid elevation changes from about 100 m to 2500 m, significantly influences its climate (Joy et al., 2000).

Mount Taranaki, or Maunga Taranaki in Māori holds profound cultural significance for Māori, the indigenous people of Aotearoa New Zealand, who regard the mountain as a sacred ancestor. In 1863, the land was confiscated by the government, disrupting Māori connections with the area (New Zealand government, 2011). In 2017, the mountain was granted legal personhood, becoming the third geographic feature in the country to be granted this rights (Morris, 2022). This recognition acknowledges its cultural and spiritual importance and the historical relationship between Māori and the landscape. This recognition highlights the continued influence of Māori values and traditions on the management and conservation of the park today (Department of Conservation, 2002).

Egmont National Park provides a habitat for a variety of species, including threatened and endemic flora and fauna (Taranaki Regional Council, 2007). This park is important nationally due to its diverse vegetation which has developed in an environment of frequent volcanic activity (Efford, 2012). The vegetation ranges from semi-coastal and montane forest to tussock lands, alpine and scree communities (Clarkson

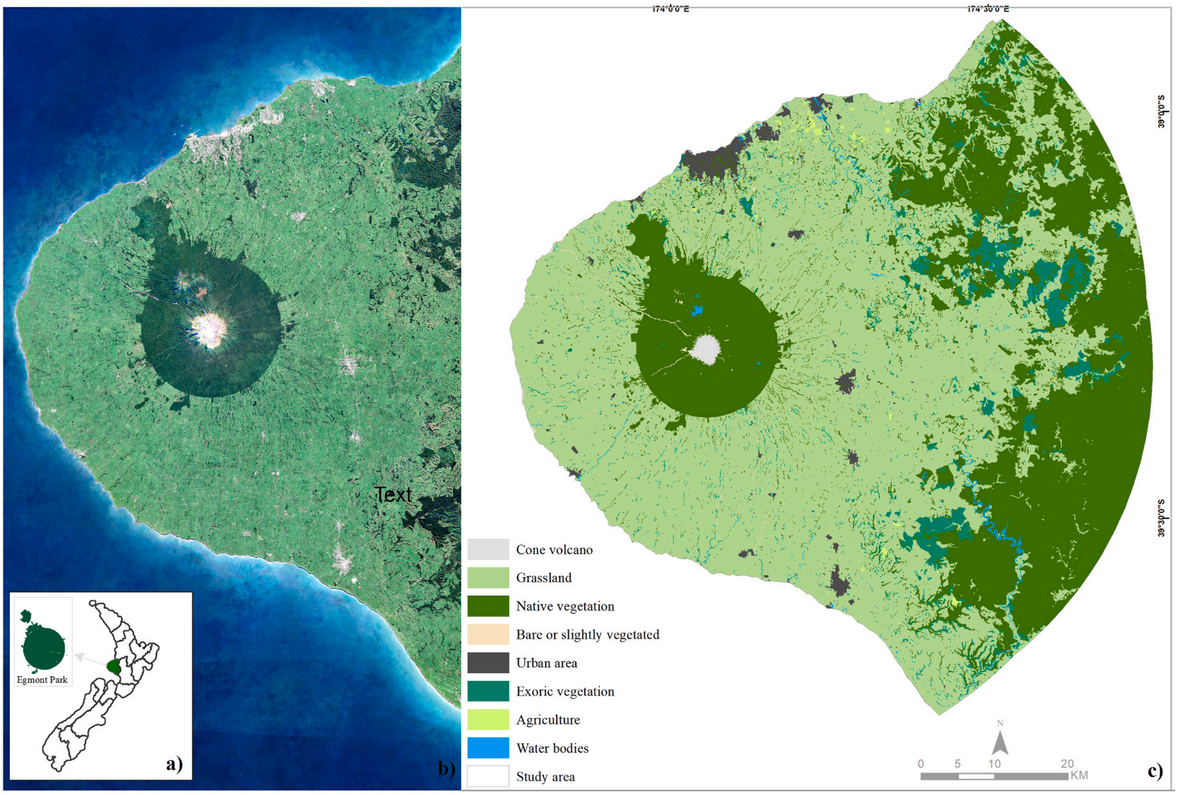

Fig. 1. a) The geographical location of the study area within the country, b) Satellite image of the study area (Source: European Space Agency Sentinel-2 satellites, captured between September 2023 and April 2024; 10 m resolution imagery downloaded from the Land Information New Zealand (LINZ) Data Service Portal), c) Land cover types of the study area.

et al., 1988). The park is home to many bird species with several unique invertebrate species. Additionally, nearly half of Aotearoa New Zealand's indigenous fish species are found in or near the park (Department of Conservation, 2024a,b). A range of recreational opportunities are available in the park managed by the Department of Conservation, including walking paths and tracks, hiking trails, car paths and access roads, bridges, huts, and campsites (Department of Conservation, 2015), see S1 Figure in the Supplementary Material). The number of visitors to Egmont National Park is estimated to be more than 350,000 annually (Department of Conservation, 2013).

We delineated a 50 km buffer around the national park as our study area. This buffer distance was selected to encompass a variety of habitats, assess potential threats, and evaluate connectivity to other natural habitats. Previous studies have also employed this buffer zone to investigate the isolation of protected areas resulting from land use changes in their surroundings (Radeloff et al., 2010), and to analyse the interactions between protected areas and their surroundings (DeFries et al., 2005). Within the study area, vegetation comprises both native and exotic types. The native vegetation in Egmont National Park includes a diverse mix of native conifer and broadleaved tree species. Key features include the abundance of northern rātā (Metrosideros robusta) trees and one of the largest semi-swamp forests in the North Island, dominated by kahikatea (Dacrycarpus dacrydioides), rimu (Dacrydium cupressinum), and kāmahi (Weinmannia racemosa). In contrast, the exotic vegetation primarily consists of radiata pine (Pinus radiata) plantations, which cover approximately 90 % of the exotic vegetation area, with smaller sections of Douglas fir (Pseudotsuga menziesii) and other species primarily cultivated for timber production.

2.2. Quantification of ESs

Five ESs were quantified in this study based on the Millennium Ecosystem Assessment (MEA) (MEA, 2005) and the Common International Classification of Ecosystem Services (CICES) (Haines-Young and Potschin-Young, 2018), comprising regulating, provisioning and cultural services (Haines-Young and Potschin-Young, 2018). The regulating services include carbon sequestration and habitat quality, provisioning services include timber production and pasture production, and cultural ESs include outdoor recreation. Fig. 2 illustrates the methodological framework used for guiding the study. We integrated land cover map with data on biodiversity loss extracted from the threatened environments classification map in Aotearoa New Zealand as input data for the ESs modelling. This integration provides a more detailed understanding of land cover data by considering its indigenous vegetation remaining. This approach moves beyond the conventional emphasis on generalized land use/land cover (LULC) data, which can be overly simplistic for ESs modelling and have been used in various studies (Wang and Dai, 2020; Xu et al., 2018; Yuan et al., 2023). By categorizing land cover data based on biodiversity levels, we enhance the accuracy of our models, effectively capturing the heterogeneity of ecosystems.

The rationale for selecting these services is in line with the study's objective – that is, to analyse the isolation of protected areas by examining ESs associated with contrasting land covers and uses within and surrounding Egmont National Park. Habitat quality was selected due to the dominance of indigenous forest and natural habitats, crucial for biodiversity conservation. Carbon sequestration, a globally significant and extensively studied ES, underscores its importance at local and international levels (Wu and Fan, 2022). Pasture production reflects the prominence of intensively grazed grasslands around the park, which contribute to its isolation. Although exotic forest plantations have smaller coverage, their role in timber production and associated habitat loss justified inclusion (Booth et al., 2022). Outdoor recreation highlights the aesthetic and recreational value of protected areas, significant visitor attractions in Aotearoa New Zealand (Brown and Brabyn, 2012;

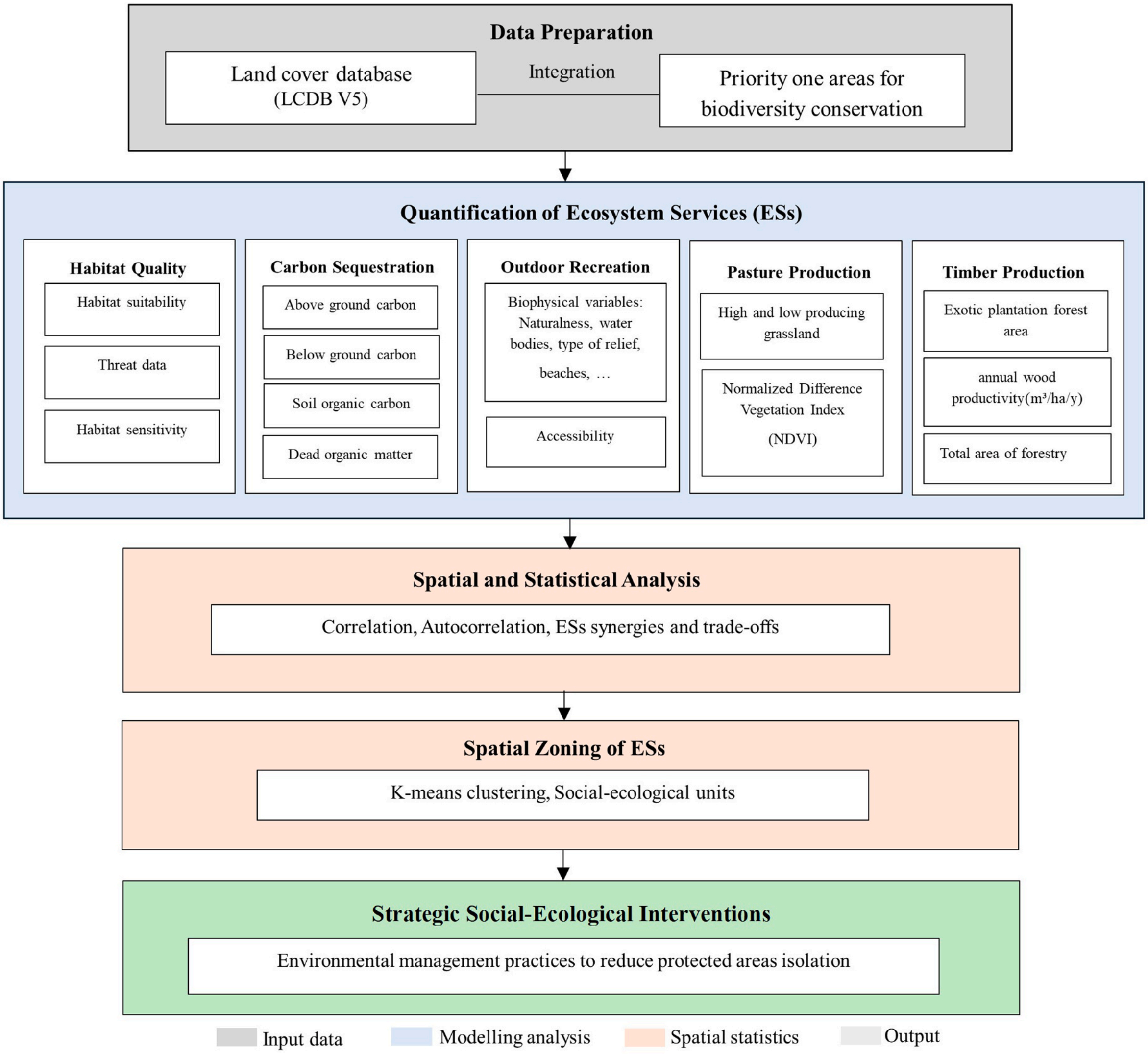

Fig. 2. Methodological framework of the study.

Department of Conservation, 2024). The detailed methods and data sources used for quantifying selected ESs are presented in Table S1.

It is important to note that some of the datasets used in this study are time-sensitive, which may influence the accuracy and applicability of the results over time. For instance, the relative impact and significance of identified threats to habitat provision may vary with changes in land use practices and environmental conditions. Similarly, carbon storage estimates derived from forest and soil carbon data are subject to annual variations due to natural and anthropogenic factors. NDVI-based pasture production data reflects temporal changes in climate conditions and land management, making it time-sensitive. In contrast, timber production and outdoor recreation model data are relatively less sensitive, experiencing slower and less frequent changes. Regularly updating the more time-sensitive datasets is crucial for maintaining the relevance and accuracy of the models and analyses presented in this study.

2.2.1. Habitat provision

Habitat quality, as a regulating ES, estimates the suitability of habitat and vegetation across a landscape to address biodiversity conservation requirements (Wu et al., 2019). The assessment of habitat quality depends on habitat suitability and three key threat parameters: the relative impact of each threat, the relative sensitivity of different habitat types to threats, and the maximum distance of influence of these threats (Huang et al., 2023; Sallustio et al., 2017). Based on previous studies (Mengist et al., 2021; Moreira et al., 2018; Zhang et al. (2020a,b), the following threats were identified within the context of the study are: farming, forestry, invasive species, over-grazing, built-up area, railway, hiking and mountain biking, highway and secondary roads.

We determined weights and maximum impact distances for threats within the study area by calculating average values from existing literature. Habitat suitability and sensitivity scores were assigned to each land cover type based on the extent of indigenous vegetation remaining and protection level, with higher values indicating greater suitability. A linear scale was employed, assuming a gradual increase in habitat quality with increasing levels of indigenous vegetation remaining and protection. For example, if the least suitable class has a value of 0.6, we assume an increase of 0.1 between each class up to the most suitable. The choice of a 0.1 increase is supported by the literature (Moreira et al., 2018), which suggests that this slight increase is reasonable when comparing the differences in suitability across different habitats. The required data as input for InVEST model is provided in the Supplementary Material (Tables S2, S3 and S4).

2.2.2. Carbon storage and sequestration model

We defined carbon storage as an indicator of the capacity of ecosystems to contribute to climate regulation because of their potential to store carbon in the different pools (Spanò et al., 2017). We used the InVEST carbon storage model, which uses data from carbon storage pools (t/ha/year) as the input and calculate the total carbon storage as the output (see Table S5 in the Supplementary Material). The model considers four different carbon pools: (1) carbon stored in aboveground biomass; (2) carbon stored in belowground biomass; (3) carbon stored in dead matter; and (4) carbon stored in soil.

The InVEST model uses LULC map and the carbon density of each LULC type to estimate the amount of carbon storage in each cell. To achieve this, forest carbon stock estimates were derived using carbon look-up tables published by the Aotearoa New Zealand government (Case and Ryan, 2020; Paul et al., 2019). For soil carbon, this study used the national average soil carbon stocks for the different LULC types (Kirschbaum et al., 2009) in addition to existing literature (Ausseil et al., 2015; Duarte et al., 2016; García-Ontiyuelo et al., 2024; Paul et al., 2019; Sharp et al., 2015; Eggleston et al., 2006). It is important to note that the model does not account for carbon emissions from agricultural activities, such as livestock and wetland drainage, or variations in carbon storage potential across different forest types (Rimal et al., 2019). These limitations may influence the accuracy of the carbon storage estimates. Nevertheless, the model offers a valuable foundation for understanding spatial variations in carbon storage within and outside the national park.

2.2.3. Timber production

Timber includes products made from trees harvested from forest ecosystems, plantations or non-forest lands (Dai et al., 2018). In Aotearoa New Zealand, a significant proportion of the native forest is legally protected, resulting in almost all timber being sourced from the exotic forest plantation sector (Ausseil et al., 2013). Specifically, 90 percent of country's forestry area is planted with *P. radiata* (NZIER report, 2017). In this study, the timber production map was generated by multiplying the existing forestry area by the annual wood productivity per unit of land area (m^3/ha/year). The average annual wood production is estimated at 27 m^3/ha, based on Aotearoa New Zealand forestry estimations of 810 m^3/ha wood yield over a harvestable age of 30 years (Lee-Jones and Vlosky, 2020).

2.2.4. Pasture production

Pasture productivity is the most important provisioning service in Aotearoa New Zealand, given the dominance of pasture-based farming (Tran et al., 2022). In this study, pasture production was estimated based on the Normalized Difference Vegetation Index (NDVI) data derived from Sentinel-2 L2A, which provides a spatial resolution of 20 m. Several studies have demonstrated a significant correlation between annual pasture yield and NDVI ($r = 0.7$, $p < 0.05$) (Amies et al., 2021a; Grêt-Regamey and Weibel, 2020; Tran et al., 2022). Consequently, NDVI data can be used to estimate the pasture yield. Higher NDVI values are related to higher productivity of ecosystems and the services they provide (Paruelo et al., 2016). NDVI data were extracted from high and low producing grassland to estimate pasture production based on Aotearoa New Zealand LCDB. Other land covers within the study area were assigned a pasture yield value of zero. In this study, we used NDVI data for each season of 2022 that had higher quality (with less than 10 % cloud cover) and calculated the mean NDVI value from four images using the cell statistic tool. The approach of using mean seasonal NDVI values to estimate forage provision has been adopted in other studies as well (González-García et al., 2022).

2.2.5. Outdoor recreation model

Outdoor recreation is referred to the capacity of ecosystems to provide recreational opportunities (Scholte et al., 2018). To quantify this model, we used various biophysical indicators, including the degree of naturalness, presence of water bodies and beaches, relief type, designated recreation areas, and presence of historical sites. These indicators were selected based on their influence on recreational value (Paracchini et al., 2014; Peña et al., 2015; Schirpke et al., 2018; Ghasemi et al., 2023, 2024). Accessibility was incorporated to account for the potential use of the recreation site (see Table S6 in the Supplementary Material). All spatial indicators were quantified at a regular grid resolution of 30 × 30 m. Then, we normalized all layers to a scale of 0–1. Finally, the recreation service was calculated by performing a weighted sum of all the layers.

2.3. Exploring spatial trade-offs and synergies among pairs of ESs

Pearson correlation analysis and significance tests were utilized to determine the interactions (trade-offs/synergies) between pairs of ESs. Significant negative correlations ($p < 0.05$) indicate significant trade-offs, whereas significant positive correlations ($p < 0.05$) indicate significant synergies between pairs of ESs. To perform this analysis, first, the grid cells of the study area were converted to 1000 sample points, effectively covering the entire study area. Then, pixel-scale ES value for each sampling point was extracted using the Extract Values to Point tool.

The weight and spatial modules of the GeoDa software package were utilized to conduct bivariate spatial autocorrelation analysis of ESs at the spatial unit level. This analysis aimed to measure the spatial trade-offs and synergies among ESs. High–high and low–low aggregations indicate spatial synergies, while low–high and high–low aggregations represent spatial trade-offs (Li et al., 2022). To achieve homogenous spatial units for statistical analysis, we created a hexagonal grid using a Tessellation tool. Hexagon scales must closely align with decision scales to effectively represent information supporting those decisions. Side lengths ranging from 500 to 1000 m are considered suitable for local decision-making, resulting in hexagons covering an average area of 50–250 ha (Bousquin, 2021). In this study, we employed a fine resolution of 50 ha hexagon to more precisely capture variations within our study area.

We then calculated the mean value of ESs within these cells using a zonal statistics tool. Hexagonal grids have several advantages over square grids for ecological applications (Molné et al., 2023). A hexagonal grid was chosen instead of a rectangular grid because it more effectively represents spatial connectivity in a complex landscape (Schindler et al., 2008; Tammi et al., 2017). Another benefit of using a hexagonal grid is its enhanced clarity in visualizations compared to a rectangular grid (Birch et al., 2007).

2.4. Identifying spatial zoning of ESs

To identify areas with similar ES associations, we performed a k-means cluster analysis to delineate ESs zones as social-ecological units that are spatially contiguous across landscapes (Yang et al., 2019). These units are homogeneous in terms of capacity to provide the five selected ESs and help guide spatial planning and land management decisions (Spake et al., 2017). The optimal number of clusters was determined based on the largest pseudo F-statistic values, which represent within-cluster similarities and between-cluster differences (Wu and Fan, 2022b). We analyzed the proportion of LULC within each zone to better understand how different land cover types influence the spatial variation of ESs provision. The resulting ESs zones were utilized to formulate targeted management strategies to mitigate the isolation of Egmont National Park and improve protected areas management.

3. Results

3.1. Spatial distribution of ESs

The distribution of individual ESs provision exhibited considerable variation throughout the study area, showing different spatial patterns (see Fig. 3). The maximum habitat quality was observed within the national park, dominated by indigenous forests, particularly in its eastern region. The analysis revealed that significant habitat quality was linked to areas free from threats and with high biodiversity levels, where more than 30 % of the land cover was indigenous and effectively protected from degradation. In contrast, lower habitat quality was found outside the national park, particularly in built-up areas such as urban areas and transportation networks. Interestingly, the study area shows a linear feature of low habitat quality, coinciding with highways that connect urban areas and significantly disrupt habitat connectivity. Additionally, the model estimates low habitat quality near Mount Taranaki's summit due to rocky, snow-covered terrain, reflecting its sensitivity to vegetation cover.

Egmont National Park and the eastern part of the study area, predominantly covered by indigenous forests, showed the highest carbon storage values (up to 49.194 t/pixel; 547 t/ha). The areas covered by broadleaved indigenous hardwoods and exotic forest also showed high carbon storage values (up to 37.2 t/pixel; 413.3 t/ha). Medium values of carbon storage were observed in the grasslands, shrublands and scrublands. Urban areas showed the lowest values for carbon storage, except for urban parks, which had higher values (5.9 t/pixel; 65.5 t/ha).

Timber production is concentrated in areas covered by exotic forests, primarily consisting of *Pinus radiata*. These exotic plantations represent a relatively small portion of the overall study area. Spatial variations in average annual wood production across these exotic forest patches resulted in a range of timber production values within the study area, with a maximum of 2.5 m^3 per pixel (27.7 m^3/ha). Land cover types other than exotic forests are assigned zero values for timber production.

High producing grasslands surrounding Egmont National Park support intensive pastoral farming, particularly dairy cows, which has the highest value of pasture production. However, these productive grasslands also exhibit significant biodiversity loss, with less than 30 percent of indigenous vegetation remaining. Outdoor recreation ES showed the highest values within the national park and its northern part, where natural features such as mountains, indigenous forests, water bodies, and recreational facilities are present. In contrast, urban areas and regions with relatively fewer mountains, lower levels of naturalness, and limited recreational facilities exhibited lower values for outdoor recreation. These areas are primarily concentrated in the middle and eastern parts of the study area.

3.2. Spatial trade-offs and synergies among ESs

Table 1 presents the statistical correlations among 10 paired ESs. Based on the absolute values of the correlation coefficients, carbon storage and habitat quality exhibited a strong and positive correlation ($r = 0.9$). Conversely, pasture production showed a significant negative correlation with two regulating services. No significant correlations ($r < 0.3$) were found among the remaining pairs of services. The presented correlation values reflect a global correlation across the entire dataset, which may not fully capture localized relationships between ESs. For example, it might not account for the specific relationship between outdoor recreation and habitat quality within Egmont National Park. Similarly, the lack of correlation between timber and carbon highlights the importance of considering local spatial patterns to gain a comprehensive understanding of these relationships.

The local association cluster map among ESs revealed diverse patterns of synergy and trade-offs across the study area, consistent with the correlation results (see Fig. 4). Spatial synergy was evident in the distribution of carbon storage and habitat quality. High-high aggregation areas for these ESs were located within and east of the national park. The spatial separation and distance between these two regions suggest that they may lack ecological connectivity with each other and from a broader protected areas network. Conversely, low-low aggregation areas clustered outside the park boundary, exhibiting a strong spatial association with the existing road network. This pattern highlights the role of transportation infrastructure as a source of human disturbance, contributing to habitat fragmentation and the isolation of Egmont National Park.

Spatial trade-offs were evident between carbon storage and pasture production, as well as habitat quality and pasture production. High-low aggregation areas for these pairs clustered within and east of the national park, while low-high aggregation areas surrounded it. Similar spatial patterns emerged between carbon storage and timber production, highlighting competition between regulating and provisioning services. These trade-offs underscore competing land management objectives and limited connectivity between the national park and other natural habitats. The relationships between regulating services and outdoor recreation varied, with high-high aggregation areas concentrated in regions where indigenous forests coexist with recreational attractions like mountains and water bodies, and low-low areas linked to transportation infrastructure and grasslands. High-low aggregation areas were dominated by indigenous forests but lacked recreational facilities, while low-high areas were concentrated in coastal regions, with recreational facilities but lower values of carbon storage and habitat quality.

3.3. Spatial distribution of ESs zones

We identified three types of ESs zones as social-ecological units through cluster analysis, each differing in the levels of ESs provision (see Fig. 5). Each unit was described according to their characteristics of multiple ESs (see Table S7 in the Supplementary Material), and dominant LULC types (see Fig. S2).

Zone 1 (Habitat conservation area): This unit is notable for its extensive indigenous forest cover, encompassing 29.3 percent of the study area. It features the highest levels of carbon storage and habitat quality. Interestingly, Zone 1 is divided into two disconnected parts: one covering Egmont National Park and the other located to the east. Both parts play a critical role in biodiversity conservation. The indigenous forests cover 90 percent of the total area of this zone, contributing significantly to its exceptional ecological value.

Zone 2 (Pasture production area): This zone, composed of 90 percent grasslands, encircles the national park and serves as a barrier to habitat connectivity, potentially hindering species movement and the flow of ecological processes between the park and its surrounding landscapes. It has high pasture production but medium to low habitat quality and carbon storage, covering 38.9 percent of the study area. Intensive grazing isolates the park, creating social-ecological conflicts due to trade-offs between regulating services and pasture production. Balancing agricultural needs with ecological conservation requires integrating production and conservation activities.

Zone 3 (Habitat transition area): This zone, comprising 31.8 percent of the study area, includes a mix of grassland, indigenous, and exotic forests, offering average levels of carbon storage, habitat quality, outdoor recreation, and pasture production. Its mix of grassland and forest indicates a shift from farm-based landscape to diverse natural habitats. The multiple ESs offered by this zone highlight the link between human activities and ecological conservation, necessitating diverse and integrated management interventions to balance regulating, provisioning, and cultural services. Sustainable practices are required for long-term social and ecological benefits.

As shown in Fig. 4, Zones 2 and 3 exhibit some degree of permeability, indicated by the overlapping areas where Zone 2 is dotted inside Zone 3. This permeability is largely influenced by the presence of scattered reserves and conservation areas, most of which are less than 3 ha in

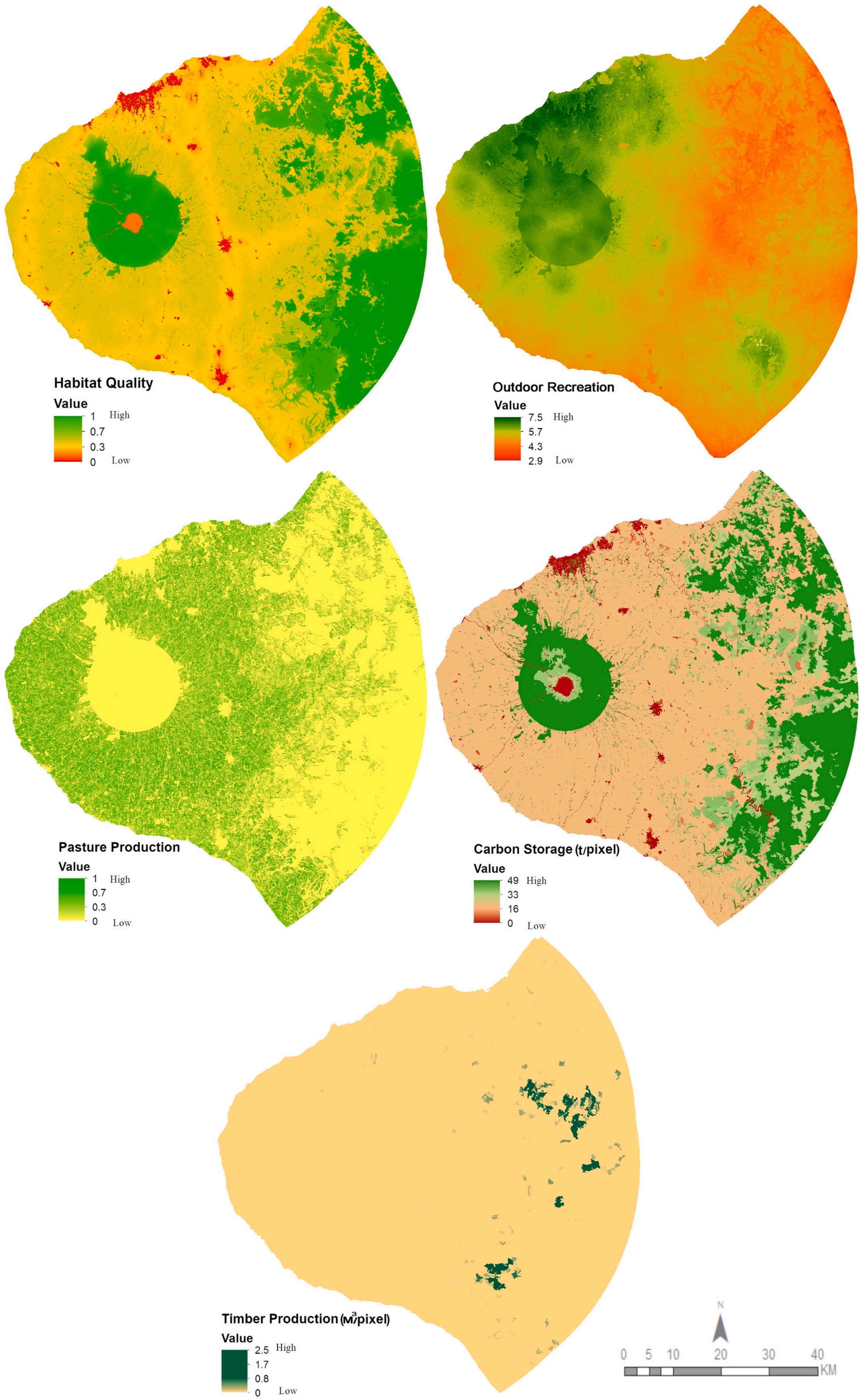

Fig. 3. Spatial distribution of Ecosystem Services (ESs) within the study area.

Table 1
Pearson correlation matrix between Ecosystem Services (ESs).

	Timber	Pasture	Carbon	Recreation	Habitat
Timber	1.0000				
Pasture	−0.1061[a]	1.0000			
Carbon	0.0003	−0.5599[a]	1.0000		
Recreation	0.0036	0.0281	−0.0258	1.0000	
Habitat	0.0008	−0.5285[a]	0.9300[a]	−0.0371	1.0000

*Correlation is significant at the 0.05 level.
[a] Correlation is significant at the 0.01 level.

size (Bayfield and Benson, 1986) but enabling functional connectivity for ESs flow and species movement (Powney et al., 2011). To further enhance this connectivity, efforts should be directed towards maintaining and enhancing continuous natural covers within these zones, alongside implementing sustainable land management practices.

The carbon storage model was validated by comparing its results with the current carbon stock estimates in conservation land provided by Aotearoa New Zealand's Department of Conservation. These estimates were based on sample data using a systematically sampled national scale plot (Mason et al., 2012). In Egmont National Park, the current carbon stock was estimated to be around 400–600 t/ha/year. Our model produced values within this range for the national park, with an estimated 35.6–49.2 t/pixel, which translates to 395–547 t/ha for a 30 × 30 m pixel size, matching the Department's estimates.

To validate the habitat quality model, we performed a sensitivity analysis to identify how the model responded to changes in input data. We increased the weight assigned to highway, a primary threat to habitat quality, by 10 and 30 percent to evaluate the model's response. The resulting changes in habitat quality were proportional to the weight increase, with a 10 percent weight increase leading to a 0.1 percent decrease in habitat quality, while a 30 percent weight increase resulted in a 3.3 percent decrease within the study area. These relatively small fluctuations in model output indicate that the model is robust and stable, as it is not overly sensitive to variations in input data. The model output followed a similar trend with minimal changes when we altered the weights of other threats, further indicating its robustness. In addition, our results concur with a similar study conducted in New Aotearoa Zealand by Ausseil et al. (2013), which found that the habitat provision is high in native land covers.

The recreation model was validated using the 2013 Regional Tourism Report (Department of Conservation, 2013), which identifies Taranaki Mountain, its surrounding areas, and the northwest coastline as major tourist attractions. Our findings align, showing high recreation services concentrated in Egmont National Park and along its coastline. The eastern part of the park, including the Tarere Forest Conservation Area, has high recreation value due to activities like fishing, jet boating, and water skiing. While specific visitor data for this area is unavailable, government estimates (Department of Conservation, 2024a,b) report significant growth in domestic and international visitors to public conservation areas from 2012 to 2018, supporting the observed trends.

To validate the pasture production model, we compared our results with the national map of pasture productivity. This map was generated using NDVI maps and collected pasture yield measurements. We employed spatial analysis tools in ArcGIS to create random points ($n = 20$) and extract values of pasture productivity from both maps at those points. Subsequently, we conducted a correlation analysis for comparison. The results revealed a strong correlation between the values ($r = 0.87$), indicating the reliability of our findings and a very small discrepancy when compared with the data from the comparative study (Amies et al., 2021).

The timber production map was generated based on the estimated data on annual wood productivity from New Zealand Forestry and Wood production data. This approach ensured that our model reflects real-world conditions and contributes to its validity.

4. Discussion

4.1. Utilizing ESs modelling to analyse protected areas isolation

This study modelled five distinct ESs, each displaying unique distribution patterns across Egmont National Park and its surrounding areas. Our results revealed varying spatial correlations between ESs across different regions (e.g., high correlation between recreation and carbon sequestration in some areas, but low correlation in others). These variations highlight the potential of ESs modelling to inform conservation policies aimed at reducing isolation and enhancing connectivity for protected areas. This aligns with other research that underscores the value of ESs models in identifying critical conservation hotspots (Spanò et al., 2017).

Our findings revealed a clear pattern of habitat quality, with the highest values found within the national park and its eastern region, dominated by indigenous forests. This supports existing research, which suggests that ecosystems rich in native vegetation tend to support greater biodiversity and face fewer anthropogenic threats (Lin et al., 2017). Conversely, lower habitat quality detected in built-up areas, particularly along transportation networks, indicates significant threats to habitat quality and connectivity due to urbanization and infrastructure development. These threats are consistent with observations in other studies, such as those highlighting the detrimental effects of infrastructure like highways on habitat integrity (Wu and Fan, 2022; Bai et al., 2019).

We also observed a significant overlap between carbon storage and habitat quality, particularly in areas dominated by indigenous forests, which aligns with previous research emphasizing the role of native vegetation in both carbon sequestration and biodiversity conservation (Wang et al., 2022). However, the lower levels of carbon storage in surrounding grasslands and urban areas highlight the limited connectivity between the park and its surroundings. This limited movement of species between these areas hinders essential life cycle processes, a challenge that has been similarly noted in studies of other protected areas, such as Doñana National Park, where land use differences contribute to isolation (Palomo et al., 2014).

The distribution of pasture production services around the park is a significant factor in its isolation. The unique geography of Taranaki, with its single mountain surrounded by intensive pasture production, creates a stark contrast with other mountainous protected areas, such as Pindos National Park in Greece, where human activities are more dispersed and include regulated livestock breeding and limited agriculture (Kati et al., 2009). In contrast, timber production occupies a limited area within the study region and is concentrated in exotic forests, reflecting its role as a commercial activity. While this does not directly contribute to park isolation, the presence of invasive species like *Pinus radiata* in these forestry areas poses a significant threat to indigenous biodiversity, making it crucial to implement management strategies that mitigate their impacts (Calviño-Cancela and van Etten, 2018).

The spatial distribution of outdoor recreation services differs from other ESs, shaped by natural attractions and recreational facilities. High recreation values are concentrated within the national park and along the coast, supported by public facilities and accessibility. This contrasts with the clustered pasture production surrounding the park. These patterns, captured by our model, highlight the role of ESs distribution in habitat connectivity. For example, high recreation values along the park's northern border enhance landscape permeability, supporting species movement, ecological conservation, and recreational activities. Scenic and recreation reserves within pastureland further strengthen connectivity and cultural value (Schirpke et al., 2018).

Our findings demonstrate that targeted environmental interventions based on an ESs approach can reduce protected areas isolation by addressing differences in ESs patterns within and outside the national park. Mapping ESs like carbon storage, habitat quality, pasture

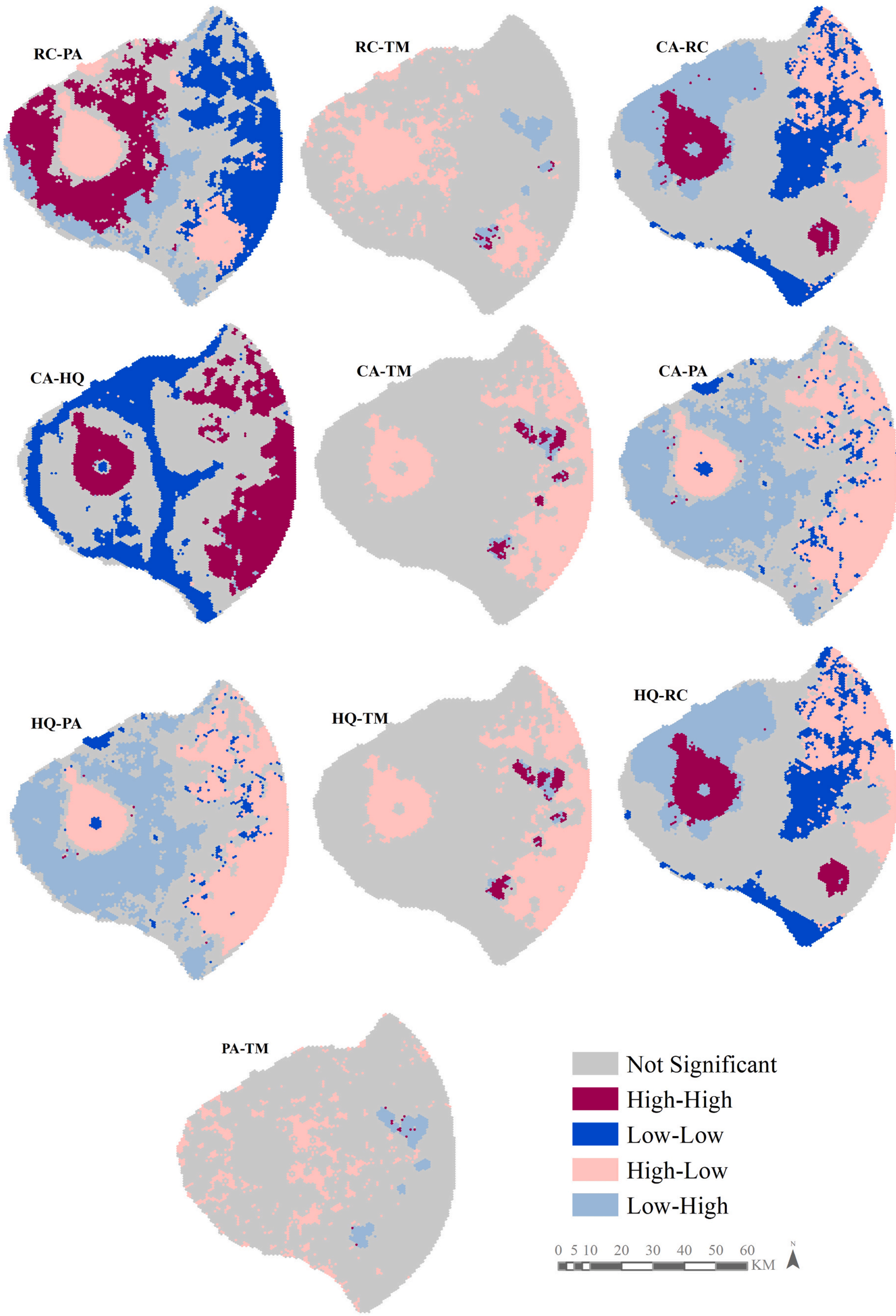

Fig. 4. Local indicators of spatial autocorrelation cluster map among Ecosystem Services (ESs) of the study area. CA: carbon storage; HQ: habitat quality; RC: recreation; PA: pasture production; TM: timber production.

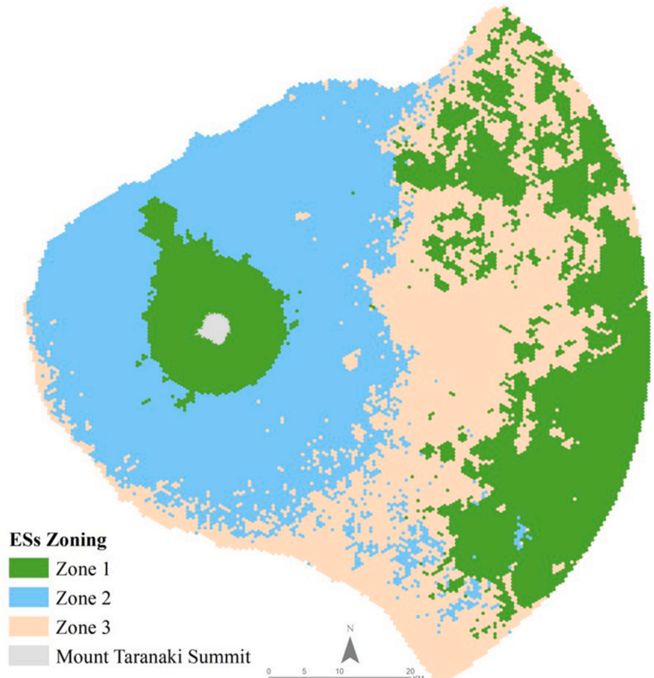

Fig. 5. a) The spatial distribution of the three ESs zones. b) Relative abundances of ESs within each zone, represented using rosette diagrams. These diagrams are dimensionless, as they rely on normalized data for each service. Longer petal lengths indicate higher production of the respective service. CA: carbon storage; HQ: habitat quality; RC: outdoor recreation; PA: pasture production; TM: timber production3. 4. Validation of the models.

production, timber production and outdoor recreation identified priority areas for enhancing connectivity and mitigating biodiversity loss, providing a foundation for strategies that balance ecological conservation and human well-being.

4.2. Contribution of ESs synergies and trade-offs to inform targeted environmental interventions

This study identified synergies and trade-offs among ESs to explore their potential in guiding targeted environmental management strategies. By adopting an integrated approach, our research contributes to balancing environmental conservation with human wellbeing. This balance is crucial and can be achieved through management strategies that maximize ESs provision while mitigating trade-offs (Huang et al., 2023; X. Wang et al., 2022). While ESs synergies and trade-offs have been explored in several studies and geographical regions (Karimi et al., 2020; Huang et al., 2023), applying these concepts to analyse social-ecological connectivity and protected areas isolation in Aotearoa New Zealand, offers a novel contribution. Our study builds on these approaches to provide new insights specific to this region.

Our analysis revealed critical social-ecological conflicts contributing to Egmont National Park's isolation. Synergies were observed between habitat quality and carbon storage within the park, particularly in areas covered by indigenous forest, demonstrating the impact of biodiversity conservation policies on regulating services (Aryal et al., 2023; Locatelli et al., 2014). Conversely, the most common trade-offs were identified between provisioning services like pasture production and regulating services such as habitat quality and carbon storage. Intensive pasture production around the park led to a decline in regulating services, underscoring the importance of managing these trade-offs to support biodiversity conservation (Ministry for the Ministry for Environment, 2021). For example, Cimon-Morin et al. (2013) highlighted that targeted management practices can significantly reduce biodiversity losses, emphasizing the need for strategic interventions.

The study also identified synergies between outdoor recreation and regulating services within the park, supporting both ecological functions and recreational opportunities (Schirpke et al., 2018). However, trade-offs were evident in the park's northwestern surroundings, where low naturalness due to infrastructure and the absence of indigenous forest impacted the balance between these services. Similarly, the eastern part of the park, despite being rich in indigenous forest, exhibited trade-offs due to the lack of recreational facilities and accessibility, resulting in low outdoor recreation service values but high carbon storage and habitat quality (Lin et al., 2017).

Understanding these spatial variations in ESs relationships is vital for informing targeted management strategies that balance ecological conservation with social wellbeing, ultimately reducing park isolation and enhancing habitat connectivity (Maes et al., 2012). For example, integrating trees into pasturelands, or adopting agroforestry practices as seen in Quindío, Colombia, where silvopastoral systems significantly improved biodiversity, could provide substantial ecological benefits while supporting livelihoods (Chazdon et al., 2009; Murgueitio et al., 2011). Such practices not only maintain species diversity and protect soil but also enhance above-ground and soil carbon sequestration (Altieri and Nicholls, 2017).

Implementing these strategies alongside measures like riparian buffers and hedgerows can further enhance multiple ESs, including carbon storage and biodiversity conservation. In Northern Australia, for instance, planting leucaena in hedgerows has shown to enhance both livestock production and biodiversity (Murgueitio et al., 2011). These findings highlight the importance of integrating biodiversity conservation with agricultural practices that are conducive to improving habitat quality and connectivity (Sibelet et al., 2019).

Balancing trade-offs between regulating services and outdoor recreation involves strategies like planting native trees, developing low-impact infrastructure, and managing tourism (Deutscher and Smolíková, 2023). Incorporating cultural identity, particularly the Māori connection to Mount Taranaki, can reveal synergies and conflicts with recreation. Increased visitation has caused conflicts among users, conservationists, and local communities, disrupting both cultural identity and conservation efforts (Schirpke et al., 2018). Mapping culturally significant sites could help reshape recreation patterns and enhance regional development, environmental protection, and heritage regeneration (Li et al., 2022).

The analysis of synergies and trade-offs among ESs provides critical insights for reducing protected areas isolation. Identifying these interactions helps to balance competing demands and prioritize interventions that enhance connectivity while maintaining key ESs. These findings underline the importance of addressing trade-offs to support biodiversity conservation and guide effective environmental management strategies.

4.3. Application of a social-ecological approach in reducing Egmont National Park's isolation

A social-ecological approach was employed to investigate the isolation of Egmont National Park and explore strategies for enhancing habitat connectivity. By examining the park within its broader social-ecological context, the study aimed to understand the complex interactions between local communities, land use practices, and ecological processes contributing to the park's isolation. This integrated perspective is essential for developing effective management strategies to address the isolation of protected areas (Cumming and Allen, 2017).

While previous studies (Martín-López et al., 2011; Palomo et al., 2013) have incorporated a social-ecological approach into protected areas management, limited research has applied this perspective to Egmont National Park. Ewers and Rodrigues (2008) assessed the park's effectiveness and highlighted its isolation due to human activities. Our study builds on this by analysing the park's isolation through a social-ecological perspective, aligning with contemporary land use strategies such as land sparing and land sharing (Chen et al., 2024; Kremen, 2015). These strategies balance biodiversity and provisioning services while minimizing trade-offs, which is particularly important in agricultural settings where biodiversity conservation needs to be integrated with production activities (Grass et al., 2019).

The current management plan for Egmont National Park emphasizes the preservation of natural ecosystems while integrating cultural values and community involvement (Department of Conservation, 2002). Our analysis suggests that combining intensive protection with strategies in social-ecological units can enhance connectivity with other natural areas and reduce the park's isolation. For instance, establishing riparian buffers within agricultural landscapes can promote connectivity, support ESs such as water filtration and flood control, and foster community engagement (Fremier et al., 2015).

To implement these strategies effectively, we proposed a clustering approach that divides the study area into three distinct zones. Zone 1, encompassing Egmont National Park, serves as the core conservation unit, with a focus on biodiversity protection. Zone 2, which surrounds the national park, is primarily focused on pasture production but also offers opportunities for integrating biodiversity conservation through land-sharing practices to manage biodiversity within agroecosystems. This strategy is a shift from traditional land management that prioritizes either biodiversity conservation or pastoral farming in isolation to a spatially integrated approach where these two land uses could complement each other (Lusiana et al., 2012).

In recent decades, plantation forestry, particularly with *Pinus radiata*, has expanded in Aotearoa New Zealand's traditional farming areas (Kerr et al., 2012). Although planting *Pinus radiata* provides benefits like carbon sequestration and soil erosion control, it negatively impacts native vegetation as an invasive species (Hulme, 2020). Protecting and restoring small remnant native habitat patches within Zone 2, through natural regeneration on farms, is crucial for improving landscape connectivity and supporting native species such as the North Island brown kiwi, whose survival depends on habitat connectivity (Innes et al., 2022). Increasing incentives for planting native species in Zone 2 would reduce reliance on exotic trees and enhance both carbon storage and biodiversity (Suryaningrum et al., 2022).

Zone 3 acts as a transition area between the national park and the surrounding biodiverse peripheral regions, highlighting the need for integrated management strategies that balance trade-offs among regulating, provisioning, and cultural services. Key strategies include implementing land-sharing principles, protecting native habitats, and establishing corridors to enhance connectivity between the park and other protected areas. For example, in a Northland radio-tracking study, 83 percent of monitored North Island brown kiwis were observed within scattered forest remnants across farmland, highlighting the importance of both protecting and creating native habitats for ensuring species survival (Robertson and Radford, 2009).

The zone also features forestry areas dominated by *Pinus radiata*. Sustainable practices like using native species, long rotation periods, and low tree density can support biodiversity while providing economic and social benefits (Fonseca et al., 2009). Additionally, biological control of wilding pines using specific insects has shown potential in managing invasive populations (Williams and Wardle, 2007), although caution is needed when applying biological controls to avoid creating other ecological issues. These strategies must incorporate local indigenous knowledge to align conservation goals with social needs, fostering collaboration and shared responsibility, which can reduce social-ecological conflicts and enhance conservation effectiveness (Bodin, 2017).

This study demonstrates that ESs zoning through clustering analysis serves as a valuable strategic planning tool for managing protected areas. By delineating distinct social-ecological zones, this approach facilitates spatially targeted interventions to address social-ecological conflicts, ultimately contributing to the reduction of Egmont National Park's isolation.

Our findings have important implications for local communities and land use policies in the Egmont National Park region. Strategies such as integrating agroforestry practices, native planting in pasturelands, and riparian buffers align with land sparing and land sharing approaches, balancing agricultural productivity with biodiversity conservation and sustainable land use (Grass et al., 2019). For local Māori communities, these strategies may support cultural and spiritual values tied to the land, especially their role as guardians of the environment. They also emphasize the importance of biocultural approaches-conservation strategies that integrate the protection of natural ecosystems and cultural values-which enable more effective decision-making at the local level and strengthen the relationship between societies and their environments, reinforcing ancestral connections and responsibilities (Lyver et al., 2019). Enhanced ecosystem services, such as improved water quality, carbon sequestration, and soil health, contribute to sustainable livelihoods while reinforcing the cultural significance of land (Plieninger et al., 2014).

Additionally, these strategies complement the Taranaki Regional Council's riparian management program, which engages landowners in planting native vegetation to improve water quality and align with the Egmont National Park management plan's focus on habitat restoration and community-based conservation (Taranaki Regional Council, 2007). These strategies and initiatives provide a clear pathway to strengthen ecological resilience and promote community-centred conservation efforts.

4.4. Limitations and challenges

This study utilized ESs modelling to analyse the isolation of protected areas, aiming to inform targeted environmental interventions for improving protected areas management. However, there are still limitations to be addressed in further research. This study used InVEST model to estimate carbon storage and habitat quality within the study area which needs to be further advanced in future research. For carbon storage model, we used existing data on carbon stock estimates for the different land cover types. However, different forest types have different capacities for carbon storage (Rimal et al., 2019), and this was not addressed in this study. Additionally, the model does not consider significant sources of carbon release associated with farming in Aotearoa New Zealand, such as emissions from livestock (particularly cows) and the drainage of wetlands. Therefore, it is important to integrate different models for a more comprehensive approach to modelling carbon storage that can capture these complexities.

This study modelled habitat quality using anthropogenic threats. However, it is important to note that habitat quality and the impact of anthropogenic threats are species-specific, and the generalizations made in this study may not fully capture the nuances for individual species. Incorporating natural hazards, which are also major contributors to species extinction (Gonçalves et al., 2024), along with species-specific threat assessments, could provide a more comprehensive understanding of habitat vulnerability. Although this study mapped wilding pines as a threat, data on invasive fauna like possums, goats, and stoats were unavailable, limiting the scope of threat analysis. Future studies with spatial data on these species could provide a more holistic assessment. Low habitat quality at Taranaki Mountain's summit, attributed to rocky and snow-covered terrain, highlights the model's sensitivity to vegetation cover but may undervalue alpine regions' ecological significance. Integrating species distribution and richness could address this. Additionally, the model assumes threats are additive, despite evidence that their combined impacts often exceed individual effects (Wu et al., 2019).

For mapping pasture production services, we used NDVI data from four seasons within a single year. However, using long-term (i.e., time series) NDVI data would provide more reliable information, as it reflects the pasture yield patterns of a farm by capturing both seasonality and variations due to changes in grazing management (Tran et al., 2022).

Regarding recreation services, this study employed different biophysical indicators to map these. However, incorporating social media data to capture visitor's preferences could provide a more detailed spatial mapping of recreational opportunities.

This study uses an ESs framework to integrate a social-ecological approach for addressing protected area isolation. Incorporating social preferences and identifying trade-offs among stakeholders including locals, the agricultural sector, recreation businesses, conservationists, and indigenous peoples. The social-ecological units developed here highlight strategies to enhance connectivity. Future research could explore temporal trends, analysing historical and projected LULC changes to understand the evolution of isolation dynamics and inform future management strategies.

The present study focuses on Egmont National Park, a highly isolated protected area surrounded by modified landscapes. While the findings are tailored to this specific context, the methodological framework-combining ESs modelling with a social-ecological approach-provides a flexible tool that can be adapted to other protected areas facing similar challenges, such as habitat fragmentation and land-use conflicts. However, applying these results to different protected areas requires thoughtful adaptation to account for distinct ecological, social, and management contexts, ensuring the framework's relevance to regional condition.

5. Conclusion

This study employed ESs modelling to analyse the isolation of protected areas within Aotearoa New Zealand, using Egmont National Park as a case study. By mapping and analysing multiple ESs, the study underscores the significance of integrating ESs into protected areas management to mitigate isolation issues and enhance habitat connectivity. The modelling approach provides a broader perspective on protected areas isolation, incorporating social-ecological interactions beyond administrative boundaries and offering insights into spatial patterns of ESs distribution. These findings emphasize the need to balance synergies and trade-offs among ESs to inform targeted environmental management strategies.

The development of social-ecological units in this study offers a practical framework for targeted environmental interventions. This approach demonstrates the potential to balance biodiversity conservation with human well-being by addressing trade-offs and fostering synergies among multiple ESs. These insights provide a foundation for prioritizing management strategies that enhance connectivity, mitigate biodiversity loss, and support sustainable land use practices. The findings contribute to advancing the application of social-ecological approaches for managing isolated protected areas in complex and highly altered landscapes.

CRediT authorship contribution statement

Mitra Ghasemi: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Alberto González-García:** Writing – review & editing, Validation, Supervision, Conceptualization. **Silvia Serrao-Neumann:** Writing – review & editing, Validation, Supervision, Conceptualization.

Declaration of competing interest

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

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2025.125459.

Data availability

Data will be made available on request.

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