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Using ecological infrastructure to comprehensively map ecosystem service demand, flow and capacity for spatial assessment and planning

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ABSTRACT

Ecosystem services provide substantial benefits to people, but the underlying ecosystems are under unprecedented pressure, compromising service delivery. Therefore, ecosystem services need to be integrated into conservation and management processes to secure their benefits for current and future generations. A key first step is a robust method to map ecosystem services for spatial planning. We aimed to develop and apply a broadly applicable, flexible and spatially accurate method for comprehensive ecosystem services mapping using Ecological Infrastructure, abbreviated to PROPSER. We evaluated the demand, flow, and capacity of three ecosystem services (sports events, recreation, and coastal protection) along the South African coast using causal relationships, including ecological condition of the EI, and approximated EI performance as a measure of its importance to society. This resulted in a high-resolution map of EI performance per service and a cumulative map of multiple-service performance created by integrating the three single-service maps. Altogether, there were 5127 EI sites, with EI close to urban nodes being most important. Post-hoc tests confirmed the spatial accuracy of the output maps, and the sensitivity of PROPSER to the variables and components of the indicator models. PROSPER is a comprehensive and innovative method for mapping ecosystem services that is flexible and can be widely applied. The outputs from this study have been taken up in a national spatial planning process, with several other applications discussed. We identify seven ways in which PROSPER can be advanced, and encourage further testing and application of our approach.

1. Introduction

People depend on intact nature to supply fundamental needs like food, water and raw materials, to provide disaster-risk reduction, and to enhance mental and physical health and well-being (Costanza et al., 1997). Yet, global declines in biodiversity and accelerating ecosystem degradation compromise ecosystem functions and, concomitantly, the delivery of these valuable ecosystem services, most felt by developing countries and the rural poor (Cardinale et al., 2012; Harris and Defeo, 2022). To halt and reverse this trend, ecosystem services need to be identified and integrated into spatial assessment and planning processes to secure them for the long term as part of fulfilling international commitments, e.g., targets in the Kunming-Montreal Global Biodiversity Framework (CBD, 2022), and the Sustainable Development Goals (Wood et al., 2018). Although several methods and tools exist to spatially represent ecosystem services in landscapes and seascapes (Burkhard and Maes, 2017), a new approach to mapping ecosystem services for spatial assessment and planning is needed that considers all aspects of ecosystem services, and is specifically suited to place-based conservation and management actions.

Ecosystem services are part of a complex social-ecological system (Potschin and Haines-Young, 2011) that can be understood and defined differently. In this paper, we adopt the cascade model as the conceptualisation of the pathway of ecosystem service creation in the environment through to transfer of benefits and values in the social and economic system (Haines-Young and Potschin, 2010). The demand for an ecosystem service originates in the social system as "the need for specific ecosystem service by society, stakeholder groups or individuals" (Syrbe et al., 2017). Ecosystem service flow connects the environment and the social and economic system through "the amount of ecosystem service that is actually mobilised in a specific area and time" (Syrbe et al., 2017). The capacity for service delivery is the "ability of an ecosystem to generate a service under current ecosystem condition and uses, at the highest yield or use level that does not negatively affect the

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future supply of the same or other ecosystem services from that ecosystem" (Hein et al., 2016). Because each of these three aspects (demand, flow, and capacity) provide insights into different dimensions of a particular service in a specific context, mapping ecosystem services comprehensively requires the inclusion of all aspects (Villamagna et al., 2013; Burkhard et al., 2014). Further, the ecological condition of the ecosystem directly influences ecosystem service capacity (Villamagna et al., 2013; Maes et al., 2018), with higher levels of physical and biological diversity, presence of specific species or functional group characteristics, or habitat presence and extent in many cases being associated with higher levels of ecosystem service capacity (Smith et al., 2017). Therefore, particularly in a systematic conservation planning context, the ecological condition of the underlying ecosystems should also be accounted for (Braat and De Groot, 2012; Villamagna et al., 2013) and can provide complementary information for identifying areas where ecosystem restoration should be targeted to enhance capacity and flow. Overall, a comprehensive method for mapping ecosystem services should integrate the ecosystem service aspects of demand, flow and capacity, and also account for the ecological condition of the underlying ecosystem.

In the cascade model, ecosystem services arise in the environment from the underlying biophysical structures or processes (Haines-Young and Potschin, 2010). In agreement with Harris and Defeo (2022), we conceptualise these biophysical structures or processes as Ecological Infrastructure (EI). In most cases, EI establishes that ecosystems (e.g., dunes) enable the flow of valuable ecosystem services (e.g., coastal protection), similar to built infrastructure (e.g., roads) providing services (transport). Various definitions of EI exist, but specifically for integration in spatial planning, it is: 'Natural and naturally functioning ecological systems or networks of ecological systems that deliver multiple services to humans and enable biodiversity persistence' (Perschke et al., 2023). Framing ecosystem services through EI shifts the focus from the sometimes intangible ecosystem service to manageable sites in the landscape (Harris and Defeo, 2022). This shift in perspective emphasises that ecosystem service provision depends on healthy ecosystems, promoting conservation measures and fostering investment-based thinking, which aligns neatly with place-based conservation and management (Perschke et al., 2023). Therefore, EI could prove to be a very useful framework for mapping ecosystem services for assessment and planning purposes, particularly if combined with the three service aspects (i.e., capacity, flow, and demand) and ecological condition, which could collectively provide a measure of EI performance (i.e., the importance of the ecological system for society) as suggested in Perschke et al. (2023). Knowing where EI is located across the landscape or seascape, the level of its performance, and which metrics need to increase to enhance performance could provide very powerful tools for securing and maintaining ecosystem services by guiding strategic conservation and management actions.

Our aim was to develop a broadly applicable method to map ecosystem services using EI as the framework, with the specific purpose of spatial assessment (e.g., spatially explicit EI performance evaluation) and planning (e.g., spatial prioritisation for place-based conservation, management and restoration) that is flexible and spatially accurate. We call this method PROSPER: comPRehensive ecOsystem Services maPping using Ecological infRastructure. We used three ecosystem services: nature-based recreational outdoor activities (hereafter recreation), nature-based sports events (hereafter sports), and coastal protection from flooding and erosion (hereafter protection) to develop and test PROSPER at a national scale along the South African coast, which is the interface between the terrestrial, estuarine and marine realms. Specifically, we: identify EI that delivers each of these three services; comprehensively evaluate the demand, flow and capacity of the ecosystem services at each EI site based on causal relationships; determine the relative performance of the EI sites; and perform a sensitivity test and validate the models using a theoretical, qualitative approach to assess the accuracy of PROSPER.

2. Methods

2.1. Study area

The study area was the South African seashore, which extends from the outer bound of the surf zone to the scrub/thicket break of the dune system, including estuarine ecosystem types (Harris et al., 2019a) along the 3113-km coastline (Harris et al., 2011) (Fig. 1). This area had to be expanded in a few places to accommodate services that extended slightly beyond the seashore (see Section 2.2). The seashore comprises 90 different ecosystem types, including various types of rocky shores, boulder shores, sandy shores, mixed shores, seashore vegetation, and estuaries (Harris et al., 2019a). Kelp forests, coral reefs, mangroves, salt marshes, reeds and sedges, and seagrass beds are also present (Harris et al., 2019a). This diverse ecological setting supports rich biodiversity with a high degree of endemism (Griffiths and Robinson, 2016). It also forms EI that provides a plethora of ecosystem services. These services provide many benefits to South Africans (Harris et al., 2019b) and make substantial contributions to the economy, e.g., through tourism (Lewis et al., 2012; Rogerson and Rogerson, 2020) and fishing (Blamey and Bolton, 2018).

2.2. Mapping ecological Infrastructure for spatial assessment and planning

Our aim included developing a method that could be broadly applied, both geographically and in terms of the ecosystem services included. Therefore, we used a cross-realm environment (i.e., the seashore zone (Fig. 1) that includes land, estuaries and the sea, and chose three different ecosystem services from two different ecosystem service categories: "cultural" and "regulating and maintenance" (Haines-Young and Potschin, 2018) to develop and test PROSPER. The cultural services were recreation and sports, and the regulating and maintenance service was protection. PROSPER comprises two main steps (Fig. 2): first, identify the specific EI sites for each service (i.e., where does the service take place; see the remainder of Section 2.2); and second, quantify EI performance using models based on causal relationships (i.e., how much flow, capacity and demand is there per service per site; Section 2.3). If needed, the performance of multiple ecosystem services can be evaluated as well (Section 2.4). An overview of the methods is presented below, and the technical details are available in Sections 1 and 2 of the Supplementary Material.

To identify specific sites of EI, in ArcGIS® 10.4 (ESRI), we extracted all polygons from the national Coastal Ecosystem Map (Harris et al., 2019a) where the respective services were present. The presence of recreation was identified when there was at least one geotagged photograph uploaded to Flickr (SmugMug Inc and Flickr Inc, 2020) between 2009 and 2018. Flickr was chosen over other social-media platforms like Instagram or Twitter because, in the South African context, it provides the highest correlation with official statistics regarding national park popularity (Tenkanen et al., 2017). In addition, Flickr photographs showed better matches for tourist preferences for less-charismatic biodiversity (e.g., small-bodied mammals and reptiles, in contrast to large-bodied, iconic species like rhinos and lions) (Hausmann et al., 2018), which was considered valuable for identifying places of more general nature-based recreational use rather than places that are popular because of their outstanding biodiversity. In addition, Flickr data are often used to estimate recreational activity and are relatively easy to access (Toivonen et al., 2019). Geolocations of the photographs were extracted following Keeler et al. (2015) in Python 3.4 (Van Rossum and Drake, 2009) using the package "flickrapi" (Stuvel, 2018). The presence of sports was identified based on the race courses from events (swimming, surfing, canoeing and triathlon) in 2018, compiled from a systematic web search. In some cases, the race courses extended beyond the seashore, necessitating a slight expansion of the study area to accommodate these events. The presence of protection was considered

Fig. 1. (a) The South African seashore zone (in red), which comprises the 90 seashore ecosystem types (dunes, shores, estuaries) as identified and mapped by Harris et al. (2019a). (b) A magnified section of the South African coast, which shows the seashore ecosystem types in Fish Hoek, Western Cape, in different colours. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

to be ecosystem polygons within 1 km of vulnerable coastal communities, where vulnerability is in terms of sea-level rise and impacts from large waves. Vulnerable coastal communities were identified as those positioned within 1 km of the shore, and less than 40 m above mean seal level (based on suggestions for coastal set-back lines in South Africa (Theron, 2016), and using spatial information on coastal development from Harris (2010).

Following the definition of EI that we adopted for this study (Perschke et al., 2023), all selected sites had to be naturally functioning. This approach helped to make PROSPER directly applicable to spatial assessment and planning because it is explicitly linked to the naturally functioning ecosystems in which the services are being delivered (i.e., it deliberately excludes artificial systems, like crop monocultures). Consequently, place-based conservation and management, including restoration, of EI sites can help to secure and maintain the benefits from ecosystem services. Therefore, all areas identified as “not natural” in the 2014 national land cover, e.g., buildings, mined areas (Skowno et al., 2019; Harris, 2010), were removed. Further, areas considered to be permanently modified (i.e., no natural habitat remaining) in the maps of ecological condition from the National Biodiversity Assessment 2018 (Skowno et al., 2019a) were also removed. These areas were: land – not natural (Skowno et al., 2019); estuaries – critically modified (Van Niekerk et al., 2019b); and marine – collapsed (Sink et al., 2019). Second, percolation theory states that at least 60% of the area needs to be intact to avoid interrupting essential ecological processes (Svancara et al., 2009). Therefore, applying a conservative approach, sites were removed where >50% of the original extent of the underlying ecosystem type was permanently modified. Specifically, sites were removed in the following cases: terrestrial – where > 50% of the landcover was classified as “not natural” (Skowno et al., 2019); marine – where > 50% of a 50-m buffer seaward of the dune base contained development (Harris, 2010); estuaries – where habitat loss was classified as ’Very High’ (Van Niekerk et al., 2019a). This initial filter for ecological condition resulted in a map of naturally functioning EI for each ecosystem service that could be used to quantify ecosystem service flow, capacity and demand.

2.3. *Measuring ecological Infrastructure performance*

Part of our aim was to develop a flexible method. Flexibility is important because modelling ecosystem services is highly context and scale-dependent (Crossman et al., 2013), making an adaptable method very useful. It was addressed in PROSPER by using simple, additive indicator models of demand, flow, and capacity for each service based on causal relationships (Fig. 2). These models are flexible because they can comprise different variables (and components) depending on different contexts, data availability, and service complexity and can be easily adjusted and adapted as needed (Lavorel et al., 2017). This modelling approach is used in other tools for mapping ecosystem services, e.g., the “Integrated Valuation of Ecosystem Services and Tradeoffs” tool (InVEST) (Sharp et al., 2018), and is useful at a national scale where data are often limited (Lavorel et al., 2017). Each indicator model consisted of several variables and, if needed, components of a variable (Fig. 2). Model building was informed by similar approaches in the scientific literature, expert knowledge, and data availability. Most of the variables and components were aggregated in an additive way to derive the indicator, assuming linear causal relationships. Owing to limited data, these causal relationships were deduced from a compiled understanding of ecosystem service dependencies and are not the result of statistical inference. Consequently, the formulated mathematical relationships were kept as simple as possible, and the resulting indicators need to be understood more as relative, comparative measures of the three service aspects rather than precise, quantitative measures. Note that sports

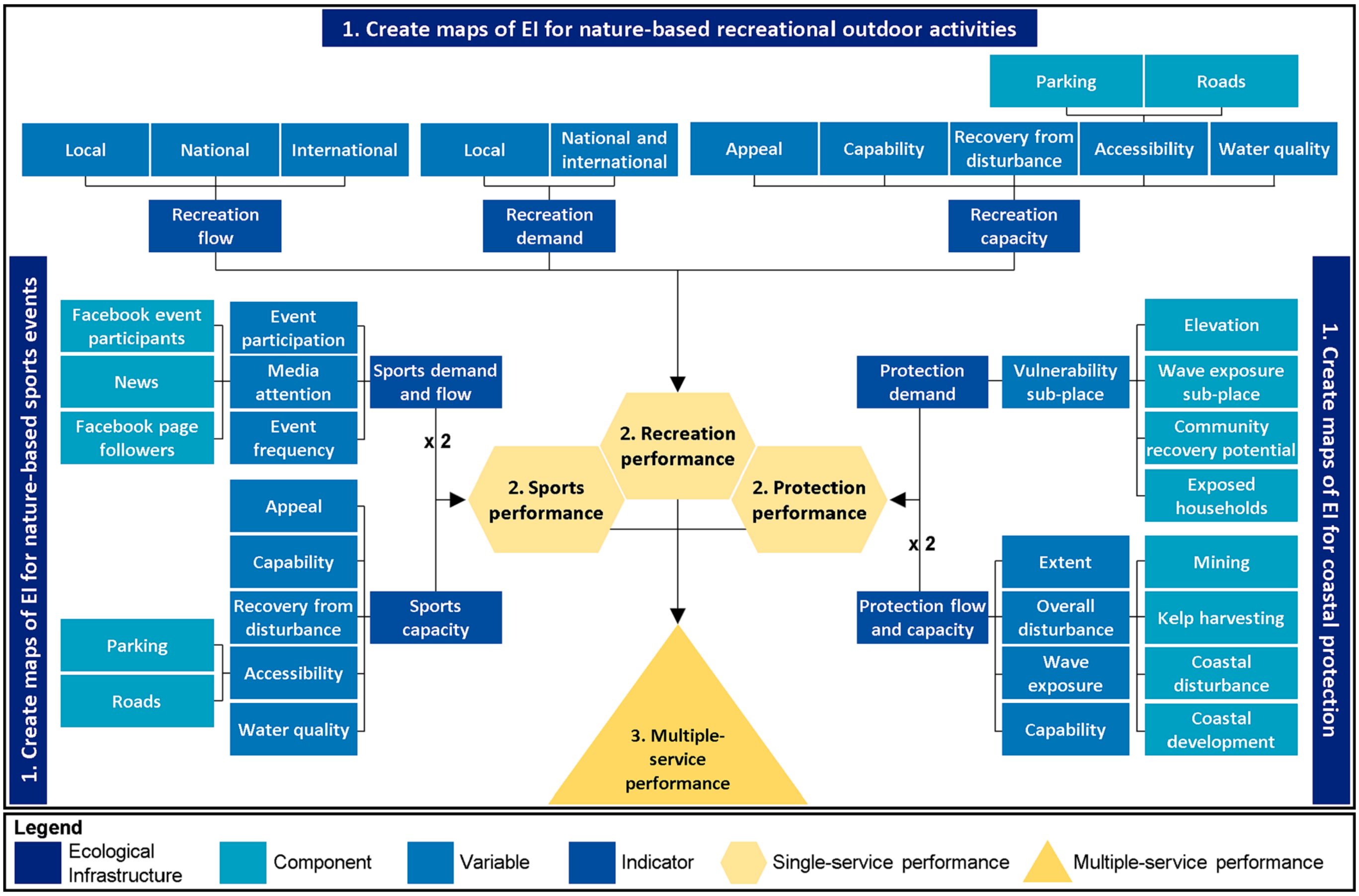

Fig. 2. Overview of PROSPER. In step 1, maps of Ecological Infrastructure (EI) are created for each ecosystem service, e.g., nature-based recreational outdoor activities (recreation); nature-based sports events (sports); and coastal protection from flooding and erosion (protection). In step 2, models based on causal relationships are built from components, variables and indicators to evaluate the performance of the mapped EI per service. In an optional step 3, single-performance values are combined to measure multiple-service performance per EI site. Note that the 'x2' indicates that the indicator is doubled when calculating EI performance because it represents two of the three possible aspects (demand, flow, and capacity; see Supplementary Material for details).

demand and flow were measured by one indicator, likewise for protection flow and capacity, because it is assumed that for both services the flow is equal to the demand and capacity, respectively (Fig. 2). For the technical details behind the capacity, flow and demand models, see Section 1 and 3 in the Supplementary Material.

The ecological condition of an ecosystem affects its capacity for service delivery, and thus should be considered in an ecosystem service assessment (Villamagna et al., 2013; Hein et al., 2016). In PROSPER, in addition to the initial condition filter, we included a pressure variable consisting of one or more pressures to the indicator models for EI capacity, weighted by pressure intensity. To be more specific, the indicator for capacity integrated ecosystem type and service-specific pressures based on the assumption that only specific functions of the underlying ecological system need to be in place for service flow (Singh et al., 2017; Singh et al., 2020). The pressures with the highest impact on service-specific EI functioning were selected based on national reviews of their impacts on seashore ecosystems (Harris et al., 2015; Harris et al., 2022b; van Niekerk et al., 2013). In the case of the protection service, several pressures were identified, and a cumulative impact score was calculated, similar to Singh et al. (2017). The relevant pressures were included in the capacity model as a factor because it was assumed that, in the case of the three selected services, the EI capacity could not be high if the pressure is high and important ecological functions are consequently compromised. For example, if water quality is poor, a sports event will be cancelled (Singh, 2019) or a beach closed (SABC News, 2022), leading to the immediate collapse of the capacity for service delivery by the EI site.

EI performance is an integrated measure of demand, flow and capacity, making it a useful tool for conservation practitioners as a measure in ecosystem service assessments and as a guideline in conservation prioritisation processes (Perschke et al., 2023). The normalised demand, flow and capacity indicator values per EI site were multiplied to determine the performance per service of each EI site x (Equation (1)). This was done to ensure that only EI sites with high demand, flow and capacity could reach high single-service performance. The premise of the approach is that EI with high flow and demand delivers the most benefits to society and is, therefore, most important. Where these EI sites also have a high capacity, they can be assumed to be naturally functioning, and service use can consequently be considered sustainable (Villamagna et al., 2013). The single-service performance was normalised to a 0–1 range by dividing by the maximum value per ecosystem service type. Jenks (natural breaks) in the distribution of the data were used to classify the single-service performance quantities into five classes. Jenks (natural breaks) were used because the distribution of the data of all indicators was skewed with a long upper tail.

$$Single\ Service\ Performance\ (SP)_{EI_x} = Flow_{EI_x} \times Demand_{EI_x} \times Capacity_{EI_x} \quad (1)$$

Where EI_x = Ecological Infrastructure at site x.

2.4. Measuring multiple service performance

EI sites that performed well for multiple services were also identified (Fig. 2). First, the single-service performance values of the three ecosystem services per EI site *x* were summed (Equation (2)). Thereby, a cumulative map of multiple-service performance was created (Schröter and Remme, 2016; similarly done by Willaarts et al., 2012). Furthermore, the sum was multiplied by the number of services (Equation (2)). This was done to give a higher weight to EI sites providing multiple services with low to moderate single-service performance than EI sites with only a single albeit high-performing service. Again, Jenks (Natural Breaks) in the data distribution was used to classify the multiple-service performance quantities in five classes.

$$Multiple\ Service\ Performance_{EIs} = \frac{\left(SP_{Sport\ EI_x} + SP_{Recreation\ EI_x} + SP_{Protection\ EI_x}\right)}{3} \times Services_{EI_x} \tag{2}$$

Where EI_x = Ecological Infrastructure at site *x*, *SP* = service performance, and $Services_{EIx}$ = the number of services at EI site *x*.

2.5. Sensitivity testing and validation of spatial accuracy

Part of our aim was to develop a spatially accurate method to ensure correct spatial representation of EI for assessment and planning. Therefore, a one-at-a-time sensitivity analysis (Hamby, 1994) of the models was conducted to test model sensitivity in R 3.6.1 (R Core Team, 2020). Ideally, model results should be validated by using a quantitative statistical approach and/or groundtruthing. However, this was not possible in our case because the models are not statistical models but determine only one score per EI site, and ground truthing was also not possible given that we were working at a national scale (with limited resources). Therefore, we performed a qualitative validation of satial accuracy of the results by identifying spatial patterns and checking whether there were plausible explanations for these patterns in the available scientific and grey literature and from expert information. Where there was a mismatch, explanations were sought as to why the models were not accurately capturing the spatial patterns that would be expected so that this could be improved in the future.

3. Results

3.1. Mapped ecological Infrastructure and its performance for single ecosystem services

3.1.1. Recreation

There were 1086 EI sites that provided recreation services. Many of these sites had very low service flow (55.8%) and generally medium, low, and very low demand (84.07%) (Fig. 3a). The demand for recreation ranged mainly from very low to medium because population densities close to the recreation EI sites were generally low (mean: 0.10; SD: 0.13) and the trips to the associated coastal districts medium (mean: 0.39; SD: 0.37). Very low flow resulted from very low counts of Flickr photo-user days across all EI sites (*local* mean: 0.35 days; SD: 2.14 days; *national* mean: 1.64 days; SD: 3.96 days; *international* mean: 5.08 days; SD: 18.04 days) except in popular cities like Durban and Cape Town and coastal National Parks where the flow indicator was high. Capacity varied widely among EI sites, with few very low (16.67%) and very high values (14.09%) (Fig. 3a,b). This indicator generally comprised medium values of *appeal* (mean: 0.33; SD: 0.40) and *capability* (mean: 0.46; SD: 0.35), and high values of *recovery from disturbance* (mean: 0.81; SD: 0.13), *accessibility* (mean: 0.72; SD: 0.28), and *water quality* (mean: 0.78; SD: 0.29). Given the very low flow, very low to medium demand, and variable capacity, most of the EI sites (95.9%) had very low or low performance for recreation (Fig. 3b). The few EI sites providing recreation with medium, high or very high performance were mainly in Cape Town, Durban, Sedgefield, and Wilderness East (Fig. 3b).

3.1.2. Sports

There were 198 EI sites that provided the sports service for 155 sports events. Demand and flow were generally low to very low (81.31%; Fig. 3c,d) because sports events tended to occur on only a few days a year (mean: 3.40 days; SD: 4.32 days) at the EI sites, with relatively few participants (mean: 517.46 participants; SD: 1034.14 participants) and limited media attention (mean: 0.08; SD: 0.17) except for EI sites near Durban or Gqeberha. In contrast, the capacity of the EI sites to deliver the sports service varied widely, with a similar distribution among all five classes: very low (19.19%); low (16.16%); medium (15.66%); high (26.77%); very high (21.71%) (Fig. 3c). This was based on generally medium values of *appeal* (mean: 0.43; SD: 0.41) and *capability* (mean: 0.46; SD: 0.34) and high values of *recovery from disturbance* (mean: 0.81; SD: 0.13), *accessibility* (mean: 0.72; SD: 0.28), and *water quality* (mean: 0.78; SD: 0.29) per EI site. Overall, EI sites providing sports seldom had high demand and flow in combination with high capacity indicators (Fig. 3c). Consequently, the values of the sports performance of the EI sites were mainly low or very low (92.42%) (Fig. 3c,d). Almost all (14 of 15) EI sites providing sports with medium, high, and very high values of sports performance were in the urban centres of Gqeberha and Durban (Fig. 3d).

3.1.3. Protection

Of the three services, protection was most widely distributed around the South African coast, with 4973 EI sites providing protection to 588 coastal communities. Demand for coastal protection was mainly low or very low (74.84%) (Fig. 3e). In contrast, flow and capacity were generally medium, high or very high (63.93%) with typically little *overall disturbance* (mean: 0.79; SD: 0.25; note that the higher the value the less the disturbance). Where *overall disturbance* was higher (in or close to urban centres), the flow and capacity indicator was lower. The combination of demand, flow and capacity led to mostly low or very low values of protection performance (83.55%; mean: 0.01; SD: 0.01) (Fig. 3e,f). Exceptions were EI sites in or near cities like Cape Town, East London and Durban, small coastal towns like Port Nolloth, Paternoster and Jeffreys Bay, and rural communities like Mbotyi (Fig. 3f). All those places had very high demand for coastal protection because they are either densely populated and low-lying (urban centres) or would suffer a high degree of financial distress after flooding or erosion events (rural areas). The EI sites protecting them had medium, high, or very high performance, depending on the capacity of the EI site (Fig. 3f). EI sites with very high protection performance were mainly high capacity EI sites (e.g., EI sites with underlying ecosystem types that are less sensitive to human pressures like rocky shores) in or close to coastal towns or urban centres that had medium to very high demand for coastal protection (Fig. 3f).

3.2. Ecological Infrastructure performance for multiple ecosystem services

The general spatial distribution of the 5127 EI sites showed that the presence of the three services was coupled with human presence in the coastal zone because the overall number of EI sites rose in more densely populated areas (Fig. 4). Many coastal EI sites delivered only one ecosystem service (78.31%) (mainly protection) and thus most EI sites had a very low value of multiple-service performance (89.78%) (Fig. 4).

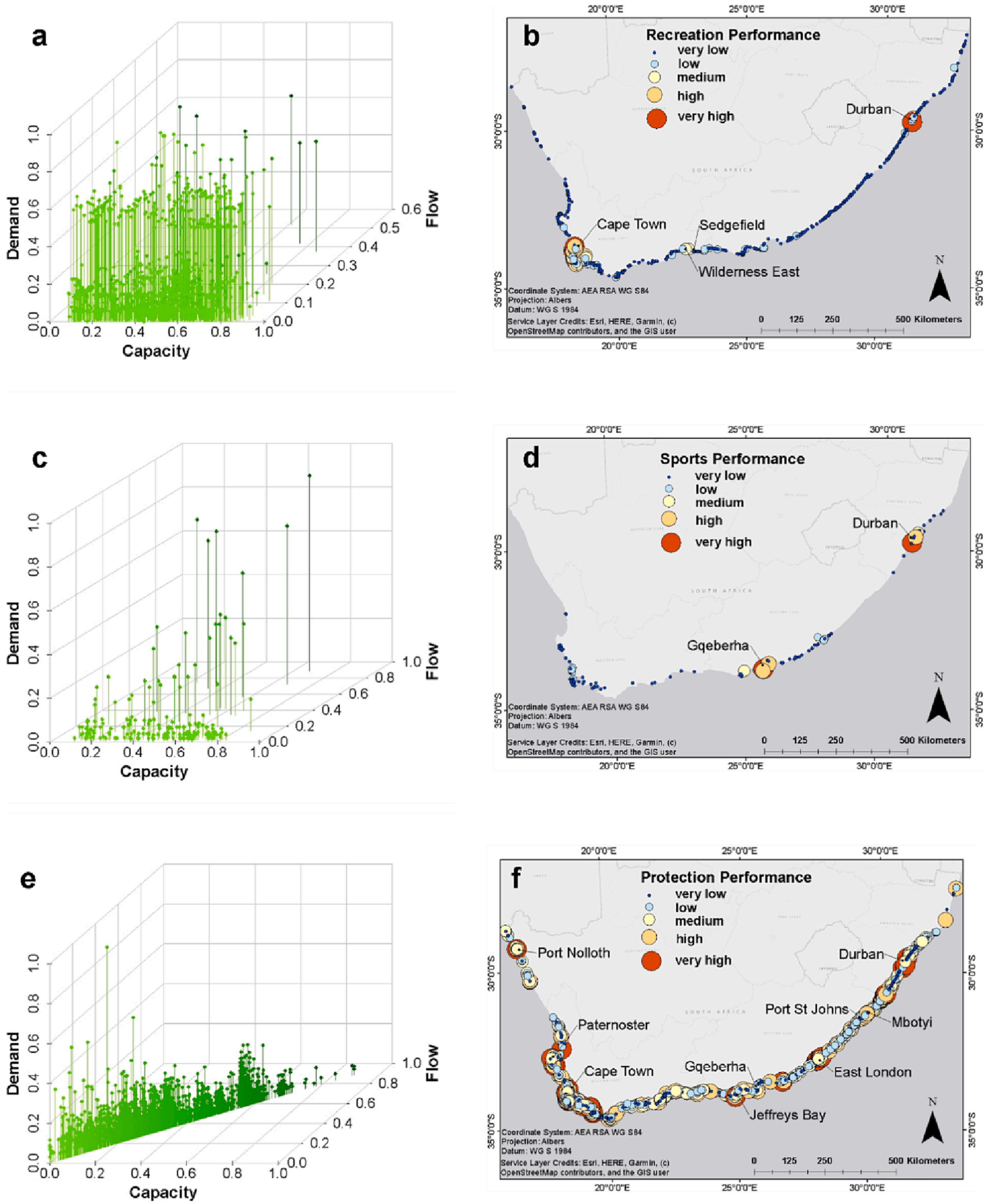

Fig. 3. The distribution of Ecological Infrastructure (EI) sites for (a,b) nature-based recreational outdoor activities (recreation; n = 1086); (c,d) nature-based sports events (sports; n = 198); and (e,f) coastal protection from flooding and erosion (protection; n = 4973) along the South African coast. (a,c,e) Three-dimensional visualisation of the relationship among the demand, flow, and capacity indicators per EI site. The colour gradient from light green to dark green visualises the flow indicator values per EI site from low to high. (b,d,f) EI sites along the South African coast that provided each service, scaled in dot size and colour by their relative performance. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

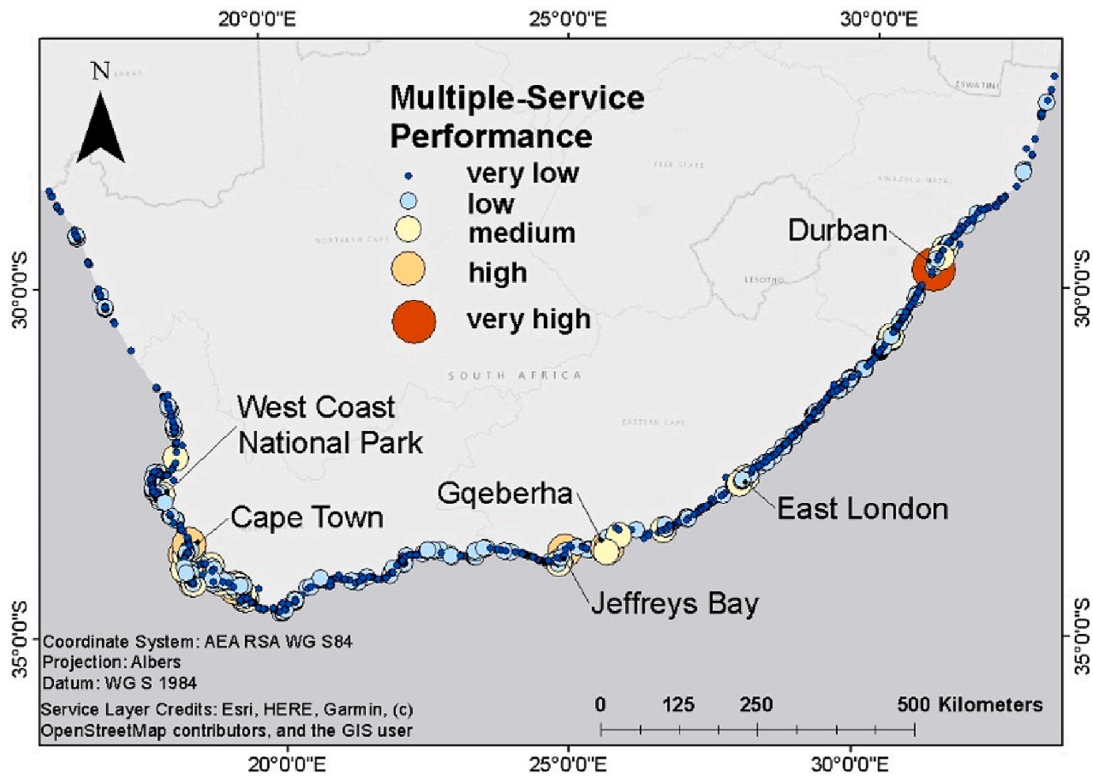

Fig. 4. The spatial distribution of the multiple-service performance of the single Ecological Infrastructure (EI) sites (n = 5127), scaled in dot size and colour by their relative performance. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

EI that was positioned nearby or within the urban centres of Cape Town, Gqeberha, East London, and Durban often had a medium, high and very-high value of multiple-service performance (Fig. 4). In addition, there were some EI sites that had a medium or high value of multiple-service performance in small coastal towns like Jeffreys Bay, or conservation areas like the West Coast National Park (Fig. 4). A very high value of multiple-service performance was reached only by the stretch of sandy shore at Durban beachfront (Fig. 4).

3.3. *Sensitivity testing and validation of spatial accuracy*

None of the variables or components were redundant in PROSPER because the data points were never positioned directly on the diagonal when a component was left out of the calculations (see Supplementary Fig. A3 in Section 6). In addition, none of the variables seemed to dominate the models: if this were the case, there would have been patterns in the data that did not follow the monotonic trends observed. Interestingly, the three variables: *participation*, *frequency* and *attention* and the components of *attention,* i.e., *news articles, Facebook page followers* and *Facebook event participants*, of the sports demand and flow model seem to have a similar effect on the indicator value (Fig. A3 b1-b6). Therefore, the indicator value could also be approximated by each of the variables alone, and each of the components could also be replaced by the other. However, this may not always be the case, and thus, to keep the model broadly applicable across many different contexts, the models were not simplified further. In addition, it comes with the benefit that fluctuations and uncertainties are averaged. The theoretical validation of the spatial accuracy of the results showed that the maps of EI broadly matched what is known or expected on the ground (see Supplementary Table A 17 in Section 6). The only outstanding discrepancy was that some popular sites for recreation by local users along the coast (e.g., Monwabisi beach and Boulders Beach in Cape Town, and Langebaan Lagoon in the West Coast National Park) had no local photo-user days. An explanation could be that, despite a good correlation between visitation rates and Flickr photograph counts, the actual use of Flickr in South Africa is generally low (Tenkanen et al., 2017). This means Flickr is much more useful in areas with high visitor numbers, but less useful in less visited areas. Another explanation that could amplify the effect of low photograph numbers at popular beaches could be that South African users do not share photographs of places on Flickr that are well-known to them (an explanation also used by Wood et al. (2013)). This results in less accurate maps of the recreation service, especially at least visited EI sites. Apart from this, the EI maps represented ecosystem services with sufficient accuracy to be useful inputs to spatial assessment and planning processes.

4. Discussion

4.1. *PROSPER: A new method for mapping ecosystem services*

In this paper, we demonstrated proof of concept of PROSPER; a method for mapping ecosystem services comprehensively by integrating information on demand, flow, capacity and ecological condition, and using EI as the framework. There were four attributes that we sought to achieve in PROSPER: broad applicability; suitability for spatial assessment and planning; flexibility; and spatial accuracy. PROSPER was developed and applied in a cross-realm environment using different types of ecosystem services, and so it should be relevant in multiple realms and transferrable to other services. Using EI as the framework for mapping ecosystem services helped to make PROSPER directly applicable to spatial assessment and planning by linking it directly with naturally functioning ecosystems that need to be maintained or restored, which speaks to spatial conservation and management. In addition, the EI performance measure is a simple, integrated measure drawing from different aspects of an ecosystem service that can guide conservation prioritisation processes towards areas of high importance for society in a comprehensive way. The use of simple additive indicator models based on causal relationships allow for the necessary flexibility of measuring

EI demand, flow and capacity in different contexts and for different ecosystem services. The flexibility in model development also means that the indicators can be built using locally relevant and available data, which further contributes to the broad applicability of the method. Finally, the model validation demonstrated that the models resulted in a spatially accurate representation of ecosystem services, except for flow of local recreation for which Flickr photograph counts do not seem to be the best measure (at least in South Africa). This could be addressed by integrating information from various photograph-sharing platforms into one overall and more comprehensive measure (Tenkanen et al., 2017; Hausmann et al., 2018), in case further resources for obtaining data are available (Toivonen et al., 2019). In short, all four attributes were addressed in PROSPER, thus contributing a method that has great potential in a number of applications (see Section 4.2).

Similar tools to PROSPER exist that also use composite and deterministic modelling approaches. For example: 1) InVEST, which was designed to inform natural resource management at multiple scales (Sharp et al., 2018); 2) the "Artificial Intelligence for Ecosystem Services" (ARIES) tool, which aims to create dynamic models of ecosystem service sources, sinks and uses using artificial intelligence to inform management (Bagstad et al., 2011); and 3) the "Ecosystem Service Mapping Tool", mainly applied for European ecosystem service mapping and decision making (Zulian et al., 2013). The availability of data, study context and aim, and modeller's assumptions and understanding of the modelled concepts (for example, the supply used in ESTIMAP and capacity used in this paper are based on different definitions) lead to differences among the mentioned tools (Seppelt et al., 2011; Schulp et al., 2014; Boerema et al., 2017).

Four attributes set PROSPER apart based primarily on its aim to be comprehensive and to serve place-based conservation and management. The first attribute is the use of EI as the framework for mapping, which deliberately excludes "not natural" systems. Second, PROSPER includes ecological condition by including service-specific pressures in the capacity model, thus accounting for the established understanding that the ecological condition directly influences the capacity for service delivery (Hein et al., 2016; Erhard et al., 2017; Maes et al., 2018). Third, the inclusion of pressures into the capacity model holds the potential of accounting for antagonistic effects of service use, which to some degree indirectly integrates trade-offs among services (i.e., securing one does decrease the benefit of the other ecosystem service; Turkelboom et al., 2016), which is an important aspect when mapping multiple services (Boulton et al., 2016). For example, "trampling" is a side-effect of many recreational activities. At the same time, "trampling" was considered a pressure to the capacity of sandy or mixed shores to deliver coastal protection, as it destabilises dunes leading to erosion. Thus, where both services (recreation and protection) flow, protection capacity and, therefore, performance should be reduced. Nevertheless, this assumption was not tested in this study and needs further investigation. Fourth, PROSPER included a performance evaluation - the first of its kind - that integrated all ecosystem service aspects: demand, flow, and capacity. This single measure of relative importance of the EI site can easily be integrated into planning processes (Perschke et al., 2023). PROSPER was developed primarily to support spatial assessment and planning for place-based conservation and management and thus may be most useful in this context. It may have application in other contexts, and potential users will need to choose an approach that best suits their objectives. Like all models, users should acknowledge the limitations of PROSPER when interpreting their results. As noted above, the outputs should be considered as relative comparisons rather than precise measures, given the simplicity of the models and inherent uncertainties in the model parameterisation and input data.

4.2. Applications of PROSPER

The outputs from this study are South Africa's first national maps of EI for the coastal zone. These maps have already been incorporated into a recently published systematic conservation plan for coastal and marine biodiversity in South Africa (Harris et al., 2022a) that is being used for national marine spatial planning and other related processes. The plan identifies sites for enhanced management and restoration (Harris et al., 2022a). This kind of application is the primary purpose of PROSPER. Ecosystem restoration is a global and national prioritiy, as reflected in the Kunming-Montreal Global Biodiversity Framework (CBD, 2022), and among the top ten priority actions for the South African coast (Harris et al., 2022b). More than half of the 4973 EI sites for coastal protection in this study have a medium to very high capacity for coastal protection. This emphasises the notable potential of investing in those coastal EI features, e.g. coastal dunes, through restoration activities as a cost-effective option for climate-change adaptation (Temmerman et al., 2013). In addition, restoring dunes has numerous complementary benefits because they are highly multifunctional EI (i.e., delivering many services) (Harris and Defeo, 2022), adding further incentive to investing in restoring and protecting these particularly sensitive ecosystems.

In a management context, highlighting areas with high or very high multiple-service performance can be helpful because the co-delivery of different services might strengthen cooperation among stakeholder groups when considering, for example, priorities for ecosystem restoration (Turkelboom et al., 2016). However, caution is needed when working with only multiple-service performance, which is analogous to maps of biodiversity hotspots (Schröter and Remme, 2016). Our measure for multiple-service performance can overemphasise areas where EI performance for one or more services is low or even absent, in the same way that not all species are present in biodiversity hotspots. In our results this could be seen for the Durban beachfront, where recreation and sports were high, but coastal protection performance was very low. This is especially true if the mapped services do not appear in bundles (i.e., ecosystem services repeatedly occur together across space or time; Saidi and Spray, 2018) and have no synergistic effects (i.e., one ecosystem service increases the benefits from another; Turkelboom et al., 2016), or even act antagonistically. Furthermore, a different set of ecosystem services, might have resulted in a very different selection of areas with high multiple-service performance. One should therefore be cautious in using the multiple-service performance maps in decision-making and be very clear about the limitations. Therefore, in certain cases it might be more helpful to focus on several maps of single-service performance instead of the single map of multiple-service performance.

Whether measured per service or cumulatively, sites with high EI performance may not always be appropriate to include in conservation areas because they tend to be linked to places with higher levels of demand, which in many cases links to areas with higher population density (Syrbe and Grunewald (2017)). Nevertheless, such sites are still important for sustainable management so that the nature-based activities people engage in (i.e., services they are accessing) can be maintained and continue to provide the same benefits and values over time, e.g., Holness et al. (2022). In these areas, management actions should focus on maintaining flow at a level that is below site-specific capacity to ensure sustained delivery of ecosystem services. The models for these aspects could thus serve as indicators for management to keep flow at sustainable levels.

4.3. Future work

We identified seven ways in which PROSPER could be further advanced in different scale and data contexts. First, it may be necessary to split the underlying polygons representing ecosystem types into smaller functional units specific to the ecosystem service to avoid overestimating the EI extent, particularly if the ecosystem map is delineated at a coarse resolution. This is likely to be most relevant when working at local scales when higher spatial accuracy is required. Second, the structure of the indicator models could be refined with expert input and Bayesian belief networks – a probabilistic approach that is highly transparent in terms of model accuracy (Landuyt et al., 2013) and already successfully applied, e.g., in the ARIES models (Bagstad et al., 2011). This would be beneficial for decision-making, especially at a more local level. Third, in some cases, the maps of ecological condition used to extract only naturally functioning EI may need to be replaced with an initial service-specific cumulative threat assessment (e.g., Singh et al. (2017)). In our case, for example, some EI sites with very low values of coastal protection capacity were potentially falsely included as "naturally functioning", e.g., urban beachfront in Durban, as a result of known limitations of the map of ecological condition at the land-sea interface (Harris et al., 2022b). Fourth, the capacity models consider pressures on EI sites to be linear, which is unlikely to be true. Maximum sustainable service flow is hypothesised to be achieved at different levels of EI integrity depending on the ecosystem service (Cimon-Morin et al., 2013) and most probably reaches a threshold (Defeo et al., 2021). Therefore, thresholds for pressures influencing EI should be investigated, including, if applicable, the service itself as a pressure (Ortiz and Geneletti, 2018), and incorporated into the composite, deterministic models. Fifth, temporal variability could be integrated into the models to reflect changes in the biophysical and socio-economic environments (Renard et al., 2015). Sixth, mapping additional EI (e.g., Holness (2017)) could further advance PROSPER. Additional EI includes all ecological systems that are essential for sustainable service delivery, which could lead to creating an EI network rather than mapping single sites of EI. For example, if an intertidal sandy beach was the EI, the additional EI would be the adjacent dunes and surf zone that function together as a single geomorphic unit called the littoral active zone (Harris and Defeo, 2022). Finally, PROSPER needs to be tested at, and adapted to, different scales. Similar to InVEST (Tallis and Polasky, 2009), a tiered approach that uses more data and parameters at more local scales could be a useful way to improve spatial accuracy at a higher resolution.

4.4. Conclusion

In the current biodiversity and climate crisis, it is necessary to develop and implement practical, relatively simple and functional methods to prioritise conservation areas effectively in various contexts. This is foundational to the actions needed to secure adequate representation and persistence of biodiversity and the health and well-being of current and future generations. Our method, PROSPER, combines an EI framework with an evaluation of all three ecosystem service aspects: demand, flow, and capacity, and integrates human pressures on EI. This innovative approach makes PROSPER particularly useful for spatial assessment and planning processes. We demonstrated proof of concept at a national scale for different services, the outputs of which are already informing place-based actions to secure coastal and marine biodiversity in South Africa. Additional applications include guiding restoration activities and supporting sustainable management. In short, PROSPER is a useful new method for integrating ecosystem services into conservation and management actions, and because of its flexibility, it has the potential to be adapted to different contexts worldwide and be broadly applied. We encourage further use, testing and refinement of this method as we collectively work towards innovation to ensure the long-term persistence of the benefits from healthy ecosystems.

Data availability

See Supplementary. The EI maps are also available for download at: 10.6084/m9.figshare.22340401.v2.

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CRediT authorship contribution statement

Myriam J. Perschke: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing. **Linda R. Harris:** Conceptualization, Funding acquisition, Methodology, Project administration, Supervision, Validation, Visualization, Writing – review & editing. **Kerry J. Sink:** Funding acquisition, Project administration, Supervision, Validation, Writing – review & editing. **Amanda T. Lombard:** Funding acquisition, Project administration, Supervision, Validation, Writing – review & editing.

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.ecoser.2023.101536.

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